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W. A. Milne-Home

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Foreword

The Sydney Basin, as defined in the broadest geographical and geological senses, has been the subject of intensive investigations covering the fields of hydrogeology and related disciplines over the past several years. These investigations have led to a large increase in the body of knowledge about various aspects of the Sydney Basin, but the results of this new work have not been readily available to hydrogeologists and other interested professionals. The Symposium *Groundwater in the Sydney Basin* was convened by the New South Wales Branch of the International Association of Hydrogeologists to provide a forum at which these results could be presented and discussed. It is envisaged that the publication of the CD ROM of these Proceedings will assist in the dissemination of the new knowledge into the scientific and public domain.

The breadth of topics addressed by the investigations was extensive and suggested the division of the scope of the Symposium into five themes:

1. mine water and dewatering;
2. groundwater resources characterization;
3. surface-groundwater interaction;
4. ecohydrology and groundwater dependent ecosystems; and
5. salinity.

Forty four manuscripts included in these proceedings, representing both oral and poster presentations, of which seventeen address Theme 2. Themes 1 and 3 include ten manuscripts each. Of the remaining manuscripts, three were allocated to Theme 4 and four to Theme 5. Some presentations describe work which covers more than one theme and have been assigned by the Committee on the basis of their main area of concentration. Subsequent sections of this Foreword summarize the papers in each theme.

Mine Water and Dewatering

The majority of manuscripts within this theme describe investigations and modelling of the potential and actual impacts of longwall mining in the Southern Coalfield on surface and ground water, with one manuscript on the Hunter Valley. Booth provides an international perspective on hydrogeology and longwall mining in his keynote address. The keynote paper by Jankowski gives an overview of these impacts in the Southern Coalfield and extends the information in the poster by Jankowski and Madden. Information specific to the Dendrobium Colliery Area 1 is given by Madden and Ross, while investigations at Dendrobium Area Colliery 2 are described by Madden and Merrick. In another paper, Merrick discusses the application of the MODFLOW family of modelling codes to these issues at the Metropolitan Colliery of the Southern Coalfield. Dundon extends the modelling approach to a discussion of longwall mining impacts in the Hunter Valley.

In the second group of papers on this theme, Kwantes et al describe groundwater balance estimates for the unlined rock storage cavern at Port Botany and David et al provide an overview of the potential impacts of the extraction of coal seam methane, with emphasis on the Sydney Basin. Parra discusses modelling the impact of dewatering a construction site near Raymond Terrace on nearby groundwater dependent ecosystems.

Groundwater Resources Characterization

The stimulus for many of the recent investigations has been the Metropolitan Water Plan developed by the government of New South Wales in 2004 to provide a drought water supply for the Sydney metropolitan region. The principal hydrogeological targets were aquifers within the Hawkesbury Sandstone sequence of Triassic age in Western Sydney and the Southern Highlands, although other formations and areas also have been investigated.

The keynote paper by Ross establishes the technical, environmental and resource management framework for characterizing the region's groundwater resources. Studies of the hydrogeology and groundwater resources of areas within the regional exploration program are described in three papers: Hawkes et al on Leonay-Emu Plains; Webb et al on the Lapstone Structural Complex in Leonay and Wallacia, and Ross and Carosone on water level trends in Kangaloon. Technical aspects of the work are the subjects of a further three papers within this group. Tammetta and Hawkes discuss the analysis of aquifer tests of the Hawkesbury Sandstone at Leonay, and McLean and Ross show how chemical and isotopic studies were applied in Leonay and Wallacia. In the third paper, Cook and Ross present the results of a resistivity imaging and sounding survey near Kangaloon.

This work was managed by the Sydney Catchment Authority but related investigations were undertaken by the NSW Department of Water and Energy (DWE). Green et al describe the aquifer systems of the lower Blue Mountains between Springwood, Richmond and Penrith. Russell et al extend the assessment to the Hawkesbury Sandstone and the Narrabeen Group across the Sydney Basin. The last paper on the DWE work is by Williams et al who concentrate on resource management policies. Included also is an investigation of hydrogeology and groundwater resource development in the Terrigal Formation and alluvium on the Central Coast by Cook under the Gosford and Wyong Councils Water Authority Joint Water Supply Scheme.

The stratigraphy of the Hawkesbury Sandstone and the recognition of hydrostratigraphic units for regional correlation are treated by Lee. Alternative interpretations of the stratigraphy and hydrostratigraphy are given in the poster by Nolan. These authors refer to the fractures in the Hawkesbury Sandstone as a groundwater flow mechanism, and De Castro et al describe borehole imaging data which show details of fracture properties of the Hawkesbury Sandstone in the Sydney Basin.

Borehole techniques for the detailed characterization of the hydraulic properties of aquifers are demonstrated in two papers. The first paper, by Peterson et al, shows how discrete zones within a borehole may be pressure tested and sampled by a straddle packer technique. Waring et al illustrate the potential of down-hole geophysical logging for deriving estimates of relative porosity and, in combination with the injection of a tracer, to measure hydraulic conductivity. Finally, Timms and Acworth quantify potential impacts of leaky boreholes drilled into the Hawkesbury Sandstone by use of a numerical model in their poster

Surface-groundwater interaction

Papers in this theme examine the nature of the interconnection between surface and groundwater. Various techniques of measurement and modelling of runoff, streamflow and the use of environmental isotopes as tracers in the hydrologic cycle are described. One paper discusses the enhancement of the recharge phase of the cycle through managed aquifer recharge (MAR). McKay, in his keynote address, illustrates the role of fractures and macropores in the infiltration and movement of water and contaminants in fine grained sediments such as clays.

The management of water resources volumes and quality necessitates a clear understanding of the hydrologic cycle. Biswas et al discuss a water balance model for predicting streamflow and groundwater levels, applied to Wybong Creek in the Upper Hunter catchment. Modelling rainfall, streamflow and salt loads in Widden Brook, which flows into the Goulburn River in the Upper Hunter River catchment, is the subject of the poster presented by Somerville et al. Studies of streamflow and water quality in the Goulburn River, including the use of strontium isotopes, are reported by Macdonald et al.

Isotopes as environmental tracers on various scales are investigated by a group of papers within this theme. Scarff et al used a suite of tracers to assist in hydrograph separation from a rain event in a small agricultural catchment in the Southern Highlands. On a larger scale, McLean et al show the application of multi-isotope methods, including applied tracers, to the evaluation of fractured Hawkesbury Sandstone within the Nepean River catchment. Similar approaches, concentrating on fluorescent dye techniques, are reported by McFarlane et al for a field study in Waratah Rivulet catchment, a tributary of Woronora Lake. Woronora is an important part of the system of water supply storages operated by Sydney Water. The last paper in this group, by Short et al., shows how the interaction between surface and groundwater in the Woronora Plateau was monitored by field measurements, modelling and the use of tritium isotopes.

Upland swamps are features of the Woronora and Illawarra Plateaus, and Ross describes major aquifer pumping tests in the Kangaloon area during which the effects on water levels in neighbouring upland swamps were monitored. In contrast to groundwater pumping, MAR provides an alternative for subsurface water storage. The potential for this water management technique for application in the coastal sand aquifers of Sydney is discussed by Badenhop and Timms.

Ecohydrology and groundwater dependent ecosystems

Three submissions fell within the scope of this theme: two of these address faunal issues, and the third describes interactions between vegetation and groundwater. Hose and Lategan demonstrate the occurrence of stygofauna within fractured sandstone aquifers at Kangaloon and Kulnura. Hancock presents an investigation of the effects of drought on groundwater invertebrates in alluvial aquifers. The reduction in groundwater levels reduces the supply of nutrients to rivers as groundwater discharge decreases during drought.

In the case of mine and municipal waste storage sites enhancement of evapotranspiration by vegetation to reduce deep drainage can be a viable technique. Eamus et al provide an example of combined modelling and field measurements in the Cumberland Plain woodland to show how the establishment of appropriate vegetation at waste sites can be an effective tool for their management.

Salinity

Three of the four papers represented in this theme extend the scope of the surface-groundwater interaction studies in the upper Hunter Valley catchment to focus on salinity. Jasonsmith et al pose a rhetorical question on the origins of salinity in Wybong Creek. The paper by Somerville et al approaches the topic of salinity in Widden Brook through the use of major ion chemistry of streamflow, groundwater, supplemented by stable isotopes, together with a discussion of mineral weathering. This hydrogeochemical approach is combined with streamflow discharge and salinity by Macdonald et al to describe the salinity dynamics of Wollombi Brook catchment.

In the fourth paper McNally presents a discussion of salinity in areas of Western Sydney. He suggests that the salt originates from windblown aerosols rather than from relict seawater in the pores of the Ashfield and Bringelly Shales.

Acknowledgements

The Symposium Convening Committee would like to express its deep appreciation of the rigorous and insightful reviews of submissions by the Technical Review Panel. These reviews have added to the value of the papers and posters included in the Symposium proceedings.

The Committee also thanks the sponsors whose support is essential to the Symposium. These sponsors are:

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Also, the Committee acknowledges Dealers Group, especially Cheryl Samarasinghe and Heidi Jeptha for their unfailing good humour and wholehearted collaboration with the Committee in the planning and organization of the Symposium. Finally, members of the Committee are thanked for their role in developing the symposium from concept to fruition.

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Oral Presentations

Presenters of Keynote Addresses are listed in **Bold Type**
Themes are parenthesized

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Posters

IAH NSW, *Groundwater in the Sydney Basin Symposium*, Sydney, NSW, Australia, 4-5 Aug. 2009, W.A.Milne-Home (Ed)
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Managed Aquifer Recharge in Sydney Coastal Sand Aquifers

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Abstract

Integrated water management projects such as managed aquifer recharge (MAR) have the potential to be a vital component of Sydney's future diversified water supply. In addition to large scale MAR in the Botany aquifer, there is also potential for small scale local MAR projects to contribute to (or offset) the water use of local amenities. MAR schemes have been commissioned at UNSW, and are being considered at Manly Golf Course and development areas of the City of Sydney.

The Botany sand aquifer is the most significant aquifer in the Sydney region. With generally good quality groundwater, permeable sands and naturally high recharge sites, the north-eastern Botany sands are well-suited to recharge schemes. Given that the sustainable yield of the Botany aquifer is under debate, and groundwater usage data is not available, it is uncertain how many MAR schemes would be feasible, however a first pass assessment indicates that multiple schemes with a capacity of up to 5 ML/day are possible. Sewer mining could provide a reliable source for continuous MAR operation, particularly during dry periods.

Groundwater extraction at Manly Golf Course has led to groundwater flow reversal and declining yields since 2002, with 20% increases in groundwater salinity. To improve water quality discharging to Manly Lagoon and secure groundwater supply by mitigating saline intrusion, incidental aquifer recharge could be boosted with appropriate MAR systems, including a recharge pond and an adjustable weir. A first-pass quantitative assessment has indicated minor mounding of the watertable during MAR. With detailed assessment, design and management, the possibility of mounding and waterlogging at this site could be reduced to a low residual level (EPHC, 2008). This case shows that infiltration and recharge of coastal sand aquifers could improve stormwater quality to comply with ANZECC (2000) and EPHC (2008) guidelines, with a monitoring and response plan to ensure effective attenuation of contaminants.

Keywords: Groundwater, managed aquifer recharge (MAR), Botany Sands

Introduction

With the population forecast to reach 5.3 million by 2031, the demand for water in Sydney is increasing.. One of the key principles undergirding the 2006 Metropolitan Water Plan is to "*minimise the risks of water shortages by diversifying sources of supply*" (NSW Government 2006). While managed aquifer recharge (MAR) was not mentioned as one of the possible suite of alternatives in the Plan, MAR has the potential to be a component of Sydney's future diversified water supply. The Draft Australian Guidelines for Water Recycling – Managed Aquifer Recharge (EPHC, 2008) defined managed aquifer recharge as "*the intentional recharge of water to aquifers for subsequent recovery or environmental benefit; the managed process assures adequate protection of human health and the environment. Aquifers may be recharged by diversion of water into wells or infiltration of water through the floor of basins, galleries or rivers.*"

Recharge of treated stormwater and wastewater to shallow sandy aquifers has been practiced at many sites around the world, including a successful trial of infiltration galleries in a shallow sandy aquifer in Perth (Toze and Bekele, 2009). This project has highlighted the advantages of MAR in an urban environment as a relatively cheap water storage option with documented potential to improve the quality of recharge water. Elsewhere, treated river water is used to recharge shallow sandy aquifers that supply Amsterdam in the Netherlands, while river bank filtration is common in Germany. The South African town of Atlantis (population 100,000) has relied on 15 ML/day of potable supply from aquifers that have been recharged with stormwater and treated wastewater for over 30 years. At Atlantis, there are now over 400 exploration, production and monitoring bores in the unconfined sand aquifer that is up to 40 m thick (Wright and Parsons, 1994).

The Botany sands aquifer has good potential for large scale MAR in the Sydney metropolitan area. Located within the Botany catchment a few kilometres south of the Sydney CBD (Fig. 1), the Botany sand aquifer is classed as a highly vulnerable aquifer. Groundwater extraction in the southern Botany aquifer is embargoed in Zones 1-4 due to industrial contaminants (Fig. 1A), however, excellent groundwater resources are available in the north-east of the aquifer in the suburbs of Randwick, Kensington, East Lakes, Kingsford and Maroubra. The aquifer consists of approximately 30 metres of unconsolidated aeolian sands intercalated with minor clay and peat deposits (Fig. 2). The windblown sands fill deep, steep-sided valleys incised into Triassic age Hawkesbury sandstone (Griffin, 1963; Albani et al, 1981). The natural groundwater flow direction is from the recharge areas in the north-east towards Botany Bay at rate of about 150 m per year (Yu, 1994; McNally and Jankowski, 1998).

In addition to large scale MAR in the Botany aquifer, there is also potential for small scale local MAR projects to contribute to (or offset) the water use of local amenities, with MAR schemes commissioned at UNSW, and being considered at Manly Golf Course, development areas of the City of Sydney and elsewhere.

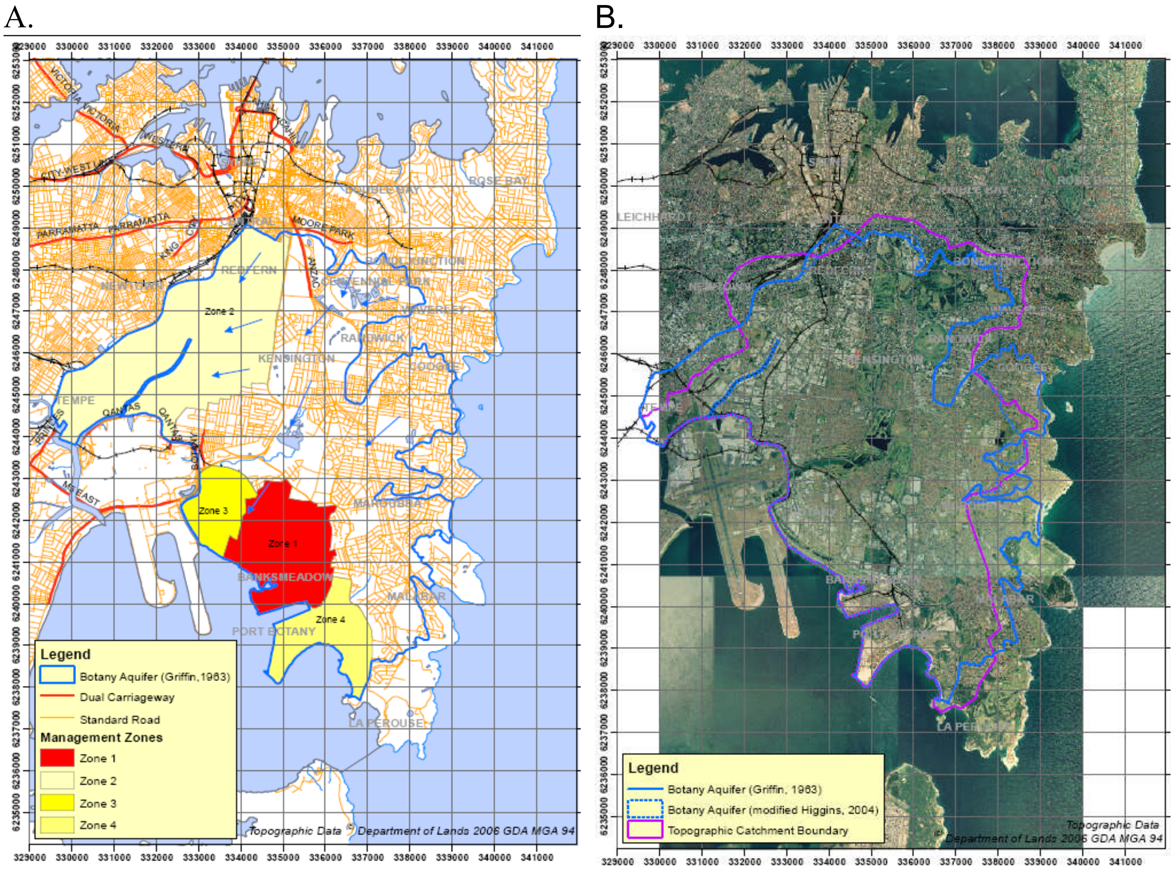

Figure 1: A) Botany aquifer location, management zones and groundwater flow directions and B) catchment and aquifer boundaries (Higgins, 2004).

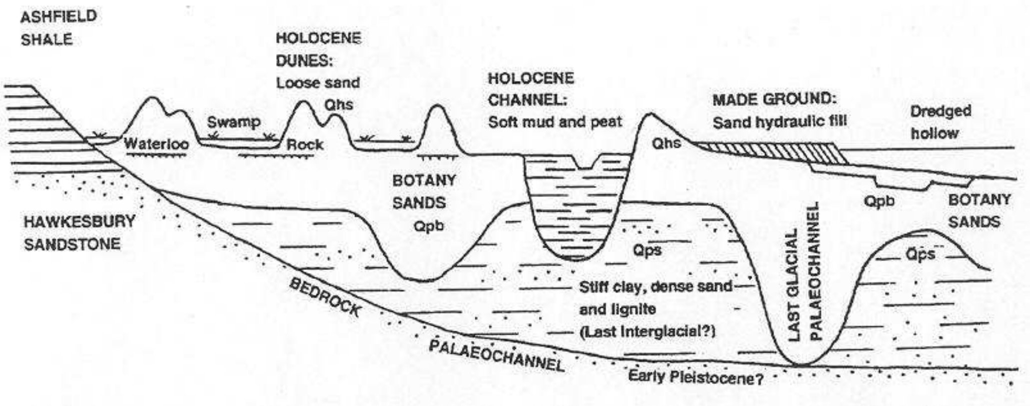

Figure 2: Section through the Botany aquifer north-east to south-west (McNally and Jankowski, 1998).

Large Scale MAR – Botany Aquifer

Hydrogeology of the Botany Aquifer

The Botany aquifer (5,314 hectares), as defined in Fig. 1B, occupies about 84% of the Botany catchment (6,356 hectares). Although much of the upper catchment is underlain by shallow rock rather than saturated aquifer, the area remains an indirect source of recharge.

The aquifer is bounded by thick clay deposits in the west, and numerous rock outcrops in the east. Unconsolidated sediments include significant sand deposits, coffee rock and peat, and are increasingly silty and clayey in the western part of the basin. Paleochannels within these sediments are important groundwater flow conduits, however, depth and channel morphology in some areas are subject to some uncertainty. For example, although the maximum aquifer depth is commonly reported as 80 m, detailed work by Woodward Clyde (1996) indicated the actual paleochannel depth near Botany Bay is approximately 65 m. There is a need for improved definition of aquifer geometry based on additional geophysical surveys (eg. gravity method) and test holes in key locations.

The Botany aquifer is in a state of dynamic hydraulic equilibrium and, unlike many other aquifers in NSW, has shown no evidence of stress prior to 2003. Detailed evaluation is required of groundwater level data (1970’s to 2009) that is representative of aquifer conditions, and pumping stresses, including recent automated logger data.

Sustainable Yield & Usage

Inflows, or recharge, to the Botany aquifer include rainfall, leakage from ponds and probably a minor leakage component from sewers and mains supply. Groundwater modelling has indicated rainfall recharge of 22-44 ML/day during a dry and wet period respectively (Merrick, 1994). It is estimated that 30% of rainfall recharges the catchment area, similar to shallow sandy aquifers at Tomago and below Perth. However, there is significant uncertainty as various groundwater models of the area have used recharge values ranging from 6-96% of rainfall.

The long-term sustainable yield (or abstraction limit, defined as 70% of the estimated annual average recharge) for the northern aquifer zone between Botany Bay and Centennial Park was estimated by DNR in 2000 to be 39 ML/day (14.3 GL/year) (Bish et al., 2000). Scientific studies are needed to identify realistic recharge rates, and to inform a review of groundwater dependant ecosystem (GDE) water requirements and sustainable yield limits.

It appears that groundwater usage may be less than the currently defined sustainable yield. Over 600 registered bores are located in the Botany aquifer, with some 70 licensed but mostly unmetered bores; therefore groundwater usage data is not available. Based on the latest groundwater status report (Bish et al., 2000), the aquifer could probably support ~10 ML/day increased abstraction in the northern zone without the need for MAR. However, this additional available volume is probably within the error margin of estimated sustainable yield and cannot be assumed with confidence.

Water Quality

Other than areas of point source contamination, groundwater in the north-eastern aquifer requires only minor treatment to achieve the beneficial use category of drinking water. Precautionary disinfection using UV for example, and removal of high iron and manganese concentration would be required prior to potable use. It is therefore important that this water is not degraded to a lower beneficial use category. The Water Research Laboratory has assessed groundwater quality in numerous irrigation bores and spear-points over the past 15 years. Groundwater in the north-eastern part of the aquifer is generally low salinity (EC 125-202 μS/cm), slightly acidic (pH ~5.5), with dissolved oxygen at concentrations of <3.5 mg/L. Bacterial indicators and higher nutrient concentrations have been observed near main sewers, unlined landfills (Acworth and Jorstad, 2006) and other nutrient sources. Sampling at the UNSW campus (9 samples, January 2007) confirmed that groundwater quality is good, though not pristine. Total dissolved salts were 153-315 mg/L, nitrate concentrations 0.5-8.9 mg/L as N, and *E.Coli* <2 to 170 CFU/100 mL. Faecal Streptococci and Enterococci were also detected at low levels (WRL unpublished data).

A minimum residence time of 50 days has been adopted in Australian guidelines for injecting undisinfected water in aquifers where water is to be used for irrigation or recreation (Dillon and Pavelic, 1996). MAR could provide additional treatment for stormwater (eg pathogens and trace metals) and for treated wastewater (eg persistent chemicals of concern, COCs). Aquifer recharge could therefore be an important component of a ‘multiple barrier’ approach to water reuse, provided that beneficial use of the aquifer is not compromised. The sand aquifer would likely act as an effective filtration and attenuation medium for a range of specific contaminants. Detailed assessment of the fate of specific pathogens and COCs in simulated groundwater conditions is required to determine opportunities and risks for water reuse through MAR in the Botany aquifer.

Potential Water Sources for Recharge

Recharge water could be provided by additional stormwater diversions or by the addition of high quality treated wastewater. A pre-feasibility assessment by Timms et al. (2006) reported that additional recharge water from sewer mains may be the preferred option for a secure additional source of recharge water (Table 1). As sewers are operated using mains supply imported from catchments outside the Sydney CBD, the use of sewer mining combined with MAR would represent an importation of water to the Botany catchment. Although sewer mining volumes would vary somewhat diurnally and seasonally, this water source would be relatively reliable and mostly independent of climatic factors. However, the possibility of additional recharge water from stormwater sources from some areas not already diverted to ponds and areas located adjacent to the Botany catchment warrants further investigation.

Extraction of wastewater can occur before or after the sewage treatment plant (STP). Sewer mining is the process of extracting wastewater from a sewerage system and treating it for a specific end use (Sydney Water, 2006). There are a number of sewer mining projects under development in Sydney following the success of the schemes at Olympic Park and at Kogarah, however, no sewer mining has yet been developed in NSW in conjunction with MAR.

Table 1: Comparison of MAR Water Sourced from Stormwater and Sewer Mining

Characteristic	Stormwater harvesting	Sewer mining
Security of supply	Not reliable	Reliable
Available volume	High coastal rainfall with high intensity, short duration urban runoff. Available volume could be supplemented with stormwater from adjacent catchments.	Relatively constant volumes of water imported from outside the catchment. Available volumes from nearby sewer lines currently unknown.
Infrastructure requirements	Diversion and relatively large retention storage of stormwater to match MAR capacity	Access to Sydney Water sewer mains, treatment plant and balancing storage
Treatment required	None or basic treatment for suspended solids, nitrate and metals, particularly for first flush.	Advanced wastewater treatment technologies
Relative cost	Moderate	High

The volume and characteristics of sewage that may be harvested from these sewers near possible MAR sites would require an assessment by Sydney Water in regard to minimum flow rates that are required in the sewer mains. Sewer discharges in the area would be mainly residential and can be approximated at an average rate of 250

L/day/person and 2.2 persons per residence, i.e. 1 ML/day from approximately 10,000 residences.

Types of MAR Systems

Several different MAR systems may be suitable for use in the Botany aquifer in different locations. The most likely options would be the following, depending on land availability and the protection of water quality that is afforded:

- Infiltration tanks - Using porous structures (eg. recycled plastics) to maximise storage capacity and infiltration. Protection of water quality over the long term requires assessment.
- Recharge pits - Using natural porous media such as graded gravels and coarse sand to increase recharge. Long term hydraulic performance (eg. clogging) and water quality protection requires assessment.
- Ponds or basins - A spreading type of MAR usually with a number of basins used in rotation. Clogging problems can be managed by smart design and maintenance schedules. The large area of land required may be prohibitive.
- Drilled boreholes - Aquifer storage recovery (ASR) where the well/borehole is used for both recharge and abstraction, or aquifer storage transfer recovery (ASTR) where water is injected and recovered some distance away to take advantage of water treatment and delivery capacity of the aquifer. Advantageous when land is scarce.

Knowledge Gaps and Recommendations

While there are many knowledge gaps for the Botany aquifer, it is possible that multiple MAR facilities with a capacity of 5 ML/day could be constructed in the NE Botany aquifer. The conceptualisation of MAR in the Botany aquifer represents the first step assessment of the technical suitability of the aquifer, recharge sources and treatment required, and demand for groundwater supplies. Limitations and assumptions of this rapid first-pass assessment were outlined by Timms et al. (2006), along with recommendations for an updated status assessment of groundwater quantity and quality. The feasibility of any such scheme needs to be further evaluated to comply with EPHC (2008). A sustainability assessment is recommended in conjunction with detailed feasibility assessment to ensure a best practice approach. A sustainability assessment would adopt a ‘triple bottom line’ approach that could compare various MAR options, such as recharge using stormwater or treated wastewater.

A staged program of aquifer investigation should include refined groundwater flow modelling based on targeted geophysical surveys and test drilling, 3D geological modelling, independent recharge measurements using hydraulic, hydrochemical and isotope techniques, and identification of ecological water requirements. Laboratory and numerical modelling studies are required to demonstrate aquifer capacity for attenuation before proceeding to low risk field tests using water quality markers. Successful MAR schemes using stormwater should be demonstrated to protect environmental and human health, prior to any use of treated wastewater.

Small Scale MAR Projects

Small scale MAR schemes may be able to offset or supplement water use of local amenities overlying Sydney coastal sand aquifers. UNSW commenced one of the first large MAR schemes in the Botany aquifer in 2006 to counter-balance increased abstraction of groundwater. A 1ML percolation pit was constructed using recycled plastic cells and geotextile fabrics under the Village Green. It was estimated that the pit would collect 160ML of stormwater per year and return it to groundwater, allowing an increase in groundwater extraction for non-potable uses on campus. However, the efficiency of stormwater capture has been decreased by leaf litter blockage of entry screens and the need for frequent cleanout of the gross pollutant trap. Changes to groundwater levels, flow rates and groundwater quality as a result of this MAR scheme have not yet been examined to demonstrate the sustainability of this scheme.

At Manly Golf Course, MAR may be able to secure groundwater supplies where sustainability is uncertain due to saline intrusion and declining yields. Irrigation bores at Manly Golf Course (MGC) have been declining in yield since 2002 whilst groundwater extracted has increased in salinity by approximately 20% over the same period (Fig. 3). Groundwater flow has reversed in the vicinity of the irrigation bores. Manly Golf Course is an example of a location where incidental aquifer recharge has been occurring for decades, with natural infiltration of creek discharge into a relatively permeable grassy channel. However, recharge efficiency may be improved with the addition of a recharge pond and adjustable weir.

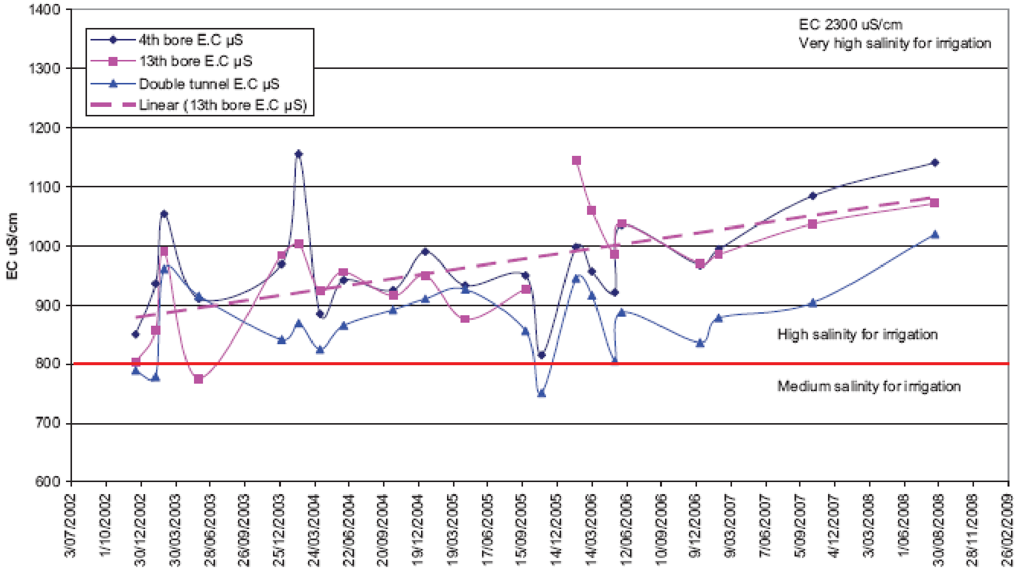

Figure 3: Measured Groundwater Salinity at MGC bores 2002-2009

MGC overlies a relatively shallow sandy/sandy-silty unconfined aquifer, with groundwater levels averaging 0.5 m – 1.3 m below ground (mbg). In the proposed recharge area the saturated aquifer thickness is approximately 15 m, while the aquifer is known to be greater than 20 m thick in parts. Transmissivities of 5-77 m^2/day were calculated by AGC Woodward-Clyde (1992) using pump test results, translating to hydraulic conductivity in the order of 1-10 m/day.

A first-pass quantitative assessment of mounding was considered essential because of restrictions for MAR in urban areas which are <8 m below ground (EPHC, 2008). The presence of a high watertable limits the potential use of recharge devices, but does not preclude well designed and managed recharge systems (ARQ, 2006). WRL has reached the preliminary conclusion that with detailed assessment, design and careful management, the possibility of mounding and waterlogging at this site could be reduced to a low residual level as per the Entry Level Risk Assessment (EPHC, 2008). In a sandy unconfined aquifer, groundwater flow away from a recharge source is relatively rapid and therefore minimizes watertable mounding. The proposed recharge site is located in an open area, only partially constrained by urban development.

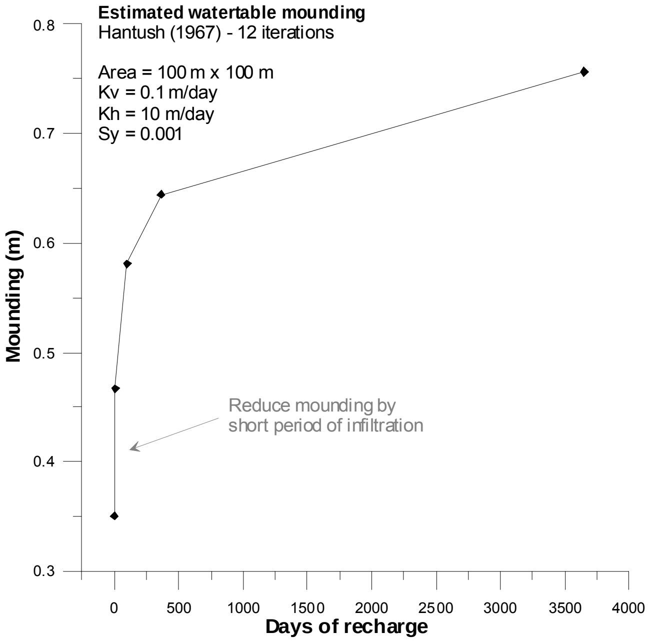

Figure 4: Mounding relative to no. recharge days

Estimates of watertable mounding were calculated based on the analytical method of Hantush (1967) where an unsaturated zone is maintained beneath the infiltration surface. The estimates for watertable mounding were based on a vertical infiltration capacity determined by the nature of the surface of the recharge area rather than the depth of water ponding, and assumed an isotropic, homogeneous aquifer of infinite extent and steady state conditions that do not account for temporal dynamics immediately following a recharge event.

The significance of the recharge time for a generic area is shown in Figure 4 with the greatest mounding shown for constant recharge (ie. steady state) over 3650 days (as recommended by Poeter, 2005). However, mounding can be minimized if the recharge surface is infiltrating for a limited time period, such as immediately after rainfall events.

Estimated watertable mounding for the proposed design of the recharge channel (ie. infiltration surface 285 m length by 5 m width) is shown in Figure 5. Figure 5A shows that mounding is minimized because of a thick aquifer, and is probably within the range indicated between 1 and 10 m/day for lateral hydraulic conductivity (K_h) of this aquifer. Figure 5B shows that estimated mounding beneath the centre of the recharge area is likely to be <1 m, and could be <0.5 m if the infiltration rate is limited 0.1 m/day (K_v).

The limitations of the analytical mounding model are important to note, as it cannot accurately determine the lateral extent of watertable mounding. These estimates also do not apply to a pond that intersects the watertable, where no unsaturated zone is maintained beneath the infiltrating surface; a situation that may occur given the shallow water table. Groundwater flow modelling coupled with surface water flow would be required to provide better estimates of the extent and timing of mounding in a 3D environment, determine recharge rates and interaction with surface water.

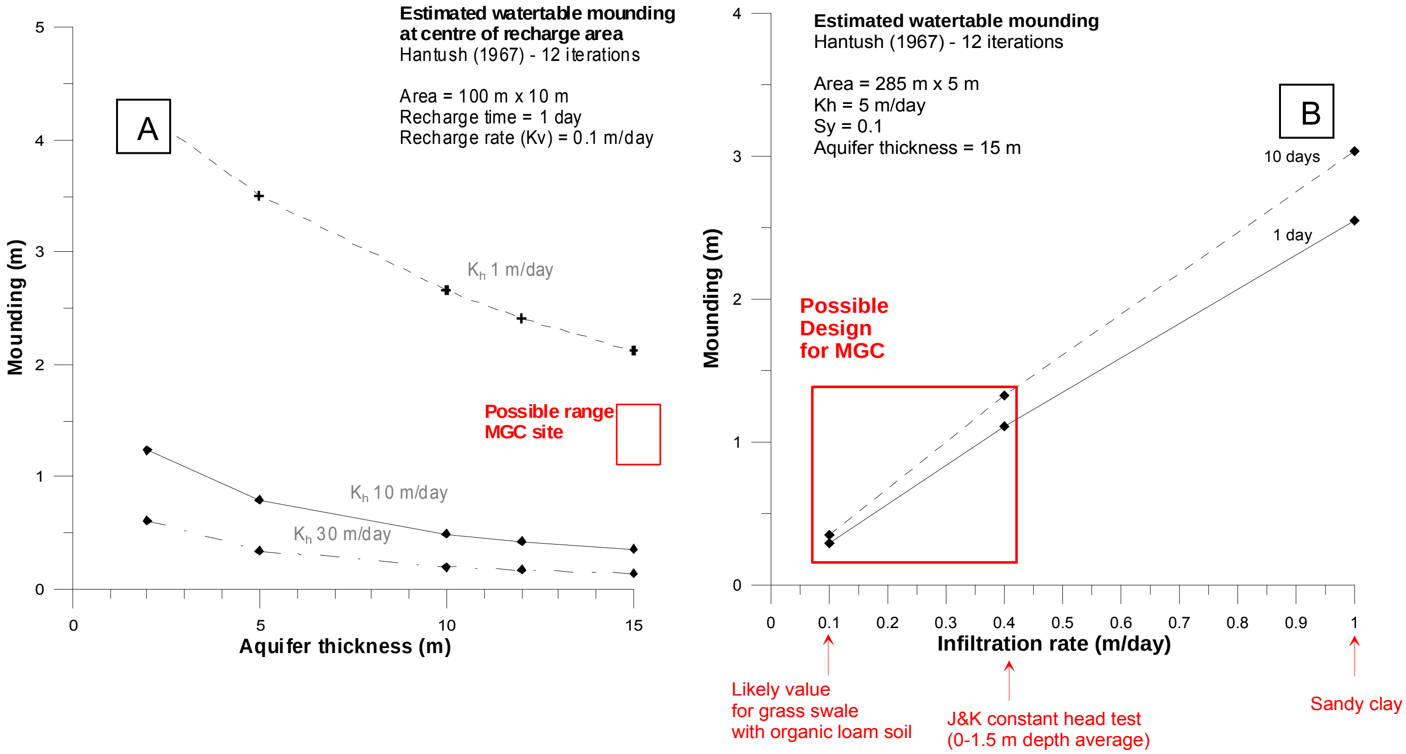

Figure 5: Preliminary Design Estimate of Water Table Mounding

As stormwater discharge to Manly Lagoon does not currently comply with guidelines for discharge to a marine or estuarine environment (ANZECC, 2000), stormwater treatment including infiltration in a MAR scheme provides an opportunity to improve overall water quality. Additional stormwater treatment is required for discharge to Manly Lagoon to achieve high attenuation factors (AF). For example, AF factors of 9 for total nitrogen (TN), 115 for copper (Cu) and 18 would be required for lead (Pb). By comparison, relatively low contaminant AF were required for MAR of stormwater (e.g. 2 for TN, 5 for Cu, 16 for Pb) to maintain average groundwater quality conditions in the aquifer.

Natural attenuation of metals and nutrients occurs during the infiltration and recharge process to varying extents for specific contaminants, and is allowed for by the draft Australian MAR guidelines (EPHC, 2008). Metals are typically attenuated by sorption to clay and organic matter, although the attenuation of nitrogen species in coastal sand MAR systems may not be as effective. A monitoring and response plan to ensure effective attenuation of contaminants is recommended. Advantages and disadvantages of the proposed MAR scheme of recharge through a grassy channel and shallow pond, with level controlled by installation of an adjustable weir are summarised in Table 2.

Table 2: Advantages and Disadvantages of MAR proposal for MGC

Advantages	Disadvantages
• Improved quality of catchment discharge to Manly Lagoon • Moderate change to current situation if recharge pond incises watertable • Soil zone improves stormwater quality during infiltration – organic and clay rich sediments above the sand aquifer largely remove phosphorous and metals. These are the contaminants which require greatest attenuation to meet current groundwater quality and ANZECC 2000 Estuarine guidelines	• Low recharge rate through grassy channel • Moderate recharge rate possible through pond that incises watertable • Minimal increase in groundwater storage • Minimal protection from saline intrusion • Small to moderate improvement in reliability of irrigation supply

The proposed MAR scheme at MGC has not yet proceeded due to factors including regulatory uncertainty, although preliminary investigation has found that shallow watertable conditions are manageable. Water quality issues are a key concern for this site, despite the net environmental benefit and the potential of the proposed MAR to improve the quality of discharge to Manly Lagoon. However, significant investment is required to cover the costs of MAR compliance and to demonstrate the success and sustainability of MAR under local conditions. In the Sydney area, schemes have proceeded in the past without an appropriate level of investigation and monitoring, with a lack of publically available information on MAR successes and difficulties. Technical MAR issues and the uncertainty of evolving requirements at local council, State and National level require further attention.

Conclusions

MAR has the potential to be an important part of Sydney’s future diversified water supply, with both small scale and large scale projects contributing to water requirements. There is significant potential for large scale MAR schemes in the north-eastern Botany sands aquifer with good quality water and current water use assumed to be below sustainable yield. Small scale projects, such as that proposed at Manly Golf Course, may also have the potential to offset water needs on a local scale, counter balance saline intrusion that is occurring and provide amenity during periods of water stress. However, there are several knowledge gaps to be addressed before these projects can be demonstrated to be successful, sustainable and economically viable. Information on successful MAR schemes would assist in resolving regulatory uncertainty regarding the application of draft MAR guidelines at a local and state level. These examples highlight the need for high quality hydrogeological data, modelling and planning for effective MAR projects.

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Groundwater Levels and Stream Flow Prediction in the Hunter River Catchment

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Abstract

Recent water sharing plans in New South Wales have highlighted the need to manage surface and ground water as a connected system. To improve water resources management there is a need to predict and quantify the interactions between groundwater levels and streamflow in catchments. In this work the use of a simple monthly, conceptual model is explored to assess its usefulness for predicting simultaneously groundwater levels and streamflow. The study site chosen was Wybong Creek in the Hunter catchment NSW. The two parameter water balance model predicts streamflow in catchments using spatially interpolated monthly rainfall and pan evaporation data as inputs. Predicted groundwater levels within unconsolidated unconfined aquifer had calibration R^2 value of 0.83. Time lags between rainfall and groundwater level response varied between 0 to1 months, appropriate to the relatively shallow bores. The results can be used to support the Hunter water management initiatives and also other management problems where long-term rainfall and evaporation data are not sufficiently available.

Keywords: Groundwater level, streamflow, water management, water balance model.

1. Introduction

Information of the impacts of water abstraction and climate variability on the stream and groundwater resources is fundamental to the sustainable management of catchments. In this paper we examine the prediction of groundwater levels and streamflow in Wybong Creek, a subcatchment of the Hunter River. The catchment produces irrigated crops and pasture, is used for dryland grazing and has major coal deposits scheduled for open cut mining. It is important that baseline information be collected before mining commences.

Monthly water balance models (for example Makhlouf and Michel, 1994) have widely been used for long term management of water resources, reservoir design and reservoir operation. Water balance models calculate the amount of water coming into is stored, and flowing out of the catchment which is explicitly conserved using an appropriate water balance equation. Thornthwaite and Mather (1955) developed a set of deterministic monthly water balance models, in which only two parameters were used. In developing an index of meteorological drought, Palmer (1965) suggested a model that divides the soil moisture storage into two layers, each with its own soil moisture capacity as the model's two parameters. Both the Thornthwaite and Palmer models used the concept that runoff and recharge does not occur until the soil moisture capacity threshold is reached. This assumption tends to underestimate runoff during summer and autumn, as runoff can still occur over a range of soil water contents. The assumption depends on the rainfall distribution of the study region and irrigation amount of the catchments. Alley's (1984) review of the water balance models concluded that prediction errors were similar among the models. Gleick (1987) developed a monthly water balance model specifically for climate impact assessment and addressed the advantages of using water balance type models in practice. In the 1990s, monthly water balance models were developed for studying the impact of climate change on the hydrological balance and for general water resources planning and management (Mimikou et al., 1991; Guo, S. 1992; Guo and Yin, 1997; Xu and Singh, 1998; Xiong and Guo, 1997). Vandewiele and Elias (1995) used a spatial surface model to fit parameter values to estimate runoff from ungauged catchments.

Most models are over parameterized leading to interactions between parameters and correlation between parameter estimates (Jakeman and Hornberger, 1993). A conceptual model with few parameters is required for reducing the computational complexity. A simple two parameter monthly water balance model was developed by Xiong and Guo (1999) and applied to seventy subcatchments located in the south of China for runoff simulation. Jellett (2005) further developed this model and applied it to predicting groundwater levels as well. In this paper the usefulness of the modified two parameter monthly water balance model in predicting groundwater levels and streamflow in the Wybong Creek cathment of the Hunter Valley is examined.

2. Overview of water balance model

The proportioning of rainfall at the Earth's surface envisaged in the simple water balance model is shown in Fig. 1. Precipitation P (mm) falls on the catchment, some water is lost through evapotranspiration E (mm) while some water leaves the catchment as runoff Q (mm). The remaining water infiltrates into the soil causing an increase in soil moisture storage ΔS (mm) and G is the groundwater level (m above mean sea level). The water balance equation for the system shown in Fig. 1 is:

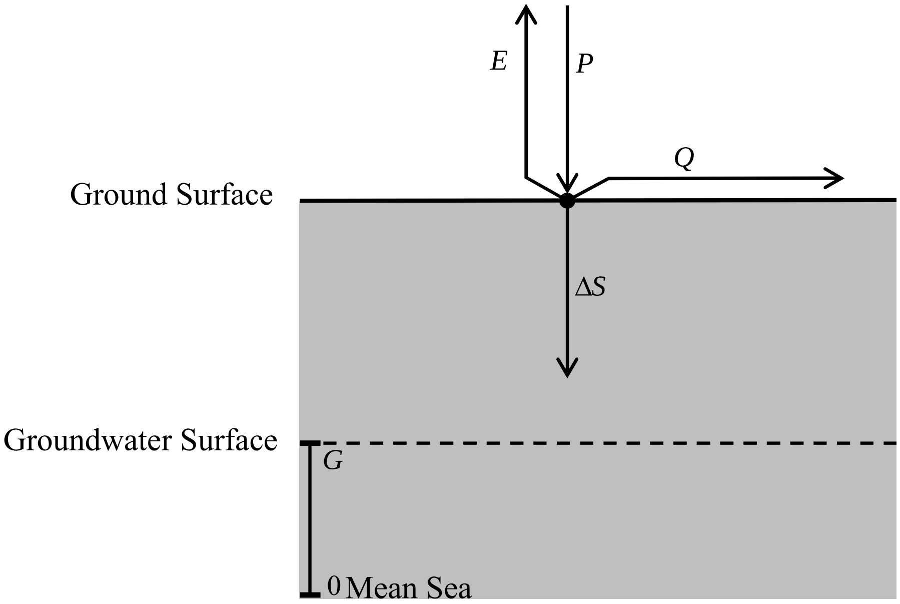

Figure 1 The portioning of precipitation at the ground surface into runoff, evapotranspiration and change in the soil moisture store

$$P = E + Q + \Delta S \tag{1}$$

or in discrete time interval, t

$$P_t = E_t + Q_t + S_t - S_{t-1} \tag{2}$$

where *t-1* is the previous time interval

2.1 Xiong and Guo Model

The Xiong and Guo (1999) (XG) model is a conceptual monthly water balance model designed to predict the runoff from large catchments. The input data used are monthly rainfall and pan evaporation. The stream flow model has two parameters: an evapotranspiration parameter and a runoff parameter. Actual evapotranspiration E_t (mm) is estimated in eq (3) using the evapotranspiration parameter β_E, the pan evaporation E_{pan_t} (mm) and the rainfall P_t (mm).

$$E_t = \beta_E E_{pan_t} \tanh\left(\frac{P_t}{E_{pan_t}}\right) \tag{3}$$

The runoff Q_t (mm) follows from the previous time period's soil moisture content (mm), rainfall (mm), pan evaporation (mm) and the runoff parameter β_Q (mm). β_Q is proportional to the soil moisture capacity.

$$Q_t = \left(S_{t-1} + P_t - E_t\right)\tanh\left(\frac{S_{t-1} + P_t - E_t}{\beta_Q}\right) \tag{4}$$

and the soil water content at time *t* is given by the water balance equation.

$$S_t = S_{t-1} + P_t - E_t - Q_t \tag{5}$$

Guo et al. (2002) demonstrated that the soil moisture content S_t in the XG model cannot exceed $0.278\beta_Q$ hence the runoff parameter β_Q does not represent the soil moisture capacity but is related to it.

Jellett (2005) further developed the model to predict groundwater level *G* using a lagged model

$$G_t = G_{t-1} + \frac{S_{t-L} - S_{t-L-1}}{\beta_G} \tag{6}$$

where β_G is an additional groundwater parameter which is the porosity of the soil multiplied by the fraction of soil water that recharges the water table. Eqn. 6 states that the current groundwater level is equal to the previous groundwater level plus a fraction of the change in soil water storage *L* time periods ago.

Streamflow W_t (m^3s^{-1}) was calculated from runoff Q_t (mm) using

$$W_t = \frac{1000.AQ_t}{M_{j(t)}}$$

(7)

where *j(t)* is the Gregorian month (1 to 12) of time *t* of the data set, $M_{j(t)}$ (s) is the number of seconds in Gregorian month *j(t)* and A (km^2) is the catchment area.

2.2 Model Calibration and Testing Criterion

Model testing includes two steps, calibration and verification. The streamflow and groundwater level data sets were divided into two parts, a calibration period and a verification period. Only when the performance of the model was satisfactory, both in the calibration and in the verification periods can the model be used with confidence in practice. This criterion used in the present study to justify the performance of the model was the Nash– Sutcliffe efficiency criterion Nash and Sutcliffe (1970), which is defined by

$$R^2 = \frac{F_0 - F}{F_0} \times 100(\%)$$

(8)

$$F_0 = \sum_t \left(Q_t - \overline{Q}_c\right)^2$$

(9)

$$F = \sum_t \left(Q_t - \hat{Q}_t\right)^2$$

(10)

$$\overline{Q}_c = \sum_{t=1}^{Nc} \left(Q_t\right) / Nc$$

(11)

where F_0 is the sum of squared deviations of the observed runoff Q_t from the mean value $\overline{Q}_c$ of the observed runoff series in the calibration period, and F is the sum of squared discrepancies of the simulated runoff $\hat{Q}_t$ from the observed runoff Q_t. The value of R^2 is always expected to approach unity for a good simulation of the observed runoff series. Similar procedures also applied for groundwater level data.

3. Data used

Continuous rainfall and pan evaporation data were obtained from Bureau of Meteorology, BOM, and groundwater level and streamflow data were obtained from Pinneena Database CD, Department of Natural Resources, DNR 2008. In addition, Australia-wide monthly rainfall and evaporation surfaces (using 16642 rainfall and 277 evaporation stations) were constructed using thin-plate smoothing splines (Hutchinson, 2002). Splines were fitted to spatially distributed Bureau of Meteorology monthly rainfall and pan evaporation data using the square-root transformation for rainfall and longitude, latitude and elevation as predictors. The monthly rainfall and evaporation surface grids were projected and then clipped to the required Wybong catchment boundary. An ARC/INFO Macro Language (AML, geoprocessing script tool) routine was then used to calculate the area-weighted monthly rainfall and evaporation for the catchment. Average annual rainfall for Bunnan (Station # 61007) within the catchment for the period 1903 to 2008 is 638 mm and ranges from 315 to 1264 mm. Daily streamflow and groundwater level data were summed to obtain monthly values. Measurement of groundwater levels in the catchment only commenced in July 2003.

4. Results and Discussion

The model was calibrated using the groundwater elevation data from July 2003 to 2008 using the adjusted R^2 value as a goodness of fit criterion. The model was fitted using spatially interpolated monthly rainfall and evaporation data. **Table 1** shows the R-squared values and parameters of the model for predicted monthly groundwater level for the Wybong catchment. The model was calibrated on streamflow data from 1990 to 1999 and verified on data from January to December 2000. The calibration R^2 value was 74% and the verification R^2 value was 86%, initial soil water content S_0 (calibrated fitted parameter) was 58.83 mm, evapotranspiration parameter β_E was 1.11, runoff parameter β_Q was 234.30 mm. Although the model was able to predict streamflow well, the fitted pan factor β_E is greater than 1. From eqn (3) it is expected that β_E should typically be less than 1. This discrepancy arises due to fitting stream flow at low rainfalls. For Australian conditions it is clear that the evaporation component needs to be improved. Under prediction has occurred most in summer (January 1996, February and December 1992) when storm cells delivered rainfall to the catchment, which was not measured in the regional gauge. Over prediction has occurred in winter (June 1991, July 1993, 1998) possibly due to water extraction or under estimation of evapo-transpiration.

The model was also calibrated on groundwater level data from July 2003 to 2008 from government monitoring within the Wybong catchment (Table 1) The calibration of R^2 value of 83%, the verification R^2 value was 46% and time lag of 0 month of bore GW080434 demonstrates that unconfined aquifer responds quickly to rain (Table 1). A significant drop of measured groundwater level occurred for bore #0809434 from August to December in 2005 (Fig. 2) this appears to be due to nearby groundwater pumping during the drought. Unfortunately there is no information on the amount of water that was pumped. The fitted parameter values (**Table 1**) appear to be physically realistic and the results show that these bores are responsive to rain.

Figs 2 and **3** show the model fits to groundwater level data for the bore at Wybong Road (#080434**)** and the Wybong Creek stream gauge at Yarraman, respectively. The XG model has the ability to predict both groundwater levels and streamflow in catchments where there are no meteorological stations located at the groundwater bore sites. It has been suggested here that the model may need modification for drought conditions.

Table 1 Results for Predicting Groundwater Level in Wybong catchment.

L = Lag time, G_o = initial ground water height, S_0 = initial soil moisture, β_Q = run-off parameter, β_E = evapo-transpiration parameter and β_G = ground water parameter

BoreID	Aquifer type	Depth (m)	L (Mon)	G_0 (m)	S_0 (mm)	β_Q (mm)	β_E	β_G (mm/m)	R^2	RMSE
080944	Consolidated semi-confined	30	2	162.54	1.0	12032.4	0.73	577.2	0.96	0.06
080945	Unconsolidated unconfined	24	1	141.70	2150.3	206139.1	0.56	290.8	0.93	0.10
080946	Unconsolidated unconfined	19.5	0	137.31	1379.1	143727.5	0.76	326.24	0.95	0.03
080947	Consolidated semi-confined	60	1	141.87	445.2	19755.3	0.69	300.54	0.93	0.06
080948	Consolidated semi-confined	41	3	144.04	1.0	4779.25	0.89	674.12	0.97	0.03
080434	Unconsolidated unconfined	17.4	0	137.82	1693	385819.7	0.99	475.55	0.83	0.12

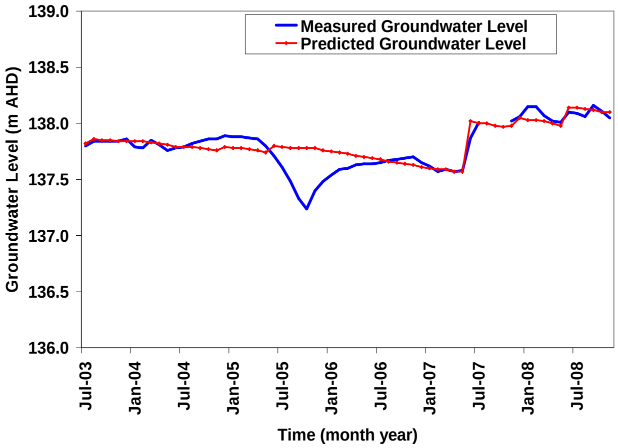

Figure 2 Measured and predicted Groundwater level data from 2003-2008 for bore #0809434 of R^2 (Cal) = 0.83

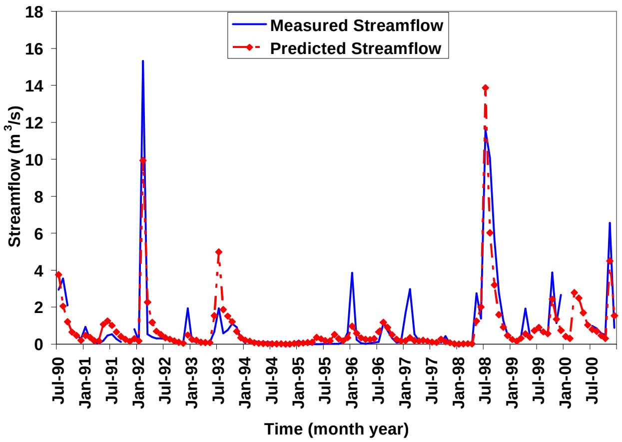

Figure 3 Measured and predicted streamflow data from 1990-2000 for gauge 210040 of R^2 (Cal) = 0.74

5. Conclusions

A simple monthly two parameter XG model has been employed for predicting streamflow and groundwater level using monthly rainfall and evaporation data. The model performed well both under calibration and verification for the Wybong Catchment. The R^2 values for calibration were more than 80% for spatially interpolated monthly rainfall and evaporation data, giving a good fit between observed and predicted values. Some adjustment of the model appears necessary for long dry periods.

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Keynote Address

Hydrogeological Mechanisms and Impacts of Longwall Mining

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Abstract

Underground mining by the longwall method completely extracts large rectangular areas (panels) of coal, collapsing the immediate roof and causing rapid subsidence of the strata in the overburden. A trough-shaped depression develops at the ground surface over the panel. Surface hydrologic impacts may include disrupted drainage and development of fracture-related local losses, gains, and intermittent diversions of stream flow. Subsurface impacts develop according to deformation zones that typically consist upwards of: the collapsed, heavily fractured roof; a deep highly fractured zone; an intermediate zone of coherent settlement with little fracturing; and a near-surface zone with substantial fracturing of strata and the ground surface. Fracturing greatly increases porosity and permeability of bedrock aquifers, though it has little hydraulic effect on unconsolidated materials. Examples of studies from the Illinois Basin and Appalachian coalfields in the USA illustrate the hydrogeological impacts and their mechanisms.

The deep fractured zone typically drains to the mine. However, the intermediate coherent settlement zone retains confining properties and blocks direct drainage of shallower aquifers, except where the mining overburden is very thin. Nevertheless, significant hydrogeological impacts occur in the shallow strata, including large head drops that result from several causes. First, sudden increase of fracture porosity during subsidence opens new void space into which water drains, lowering heads; because of their very low storativities, confined aquifers become rapidly unconfined. Second, topographically high or perched aquifers drain to lower aquifers and zones through aquitards fractured by subsidence. Third, increased fracture permeability over the panel decreases hydraulic gradients, lowering heads up-gradient. Fourth, drawdown spreads out around and ahead

of the primary head drop in the subsided area, to an extent varying with transmissivity. Whereas the primary head drop from increased fracture porosity occurs in the subsidence trough defined by the angle of draw, the extent of the transmitted drawdown itself defines the vaguer angle of dewatering influence.

In the deep fractured zone, water levels are permanently lost except perhaps when the mine floods after abandonment. However, potentiometric recovery often occurs in the shallow zone, reflecting both recompression and inflow back into the area after mining has passed. The degree of head loss and recovery varies substantially with topographic (upland or valley) setting, hydraulic characteristics of the aquifer, extent and intensity of deformation, and thickness of overburden above the mine. Groundwater chemistry is not usually affected by direct mine drainage but may deteriorate because of (a) new connections between different aquifers and (b) the dewatering and recovery of previously confined aquifers, causing the oxidation of sulfide minerals and subsequent solution and flushing of the sulfates, increasing TDS and sulfate levels.

Longwall mining produces significant environmental impacts, yet is relatively safe, predictable, and economic and may be an important factor in a local economy. It is thus often a source of controversy and dispute between environmental groups, mining companies, politicians, regulators and divided local communities. Outcomes may involve continued mining, remedial engineering of various degrees of success, and zoning restriction of longwall panels in sensitive locations.

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Groundwater Investigations – Emergency Town Water Supply Gosford-Wyong Councils Water Authority Joint Water Supply Scheme

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ABSTRACT

Recent drought-driven groundwater investigations for emergency town water supply by Gosford-Wyong Councils Water Authority Joint Water Supply Scheme resulted in the development of over 30 production bores in five borefields. Hardrock groundwater exploration was, by necessity largely restricted to the Triassic Terrigal Formation, the uppermost part of the Narrabeen Group in this region, due to the erosion of the Hawkesbury Sandstone from most areas. Alluvial groundwater investigations were centred on a large, unconfined, rainfall-recharged groundwater mound hosted by a composite Pleistocene-Holocene beach barrier system on the Woy Woy Peninsula.

Until recently, the Terrigal Formation was not considered prospective for high-volume groundwater supplies due to low recorded yields (average 0.4 L/s) and generally poor water quality. ‘Primary’ aquifers are associated with porous quartz-lithic sandstone units and ‘secondary’ aquifers with mainly sub-vertical, potentially high yielding structural discontinuities. Potential groundwater targets were delineated in several linear, structurally-controlled, alluvial-filled valleys using remotely sensed data.

Test drilling revealed relatively thick sandstone units developed mostly towards the base of the Terrigal Formation which has a preserved thickness of up to 145m. Extensive geophysical bore logging delineated aquifers, enabled stratigraphic correlation within and between borefields, and defined the base of the Terrigal Formation which is difficult to identify because of the occurrence of numerous thin to multi-metre-thick, rhythmically interbedded ‘red beds’ towards the base that are very similar to the unprospective underlying Patonga Claystone. Yields greater than 15 L/s were recorded in several bores.

The groundwater has moderate salinity, near-neutral pH and is ‘hard’ with anomalous iron concentrations. Abundant methane, carbon dioxide and anomalous barium are recorded in some bores. Methane and barium is known to occur in the Narrabeen Group but also in the underlying 500m-deep Permian coal beds.

Baseline age dating of groundwater revealed generally ‘old’ water in the range of 1000s of years.

Keywords: Terrigal Formation, groundwater, Gosford, Central Coast

1. INTRODUCTION

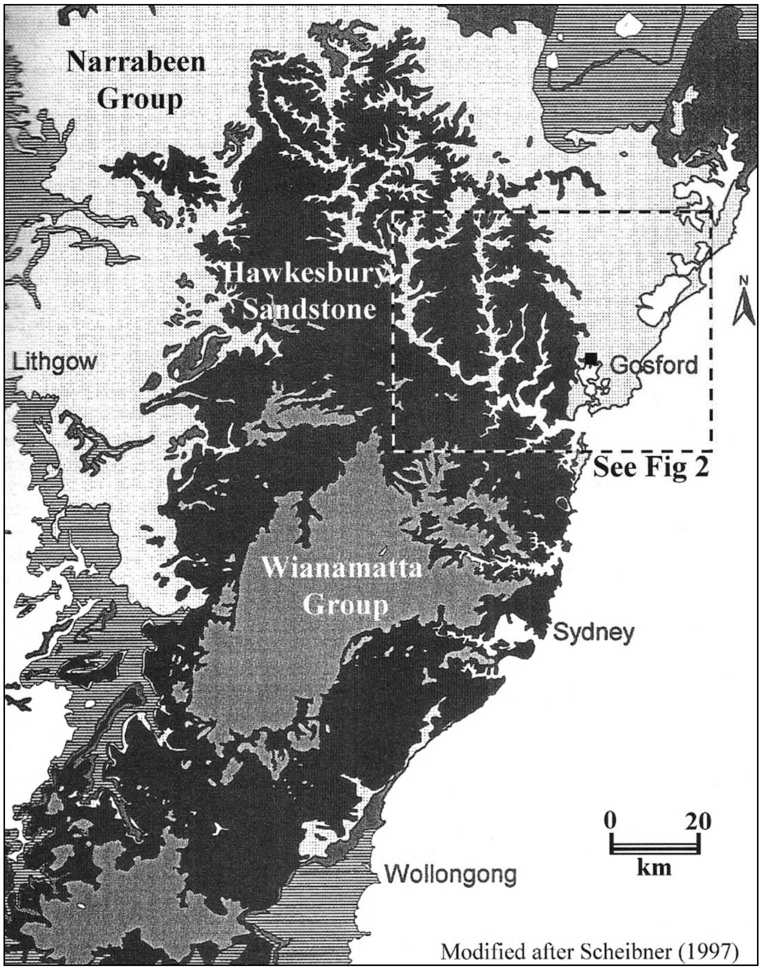
Gosford City Council and Wyong Shire Council commenced a joint program of groundwater investigations on the Central Coast in 2004 under the Gosford-Wyong Councils Water Authority Joint Water Supply Scheme as part of drought contingency measures. Mangrove Mountain Dam, the main district surface storage has been severely impacted by recent droughts falling to a historic low level of 10.3% in February 2007. The current storage level is approximately 30%.

The objective of the initial investigations was to develop groundwater resources for recreation purposes in the two local government areas (LGA). The discovery of moderate to high yields in early test bores demonstrated the potential for harvesting groundwater to supplement the town water supply for approximately 300,000 people, the third largest urban area in NSW and ninth largest in Australia.

Groundwater investigations including test drilling, aquifer testing and baseline water quality testing led to the development of five main borefields. Four borefields are developed in hardrock aquifers - Bangalow Creek (BCB), Ourimbah Creek (OCB), Narara (NB) and Mangrove Creek (MCB), and one borefield in the Woy Woy barrier beach sand dune aquifer. Current and ongoing assessment of long-term borefield sustainability incorporates comprehensive water level and water quality monitoring under production pumping conditions and regular assessment of any potential environmental impacts.

2. GEOLOGY AND GEOMORPHOLOGY

The LGA is located in the northern central part of the Sydney Basin where the upper part of the Triassic sequence is exposed (Fig. 1).



Modified after Scheibner (1997)

Figure 1 Major geological units in the Sydney Basin

The geology and geomorphology of the LGA can be divided into three main north-south trending domains shown in Fig. 2 and described below. A generalised cross section showing the stratigraphy, land surface and location of the hardrock borefields is provided in Fig. 3.

- The western half of the LGA comprises the 300m-high, deeply dissected Mangrove Mountain plateau where up to approximately 140m of Hawkesbury Sandstone is preserved comprising a thick sequence of interbedded stacked massive and cross-bedded medium to coarse quartz sandstone with occasional discontinuous interbeds and lenses of shale.
- A 16km-wide moderately dissected corridor of undulating hills up to approximately 200m elevation in the central part comprises Terrigal Formation sediments, the uppermost part

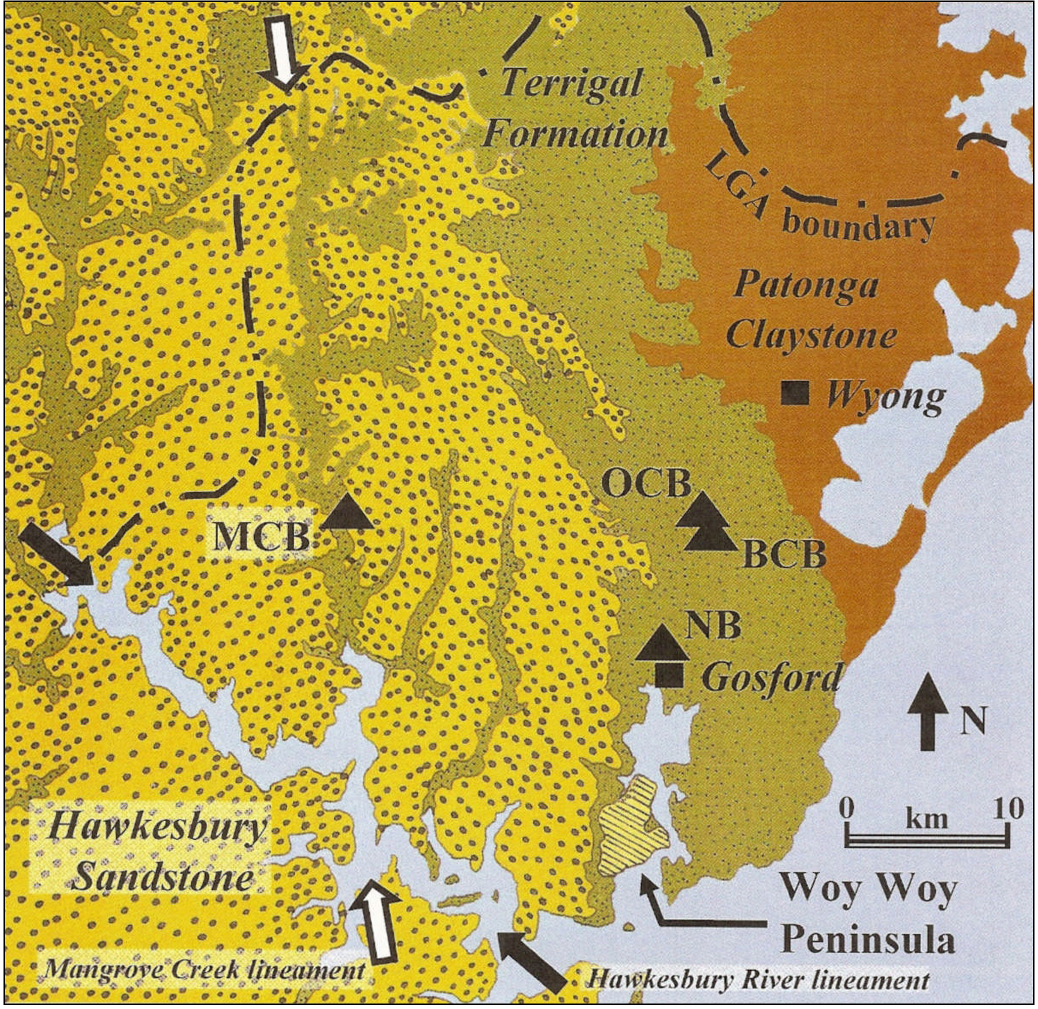


Figure 2 District geology and location of borefields

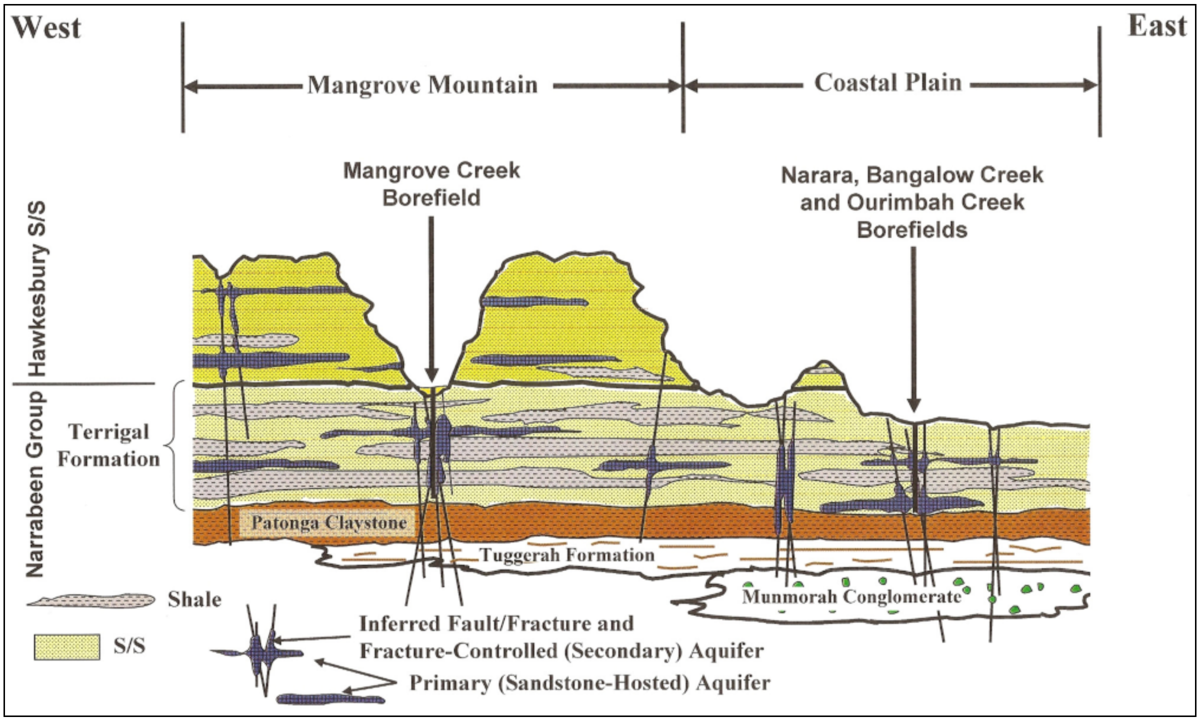


Figure 3 Generalised geological section

of the Narrabeen Group in this district which has been exposed by the erosion of the Hawkesbury Sandstone. The Terrigal Formation comprises a relatively thick fluvio-deltaic sequence of rhythmically interbedded multi metre thick medium to coarse to, in part, conglomeratic quartz-lithic sandstone interbedded with siltstone and claystone. The sandstone units are upwardly fining, coarse to fine grained, lithic quartz in composition with occasional pebble and conglomeratic bands. (Herbert, 1980).

- The north-eastern part of the LGA comprises mainly Patonga Claystone overlain in parts by Quaternary and Recent alluvium associated with the coastal lake and river systems. The Patonga Claystone consists of red-brown and grey-green, laminated claystone and siltstone which, in the north overlies the Tuggerah Formation and the Munmorah Conglomerate. Holocene beach barrier sand dune systems are developed along parts of the coastal margin with the main development on the Woy Woy Peninsula.

Although the Triassic sequence in this part of the Sydney Basin is relatively flat-lying it has nevertheless been subjected to various degrees of deformation resulting in the formation of gentle north-northeast trending regional flexures and the imposition of sub-vertical structural discontinuities such as joint sets, fractures and fracture networks that have dissected the rock mass providing potential fluid pathways and conduits (Fig. 3). These are often reflected as surface lineaments on remotely sensed data such as the broad northwest-trending and continuous Hawkesbury River lineament and Mangrove Creek lineament (Fig. 2). Complimentary sets of subsidiary sub-parallel linear features also occur in the region.

3. AQUIFER TYPES

Three types of aquifers are identified in the LGA:

- Dual porosity ‘hardrock’ aquifers; ‘primary aquifers’ hosted by relatively porous units within the Triassic sedimentary rock sequence and ‘secondary aquifers’ associated with tectonically imposed structural discontinuities that have dissected the sandstone, siltstone and shale sequence and with other features such as bedding partings and stress relief structures (Fig. 3). Evidence of fracture flow is found in geophysical bore logs, rapid increase in bore yield during test drilling (including increased flows in some shale units), elevated hydraulic conductivities and in computer output from drawdown analysis.
- Alluvial aquifers hosted by interbedded, interlensed and stacked sequences of alluvium associated with several river and coastal plain estuarine systems.
- Barrier beach sand aquifers, in particular the regionally significant and extensive Woy Woy Peninsula sand dune system which hosts an unconfined aquifer associated with a centrally located groundwater mound.

4. EXPLORATION PHILOSOPHY

The hydrogeological investigations concentrated on the delineation and development of aquifers hosted by the Terrigal Formation and the Woy Woy barrier beach sand dune system.

The principle reason for exploring the Terrigal Formation was one of necessity in that the Hawkesbury Sandstone has been removed by erosion from the eastern part of the LGA. Although the Hawkesbury Sandstone is largely preserved on Mangrove Mountain and the groundwater quality is demonstrably good, there were significant limitations for the development of a borefield. These included the fact that the plateau is deeply dissected and largely inaccessible with numerous existing, generally low yielding bores clustered along narrow ridgelines and spurs, the limited available land for exploration and development, the water management plan for the largely allocated groundwater resource on the plateau which sets rigorous zoned-based groundwater extraction limits and the high potential of impacts from any major borefield pumping on existing water users and the environment.

Prior to the commencement of the joint Council’s current groundwater investigations, the hydrogeology of the Terrigal Formation in the LGA was poorly understood. Historically, the Terrigal Formation was not considered prospective for groundwater supplies due to low recorded yields (average 0.4 L/s) and perceived poor water quality. However, drought driven groundwater investigations revealed the true hydrogeological potential with the delineation of moderate to relatively high bore yields and manageable water quality.

The investigations were restricted to Council owned or controlled land which included reserves, recreation areas and flood prone land. Therefore, although there is a paucity of information regarding the hydrogeology of the Terrigal Formation and its equivalents elsewhere in the Sydney Basin, a strategy of targeting the sandstone units hosted by the Terrigal Formation in areas interpreted to be dissected by sub-vertical geological discontinuities such as linear structurally controlled valley systems was implemented.

The underlying Patonga Claystone was assessed to have low potential for the discovery of useful flows of groundwater for the purpose. In addition, the quality of groundwater is generally poor with common high salinity levels. The underlying Tuggerah Formation and Munmorah Conglomerate have not been subjected to any detailed groundwater exploration.

5. TERRIGAL FORMATION AQUIFERS

A total of 17 test production bores were constructed in the BCB, OCB, NB and MCB (Table 1).

Table 1 Borefields, bores and hydrogeological properties

Borefield	*No. Bores*	*Depth (m)*	*Water Level (m BGL)*	*Capable Yield (L/s)*	*T (m^2/d)*	*K (m/d)*	*pH (pH units)*	*TDS (mg/L)*
Bangalow Creek (BCB)	*5*	*72-101*	*1.1-4.7*	*2.5-29* *ave. 11.0*	*13-316* *ave. 134*	*0.9-35.3* *ave. 16.2*	*6.7-7.5* *ave. 7.1*	*233-556* *ave. 400*
Ourimbah Creek (OCB)	*5*	*70-114*	*1.5-4.7*	*0.5-6.8* *ave. 3.3*	*2-28* *ave. 15*	*0.6-3.8* *ave. 2.0*	*6.5-7.2* *ave. 7.0*	*254-536* *ave. 387*
Narara *(NB)*	*4*	*130-172*	*4.0-6.2*	*14-29* *ave. 21.5*	*20-220* *ave. 106*	*0.6-20.0* *Ave5.8*	*6.0-8.0* *ave. 7.3*	*312-1489* *ave. 744*
Mangrove Creek (MCB)	*3*	*120.0* *(all)*	*2.3-3.7*	*20-25* *ave. 22.5*	*49-275* *ave. 146*	*0.9-35.3* *ave. 21.9*	*6.4-7.3* *ave. 6.9*	*1773-6520* *ave. 3668*
Woy Woy	*14*	*15.5-25.0*	*1.6-3.9*	*4-20* *ave. 14.4*	*6.1-455* *ave. 180*	*0.30-25.6* *ave. 9.10*	*6.8-7.7* *ave. 7.3*	*249-610* *ave. 336*

The bores intersected Terrigal Formation with a preserved thickness of up to 145m in the LGA. Extensive geological and geophysical bore logging delineated aquifers and enabled stratigraphic correlation within and between borefields. Gamma log correlations were useful in defining the base of the Terrigal Formation which is difficult to identify because of the occurrence of numerous thin to multi-metre-thick, rhythmically interbedded and laminated ‘red beds’ towards the base that are very similar to the unprospective underlying Patonga Claystone. Some early test bores were prematurely terminated in what was believed at the time to be Patonga Claystone. Aggregate yields greater than 15 L/s were recorded from multi-layered aquifers in several bores.

Networks of nested multi-level hardrock and alluvial monitoring bores installed in the borefields revealed direct and indirect hydraulic connection between multi-layered hardrock aquifers with varying degrees of artificially induced vertical leakage from the overlying valley-fill alluvial systems during pumping.

Although aquifer storage is difficult to determine, the interpreted presence of extensive and pervasive structural discontinuities, the occurrence of laterally extensive transmissive sandstone units and groundwater recovery (groundwater pressure) characteristics noted from aquifer testing suggests large areas of influence in these borefields. Recharge of the Terrigal Formation aquifers is considered to be largely from rainfall infiltration. Although the actual recharge areas are difficult to delineate, large areas of moderately to deeply dissected Narrabeen Group sediments occur north of the borefields, in the northern and north-eastern parts of the basin.

The hydraulic gradient and direction of regional groundwater flow in the local Terrigal Formation aquifers is also difficult to determine. The borefields are on the coastal fringe, the aquifers are below sea level and there is a general paucity of water level monitoring in the Narrabeen Group. The results of regional government geological mapping and data obtained from drilling logs as part of these hydrogeological investigations indicate that the Triassic sequence in the LGA dips gently to the southwest at approximately 1.0^o to 1.5^o. The hydraulic gradient is predicted to be small with the movement of groundwater possibly towards the lower central parts of the basin (or sub basins). However, the dynamics and distribution of the discharge zones are poorly understood and the dip of the sedimentary sequence may not be the main driver of the direction of groundwater flow.

5.1. Hydrogeological properties

Laboratory testing of 14 quartz-lithic sandstone drill core samples obtained from the BCB, OCB an MCB revealed a range of apparent (water accessible) porosity values of between 6.9 and 17.9% (mean 12.6%) for the Terrigal Formation (Emerson, 2006). Laboratory permeability testing of the same cores revealed indicative values of horizontal permeability of <0.001 m/day to 0.04 m/day (mean 0.007 m/day). It is noted that these results are indicative as the tests were conducted in the laboratory on small samples and extrapolation of these results to the in-situ sandstone units should take into consideration such properties as rock textures, lithology and anisotropy due largely to structural disturbances.

A wide range of transmissivity (T) and hydraulic conductivity (K) values were derived from formal 48-hour-duration pump tests in the four borefields. Assessment of long-term ‘safe yield’ will be based on long-term bore pumping under production pumping conditions. Water level monitoring to date indicates that the aquifer systems depressurise during designed medium to long-term production pumping with the lowering of the piezometric surface attaining equilibrium in most cases in the short to medium term. Upon seasonal cessation of production pumping, the piezometric surface is observed to gradually recover to pre-production pumping levels. Estimates of T obtained from 17 aquifer tests range from 2.0 to 316 m^2/day and estimates of K calculated from the same aquifer tests using the cumulative aquifer zones in each test bore as aquifer thickness range from 0.6 m/day to a high of 35.3 m/day (Table 1). The range of K values suggests that fracture permeability in the borefields is an important control in groundwater flow.

The variation in aquifer parameters estimated from aquifer testing and variation in groundwater chemistry (Section 5.2) within borefields suggests that anisotropic hydrogeological conditions exist. This is consistent with local structural geometry and the lateral and vertical variation in the distribution of sandstone units which reflects the complex channel braid and splay depositional environment.

5.2. Groundwater quality

The Terrigal Formation groundwater is generally ‘hard’ with near neutral pH. The salinity levels in the BCB, OCB and NB vary between 233 and 1489 mg/L TDS, although the mean level is 510 mg/L (Table 1). The measured salinity levels in the MCB are between 1773 and 6520 mg/L. The shallow alluvial-hosted groundwater and hardrock groundwater in all borefields is typically of Na-Cl type with a progression towards Na-HCO3 type in the hardrock aquifers.

Groundwater sampled in the MCB contains anomalous amounts of carbon dioxide, methane, barium and iron, and very low levels of sulphate. Significant degassing was observed during pump testing and groundwater sampling in the MCB. Elevated levels of methane and barium are known to be present in parts of the Narrabeen Group and also in the underlying 500 m-deep Permian coal beds. The Narrabeen Group in the Mangrove Creek Valley is believed to be dissected by major pervasive district structural discontinuities such as the Mangrove Creek lineament structure (Fig 2). The presence of abundant carbon dioxide may indicate close proximity of the aquifer to an igneous intrusion.

The presence of similar chemistry is noted from the groundwater sampled in the BCB, OCB and NB but with significantly less methane, carbon dioxide and barium.

The production waters are pumped to dedicated local surface storages and blended prior to municipal water treatment.

5.3. Groundwater residence times

Determination of baseline groundwater ages (residence times) under natural, pre-production pumping hydrogeological conditions using ^{14}C dating was carried out by Ansto (Cendon & Hankin, 2008) for relatively shallow ‘valley fill’ alluvial aquifers and for deeper ‘hardrock’ aquifers in the BCB, OCB and MCB.

Concurrent analysis of groundwater samples for major ions, selected minor elements, stable and radioactive isotopes (^{13}C, ^{14}C and ^{3}H tritium), and mineral analysis of rock core samples (local rock-water interactions) was undertaken for 14C interpretation and corrections.

Estimates of corrected ^{14}C ages range from ‘modern’ to 2300 years Before Present (years BP) for shallow alluvial groundwater to generally between 900 and 13000 years BP for deep ‘hardrock’ aquifers in the coastal BCB and OCB. An anomalous age of 31200 years BP was estimated for a deep hardrock-hosted groundwater sample collected in the BCB. Representative samples could not be obtained from the MCB due to significant degassing during groundwater sampling. As a consequence, ^{14}C isotopic analysis could not be satisfactorily undertaken.

Groundwater ages correlate with sample depth with deeper aquifers having older residence times.

The study provided valuable information on surface water-groundwater interaction, identification of local recharge zones and lateral flow paths in the Terrigal Formation within and immediately surrounding the BCB and OCB. It is considered important that follow-up groundwater analysis, testing, age dating and possibly borefield computer groundwater modelling be conducted to improve the understanding of the significance of the ages and assess any potential impacts of long-term groundwater borefield extraction.

6. WOY WOY SAND DUNE AQUIFER

Fourteen test production bores were constructed to an average depth of 23.2m on the Woy Woy Peninsula, a three-kilometre-wide composite Pleistocene-Holocene beach barrier system which hosts a large, unconfined, rainfall-recharged groundwater mound (Fig. 4).

The Peninsula is situated within the northern part of a 2-kilometre-wide, north-south trending valley hosted by the Terrigal Formation which is dissected by Broken Bay where the Hawkesbury River enters the Tasman Sea. Pittwater forms the southern part of the valley structure. The dunes and intervening swales trend north-east to south-west parallel to the present shoreline on Ocean Beach and orthogonal to the prevailing direction of south-east swell waves entering Broken Bay. The ridge system north and north-west of the line of wetlands including the Everglades wetland in the north of the Peninsula is believed to be a Pleistocene inner barrier system (Hails, 1969). The sand ridges south of these wetlands through to Ocean Beach are considered to be of recent age formed in response to eustatic changes.

Several campaigns of test and monitoring bore drilling since 1998 combined with geophysical bore logging and stratigraphic correlations reveal a set of five Holocene dominantly stacked and interlensed, north-east trending sand bodies ranging in total thickness of between approximately 20 and 25m. The sequence overlies strongly weathered Terrigal Formation basement.

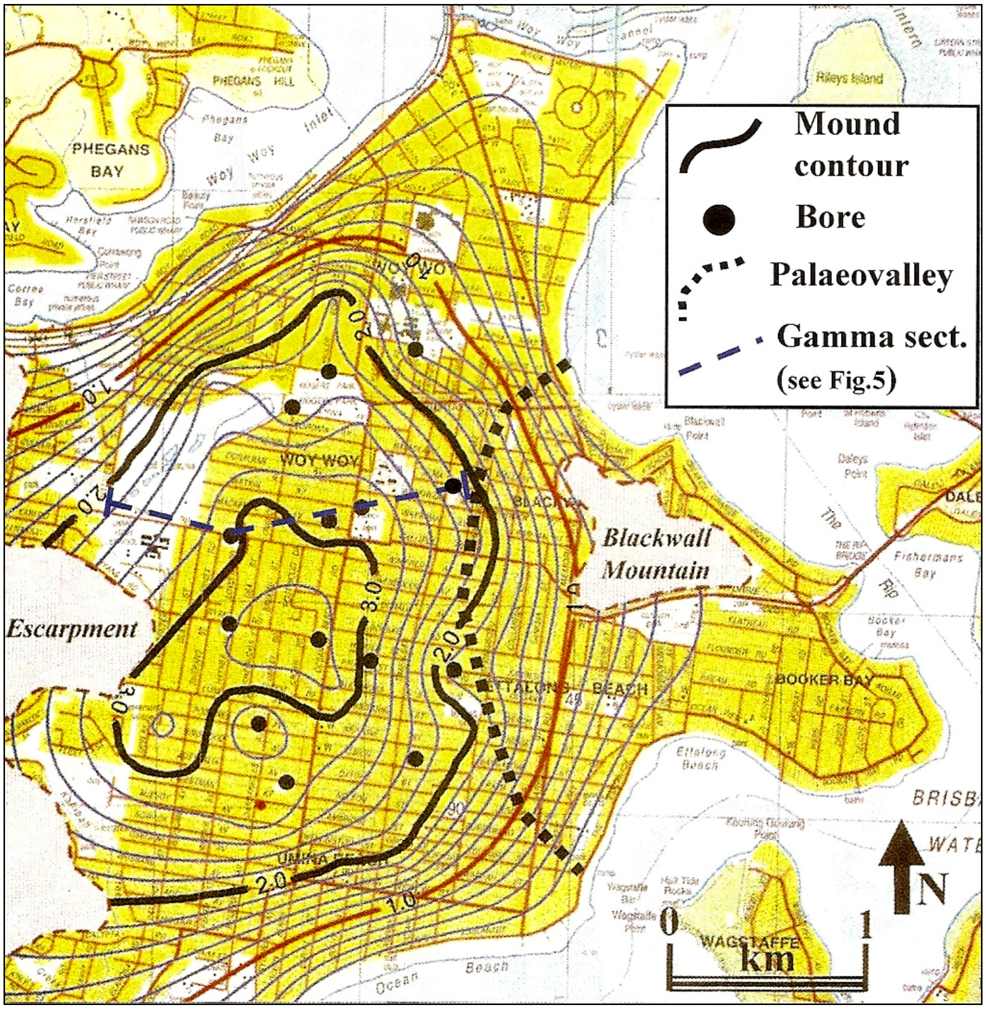


Figure 4 Woy Woy beach barrier sand dune aquifer with contours on the watertable mound

Gamma logging indicated that relatively ‘clean’ fine to coarse sand dominates the eastern half of the Peninsula and silty to clayey, in part peaty, fine to medium sand in the west. A representative E-W gamma section located in the central part of the Peninsula (Fig. 5) shows this distribution.

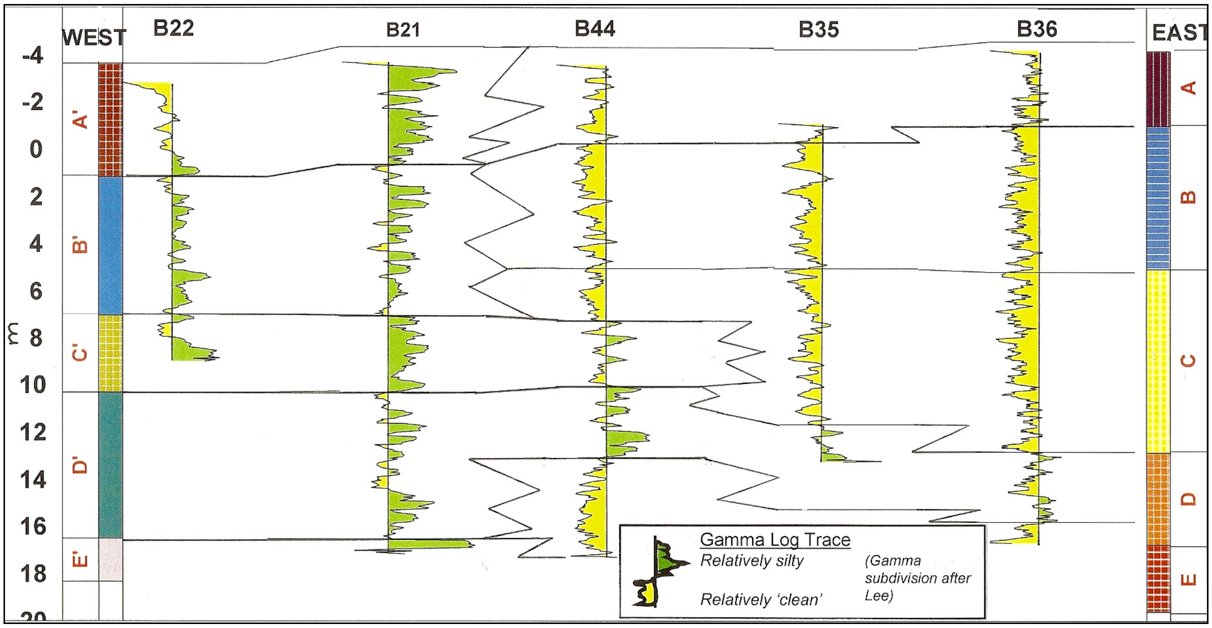


Figure 5 Representative gamma section across the Woy Woy sand dune aquifer

The sand complexes are dominantly transgressive sheet-like forms and distributed along a meridional depositional axis flanked to the west by lagoonal and wetland environments. The thickest sequences of 'clean' sand are developed in the central parts of the Peninsula extending south to Ocean Beach and thinning to the north. This sand sequence constitutes the most prospective aquifer and is essentially a 'wedge' bounded to the east by estuarine deposits and the sea and to the west by lagoonal-wetland deposits.

The groundwater mound is broadly located in the 6m-high central part of the Peninsula with the crown generally between about 3.0 and 4.0m AHD (Fig. 4). The fluctuations in water table are directly related to rainfall recharge events. The majority of test production bores were strategically positioned on the mound to target the more prospective of the Holocene sand bodies and to take advantage of the positive head. Elevation-controlled 'pump to' levels have been developed by Council in order to avoid any impact on the aquifer from artificially-induced saltwater encroachment.

Recent salinity monitoring drilling in the eastern part of the Peninsula confirmed the existence of a relatively narrow, steep-sided, sediment-filled 80-metre deep, north-south trending palaeovalley (Fig. 4). The presence of such a structure in this part of the Peninsula was suggested by a limited ground gravity survey conducted by Qureshi in the early 1970s (Qureshi, 1981).

A zone of passive saline water encroachment occurs behind the active beaches and Brisbane Water shoreline. Detailed groundwater computer modelling of the barrier beach sand aquifer by Mackie Environmental Research predicted the position of the saltwater-fresh water interface within approximately 100m of the shoreline (MER, 2005). Several strategically positioned transects of salinity sentinel bores equipped with automated multi-level salinity loggers are designed to map and monitor the fluctuating position of the interface and any salinity encroachment impacts from borefield pumping.

6.1. Hydrogeological properties

A wide range of T and K values was obtained from formal pump testing with estimates of T ranging from 6.1 to 455 m^2/day and estimates of K from 0.3 to 25.6 m/day (Table 1). Storage coefficients (or Storativity) values range from 3.7×10^{-3} to 1.0×10^{-1}.

6.2. Groundwater quality

The groundwater is generally ‘hard’ with near neutral pH and salinity levels between 249 and 610 mg/L TDS (Table 1). The groundwater is dominantly of $Ca\text{-}HCO_3$ type with minor amounts of $Na\text{-}CO_3$ waters.

The production water is treated in a purpose-built Council water treatment plant located in the central part of the Woy Woy Peninsula.

7. CONCLUSIONS

Necessity-driven groundwater exploration in the Terrigal Formation has resulted in the development of four strategically located borefields of which three are operational and have provided useful supplementary town water supplies contributing up to 10 to 15% of the LGAs daily water requirement during emergency dry periods. Assessment of long-term ‘safe yield’ is continuing in parallel with seasonal pumping of the borefields.

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Resistivity Imaging and Sounding Survey for Kangaloon Borefield Investigations Southern Highlands, New South Wales

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Abstract

A high-resolution resistivity imaging survey and a series of vertical electrical soundings were recently conducted near Kangaloon in the Southern Highlands for the Sydney Catchment Authority (SCA). The aim was to establish the viability of these methods in delineating potential groundwater drilling targets in the Triassic Hawkesbury Sandstone for the SCA drought contingency investigations and assess their use as potentially cost and technically effective pre test-drilling techniques.

The 6.2 km survey followed a line of 19 recently drilled SCA test bores that penetrated the full thickness of the Hawkesbury Sandstone which is largely preserved with maximum thickness of approximately 150 m. The results of test drilling, geophysical bore logging and aquifer testing provided excellent ground truthing.

The sedimentary sequence has been regionally deformed with the formation of joint blocks, imposition of pervasive sub-vertical NW structural discontinuities and development of horst and grabens, and monoclinal flexures. Vertical displacements of up to 70 m were recorded along the survey line. The sequence is intruded by Late Jurassic syenite and capped by remnant Tertiary basalt.

The effective penetration depth of the survey is approximately 70m in this generally highly resistive environment. Although the method could not fully penetrate the Hawkesbury Sandstone, it was successful in detecting the lateral limits of the Mt Butler basalt intrusive and steep sided resistivity anomalies which coincide with the interpreted position of regionally pervasive surface linear features. The lateral limits of these resistivity anomalies may represent structural discontinuities and prospective groundwater targets. Greater depths of penetration may be achieved using additional electrode cable and larger transmitters.

The vertical electrical soundings complimented the resistivity imaging surveying through its capacity to achieve a higher depth of investigation and delineate the base of the Sandstone.

The resistivity imaging survey demonstrated a capacity to identify and delineate potential groundwater targets, in particular structural discontinuities.

Keywords: Geophysics, resistivity, Kangaloon, groundwater, Hawkesbury Sandstone

1. Introduction

The SCA commissioned a program of trial ground geophysical surveys along the Tourist Road in the Kangaloon Borefield approximately 7 km north of Robertson in the Southern Highlands. The surveying was conducted in 2008 and formed part of a wider SCA project aimed at establishing the viability of borefield development for Sydney should future drought conditions necessitate development of new water sources.

The primary objective of the geophysical surveying was to establish the viability of the resistivity imaging and vertical electric sounding (VES) methods for the purpose of locating potential groundwater drilling targets in particular, targets associated with structural discontinuities that have dissected the relatively ‘brittle’ Hawkesbury Sandstone. These methods were chosen for their proven ability to define subsurface variability, particularly in resistive environments such as that of the Southern Highlands. The surveys were designed to assess their use as potentially cost and technically effective pre test-drilling techniques.

The design of the geophysical surveying was optimised by incorporating the results of comprehensive SCA groundwater investigations carried out since 2005 in the Kangaloon area including test drilling, aeromagnetics, formal pump testing and borehole geophysical logging. Ground truthing was achieved using the geological logs of 19 SCA test bores drilled along (and close to) the 6.2 km-long survey line that, in the main, fully penetrated the Hawkesbury Sandstone.

2. Geology

The Kangaloon investigation area is located within the upper part of the Sydney Basin (Fig. 1). The surficial geology of the area is dominated by a thick sequence of relatively flat-lying Middle Triassic Hawkesbury Sandstone which constitutes the main prospective ‘hardrock’ groundwater source in the region for the SCA’s drought investigations in the Sydney region. The Hawkesbury Sandstone consists of sheet-like to massive interbedded formations of dominantly medium to coarse quartz sandstone with occasional to locally numerous, dominantly thin interbedded mudrock units.

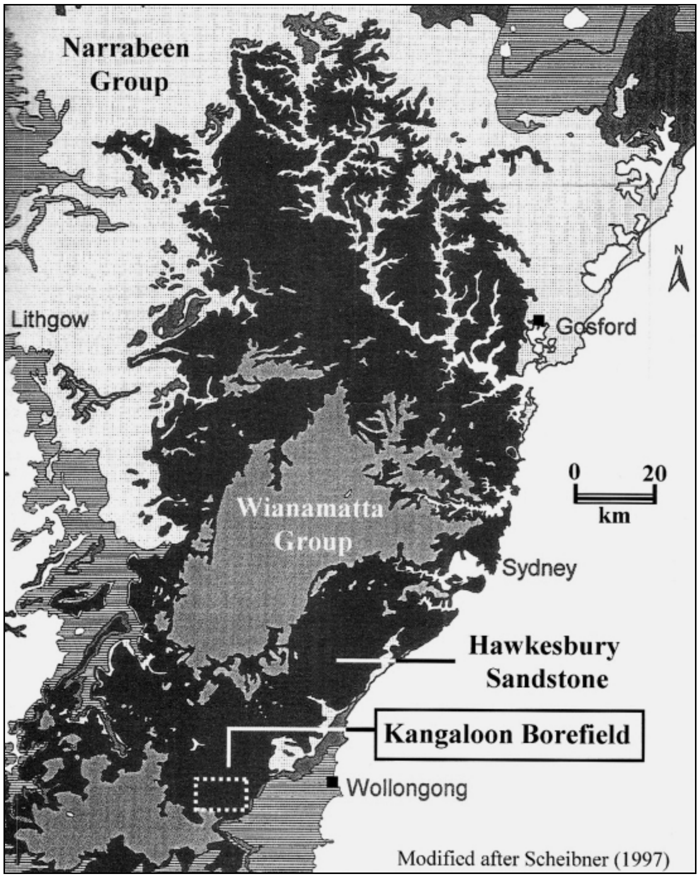

Figure 1 Major geological units in the Sydney Basin

In order to fully assess the usefulness of resistivity imaging as a pre test-drilling exploratory technique to search for groundwater supplies in the Hawkesbury Sandstone, gamma bore logs previously run in test bores were reprocessed in order to construct gamma sections and re-assess the stratigraphy of the Hawkesbury Sandstone (and underlying sedimentary units) along the resistivity imaging survey line and provide a stratigraphic framework complimentary to the existing SCA geological framework. The Sandstone can be divided into three distinct litho-stratigraphic units that persist throughout the Sydney Basin (Lee, 2000). The upper third and basal third of the Hawkesbury Sandstone are predominantly 'clean' quartz-dominant units. The middle unit is significantly more silty and demonstrably less prospective for groundwater supplies (unless substantially fractured). The geological logs from the SCA test bores record a preserved thickness of the Hawkesbury Sandstone aquifer of approximately 140 to 160m along the survey line.

The Hawkesbury Sandstone in the Kangaloon area is overlain in parts by the Mittagong Formation and the younger Wianamatta Group (Ashfield Shale). The Hawkesbury Sandstone in turn directly overlies sedimentary rocks belonging to the Narrabeen Group which include the Newport Formation, Garie Formation and Bald Hill Claystone. The sedimentary sequence has been intruded by Late Jurassic syenite and micro-syenite bodies including dykes, sills and laccoliths. Tertiary basalt caps the Mittagong Ranges to the south. The Mt Butler basalt intrusion adjacent to the survey area is early Tertiary in age (Fig. 2).

The region has been subjected to progressive deformation over the millennia resulting in the imposition of structural discontinuities such as sets of complimentary joints and major faults, and the development of several monoclinal flexures such as the Mount Murray Monocline (Fig. 2). Many lineaments interpreted from remotely sensed data are continuous on the regional scale and form ordered and complimentary networks believed to represent joints, faults and joint/fault blocks. Small to relatively large vertical displacements occur along some of these faults. The structural geometry includes the formation of a series of structural blocks at various scales, in particular the development of horsts and grabens. The location and emplacement of syenite and basalt intrusions in the district are controlled by these pre-existing structural discontinuities.

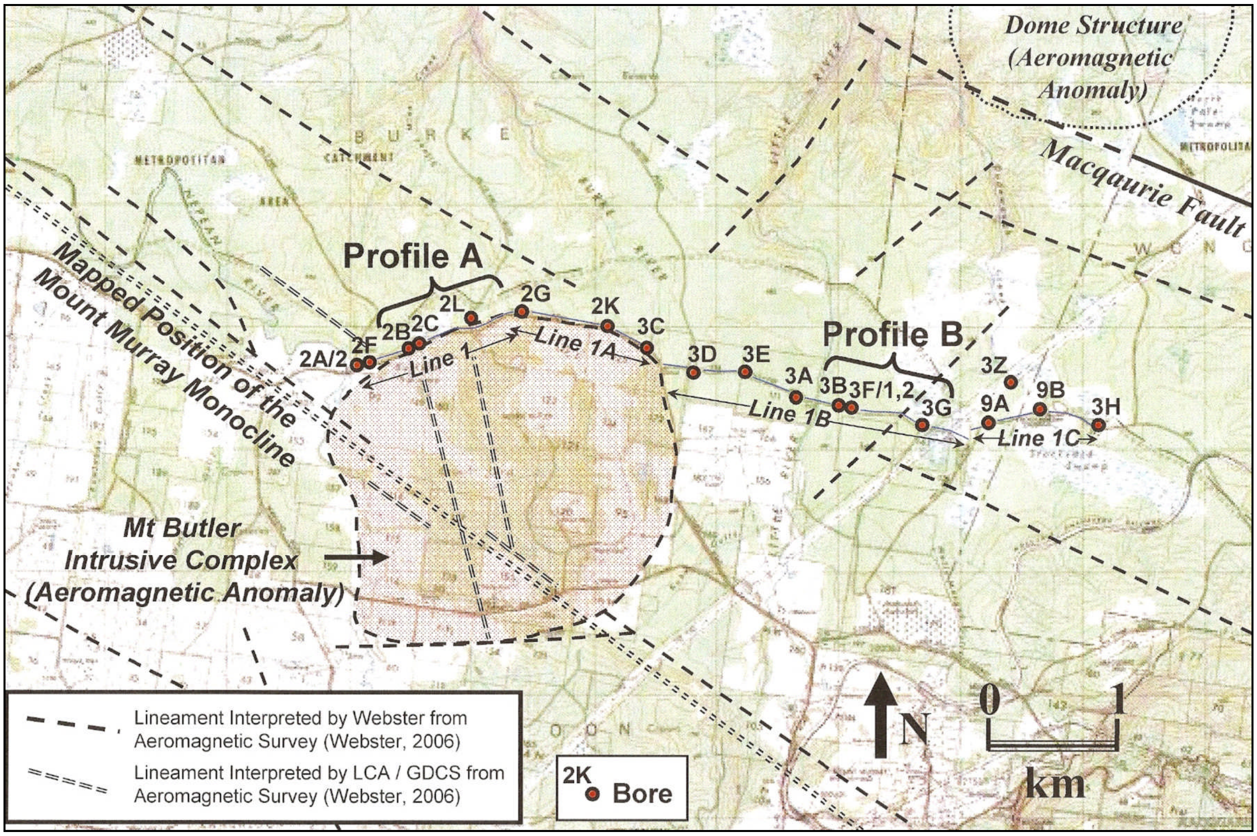

Figure 2 Location of geophysical survey line and SCA bores

3. Survey Methodology

Resistivity Imaging was used as the primary surveying technique with complimentary VESs and a small component of EM34 Ground Conductivity surveying.

The Scintrex SARIS system using the Wenner-Schlumberger electrode array with a uniform 15m electrode spacing was initially used providing an anticipated investigation depth of about 70 m. The target depth was constrained by the specifications of the imaging system - notably, electrode spacing and the number of electrodes available. The Scintrex system used for the survey consists of 2 cables, each with 13 electrodes spaced at a maximum of 15 m. An N level of 12 permits an approximate effective depth of 70 m using the Wenner-Schlumberger array. Current levels were particularly low, in the range

1-50 mA, and predominantly below 20 mA. These low values contributed to poor data quality. This array is moderately sensitive to both horizontal and vertical geological structures and in areas where both types of geological structure are expected (such as the Kangaloon area), this array represents a good compromise to maximise investigation depth while achieving acceptable horizontal and vertical resolution.

However, due to several limitations including limited sensitivity to vertical resistivity changes (e.g. layering) and the relatively small measured signal, the system was changed to the STING R1 system. Surveying with the original system proved to be slow and an additional advantage offered by the replacement system, in addition to the advantages already mentioned, was operational efficiency. The Sting system consisted of 3 cables, each with 14 electrodes spaced at a maximum of 11 m. An N level of 12 permits an approximate effective depth of 70 m using the Wenner array. Use of the Sting system with the Wenner array resulted in higher currents being available: values of 50-100 mA were typical. These higher values, though still relatively low, translated to better quality data. Edwards' effective depths were used for the purpose of survey design (Edwards, 1977). These depths are also assumed by the resistivity imaging data interpretation software. The Wenner array using an electrode spacing of 11m was used which provides higher measured signals but lower lateral resolution. Given that the survey was predominantly aimed at locating gross structural features, this loss of resolution was considered to be less significant than the data quality issue. Although the smaller electrode spacing nominally limits its depth capability, the STING system offered a larger number of electrodes to permit the approximate 70 m investigation depth to be maintained.

A total of 10 VESs were completed along the resistivity imaging survey line using the SARIS system. The standard Schlumberger electrode array was used which is generally acknowledged as the most suitable for identifying vertical resistivity variability. Electrode expansions of up to 464 m were used to achieve an investigation depth of up to 140 m.

Limited EM34 surveying was conducted with 40HD and 40VD modes of operation used to obtain maximum investigation depths of 30 and 60 m respectively.

4. Results

A total of 6.2 km of resistivity imaging surveying was completed together with 10 VESs and 2.2 km of EM34 ground conductivity surveying. The software used for interpreting the resistivity imaging data was RES2DINV and the least squares inversion algorithm was used in all cases with a two-dimensional finite difference model. RINVERT was used for inversion of the VES data; this assumes a one-dimensional model.

The resistivity imaging survey revealed significant variability of subsurface resistivity with moderately high (a few hundred to several thousand ohm.m) values consistent with the presence of the Hawkesbury Sandstone encountered in SCA test bores along the survey line. The measured sandstone resistivity agrees reasonably well with values recorded in previously acquired geophysical resistivity logs. The resistivity imaging method achieved a realistic depth of investigation of approximately 70 m on this project but was unable to penetrate the full depth extent of the Hawkesbury Sandstone.

The survey also defined the lateral limits of the Mt Butler basalt intrusive on the western part of the survey line (Fig. 2) with very high measured resistivities (10^4 – 10^5 ohm.m). Over the remainder of the survey line to the east, the survey defined several broad high and moderate resistivity zones including significant lateral resistivity changes. The lateral limits of these zones may represent features of geological structural significance and valid targets for future test drilling for groundwater supplies.

In addition to the geophysical signature and mass response from the proximal Mount Butler basalt intrusive on the western part of the survey line, some of the steep-sided resistivity imaging anomalies coincide with the surface positions of sub-vertical structural discontinuities interpreted from remotely sensed data including the SCA aeromagnetic data. The location of some of these resistivity anomalies coincides with vertical displacements previously interpreted from the SCA geological logs in bores that straddle the anomaly. These apparent displacements in the flat-lying stratigraphy over distances of tens to several hundred metres reveal the presence of faults often reflected in equi-spaced discontinuities and formation of structural blocks which constitute elements of larger-scale ordered structural networks comprising ‘stepped’ horst and graben structures of varying scale.

However, steep-sided linear anomalies revealed in the resistivity imaging data are not always accompanied by stratigraphic displacement in that area. Many of these anomalies are considered to be possibly due to the presence of fractures and joints that do not have movement along them. Nevertheless, these discontinuities can still act as effective conduits for groundwater transmission particularly if they are hydraulically connected and the density of fracturing and jointing is high. The development of regular joint and fracture blocks are common in the Hawkesbury Sandstone and in the broader Sydney Basin sedimentary rocks. It is likely that such joints and fractures constitute secondary aquifers in a ‘dual porosity’ aquifer system.

The VES method complemented the resistivity imaging surveying through its capacity to achieve a higher depth of investigation. The majority of the soundings performed during this investigation were able to delineate the depth to the base of the Hawkesbury Sandstone but provided no additional information on fracturing in the Hawkesbury Sandstone at depth.

Attempts to delineate structure using the EM34 meter were unsuccessful on this survey. The data provided no useful resolution in the highly resistive sandstone and showed very little correlation with the resistivity imaging results. This finding is not altogether surprising since the EM34 system requires a conductive target, but they are limited to environments of less than 100 mS/m (unless corrections are undertaken).

5. Case Histories

Survey results for two segments on the 6.2 km survey line are presented below to illustrate the major findings of the project. The locations of the two segments are shown in Fig. 2.

5.1 Profile A

Profile A (Fig. 3) is dominated by a central region of very high resistivity in the lower part of the profile – in the range 10^4-10^5 ohm.m which likely reflects the close proximity of the Mount Butler intrusive complex, that is, a ‘mass’ effect. The test bores in this area clearly intersected the Triassic sedimentary sequence however no intrusives are recorded in the uppermost 100 m. Outside of the dominantly high resistivity zone, interpreted resistivities are moderately high – generally well above 1000 ohm.m and consistent with the presence of between 80 and 90 m of Hawkesbury Sandstone as intersected in Bores 2B and 2C (Fig. 3).

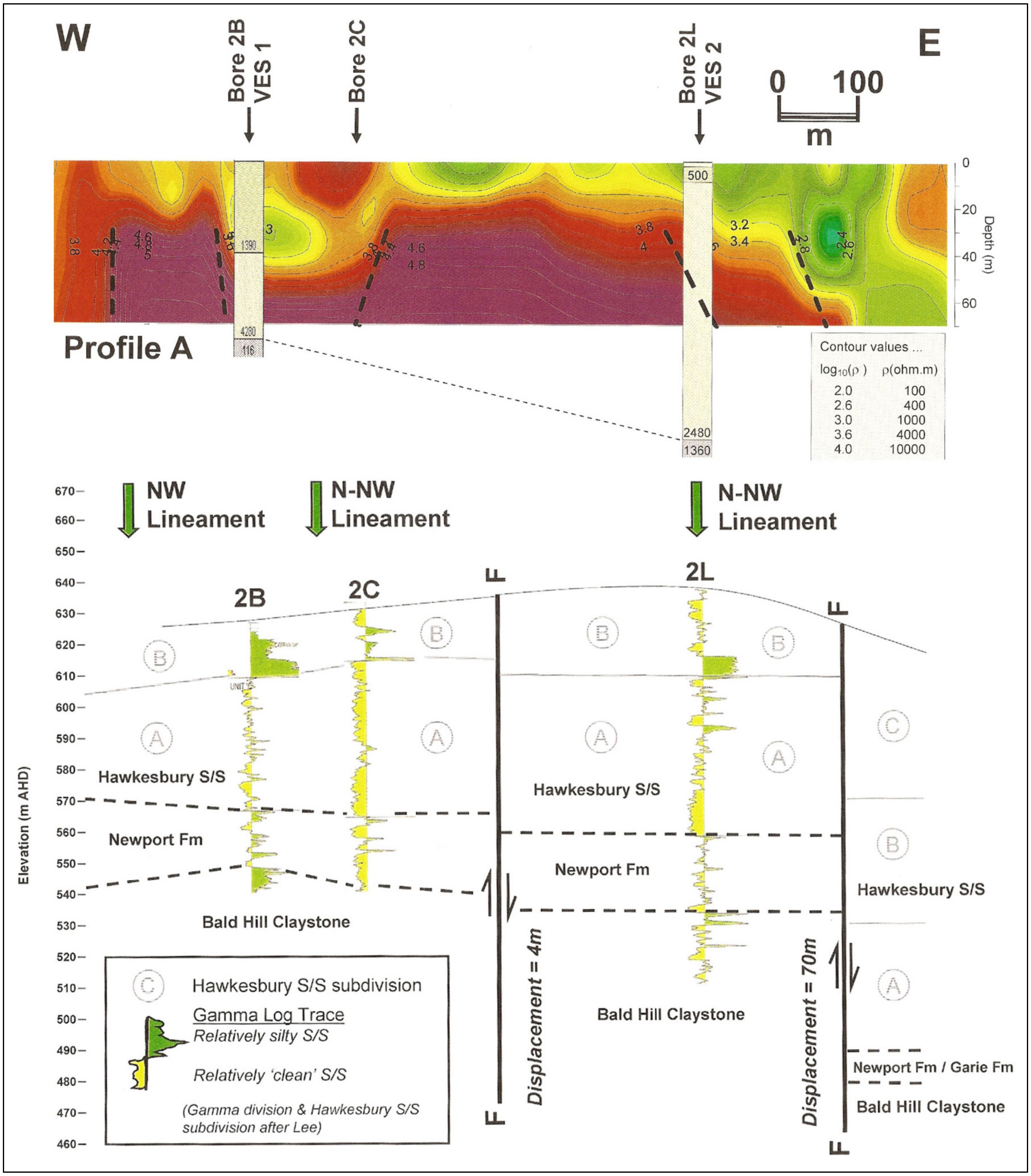

Figure 3 Profile A

Several significant lateral resistivity changes (sub vertical resistivity anomalies) are noted on the profile. Two of these anomalies are noted in close proximity to bores 2B and 2C. These anomalies may indicate vertical/sub-vertical structural features that correlate closely with the magnetic signature of the Mt. Butler basalt intrusive and likely represent a faulted contact. This evidence suggests that a network of sub-parallel fractures and possibly small-scale faults may dissect the sequence. This interpretation is supported by the occurrence of fractured Hawkesbury Sandstone recorded in the bores in this area and the occurrence of coincident NW and N-NW trending lineaments revealed on the aeromagnetic image and annotated on Fig. 3. The interpreted fault 180 m east of Bore 2C could, in realty, be closer to the bore than the section suggests and may in fact correlate with the steep sided resistivity anomaly near the bore.

The lower resistivity values and a significant change in lateral resistivity on the eastern end of Profile A correlate with an observed groundwater discharge zone (spring) which is interpreted to be a saturated sub-vertical fault zone with associated weathering that produces low-resistivity weathering products (clays).

VES 2 displays good agreement between the depth to the Bald Hill Claystone recorded in test drilling and the depth to the lowermost (conductive) layer of the resistivity model. This log (close to Bore 2L) indicates a large thickness (127 m) of Hawkesbury Sandstone/Newport Formation with underlying Bald Hill Claystone intersected at a depth of 127 m.

5.2 Profile B

The interpreted resistivities are moderately high – generally above 1000 ohm.m which is consistent with approximately 110 m of Hawkesbury Sandstone in this area (Fig. 4).

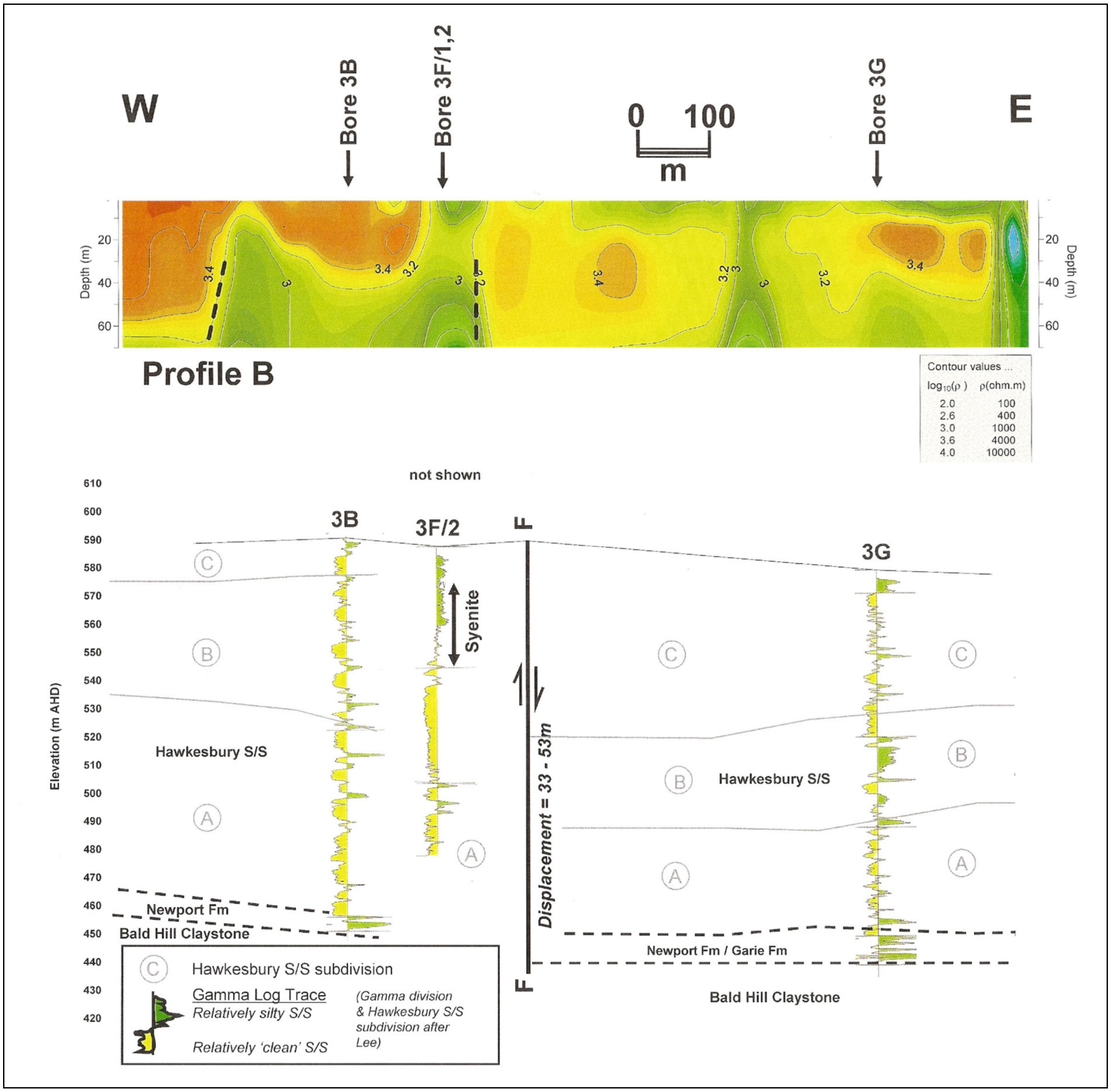

Figure 4 Profile B

A marked change in lateral resistivity is noted near Bore 3F/2 which intersected Hawkesbury Sandstone down to approximately 14 m and then a fine grained Jurassic syenite dyke or sill between 14 and 50 m before re-entering the Hawkesbury Sandstone to the base of the bore at 114 m.

A significant vertical displacement of the stratigraphy is apparent somewhere between bores 3B and 3G. The position of this structure may, in realty, be closer to Bore 3F/2 than the section suggests and is therefore considered to be a good candidate for the structurally controlled emplacement of the syenite intrusion (Fig. 4).

A resistivity anomaly at the western end of the profile indicates the occurrence of a sub vertical structural discontinuity. Although the geological evidence does not support any significant vertical displacement in this area, the sequence may nevertheless be fractured or the movement is lateral.

A VES conducted adjacent to Bore 3F/2 that intersected the syenite revealed a few metres of moderate resistivity material that suggests the presence of weathered sandstone with some possible minor clay. Underlying this is a very thick layer of 1350 ohm.m resistivity to a depth of 121 m. This resistivity is consistent with the presence of the Hawkesbury Sandstone recorded in the bore to a depth greater than 114 m.

6. Conclusions

Overall, the geophysical surveying was successful and provided positive results. The resistivity imaging method achieved a realistic depth of investigation of approximately 70 m on this project but was unable to penetrate the full depth extent of the Hawkesbury Sandstone. Greater depth penetration may be achieved using additional electrode cables and a more powerful transmitter.

The resistivity imaging geophysical surveying method has demonstrated a capacity to identify and delineate potential drilling targets for groundwater supply, in particular the delineation of structural discontinuities and defects that have dissected the Hawkesbury Sandstone including joints, fractures and faults. The Wenner electrode array provides superior data quality and is effective in delineating gross structure in a highly resistive geological environment such as that demonstrated in the Southern Highlands.

The VES method provides a viable and technically sound alternative to costly test drilling where the objective is to establish the depth extent of the Hawkesbury Sandstone. Attempts to delineate geological structures or near-surface conditions using EM34 were unsuccessful. The data provided no useful resolution and showed very little correlation with the resistivity imaging results.

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A need for groundwater assessment for coal seam methane exploration

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Abstract

Methane gas occurs naturally in coal seams but its commercial production has only been occurring in Australia as recently as 1996. Coal seam methane (CSM) is adsorbed onto the coal surface, with flow occurring by diffusion to cleats, but is can also occur as a free gas in coal seams. The commercial extraction of CSM initially requires increasing the hydraulic conductivity of the coal seam by mechanical injection of water and sand opening up fractures. Water is then pumped from the coal seam reducing the hydrostatic pressure and in turn releasing the methane. The flow of water being pumped to the well draws the methane with it and both are brought to the surface and separated. After a period of pumping the hydrostatic pressure drops in the seam sufficiently and the coal seam to no longer require dewatering in order to release the methane.

Several potential impacts have been identified with regard to the effect of the CSM exploration and extraction phases on surface and groundwater systems including: depletion of the overlaying aquifers as a result of groundwater drawdown, the release of methane to other aquifers with the potential to contaminate groundwater and the correct disposal of coal seam water once it has been brought to the surface. It is important therefore to have a thorough understanding of the groundwater conditions of any potential CSM extraction site to reduce or eliminate any of these impacts.

Keywords: Coal seam methane, groundwater, gas extraction, Sydney Basin

Introduction

In the last two decades the extraction of CSM has become an important energy industry across the world. The technology was developed in the United States and was quickly taken up in England, Germany, Russia and Australia as the demand for natural gas has increased.

Coal seam methane is extracted by pumping water from wells installed in coal beds that contain methane. The removal and discharge of this production water has renewed interest in hydrological and geochemical processes that control the water quality and quantity in the coal seam aquifers.

Coal seam gas is a hazard for underground coal mines in Australia. The advancement of coal seam gas abstraction methods could potentially ease that situation. Abstracting CSM from the seams can not only reduce the internal gas pressure within the coal seam, increasing safety but in some cases can be burnt and converted into electricity.

The two principal management issues associated with CSM exploration and extraction include:

- The potential to impact on groundwater through drawdown and depletion of overlying water supply aquifers and/or surface water resources, and any subsequent effect on beneficial use of the resource.
- Any water quality effects and disposal/reuse of coal seam water from CSM extraction.

The potential for any effect on the shallow aquifers mitigates as the depth of coal seam exploration increases. The presence of a number of potentially confining layers overlaying the coal seam has the effect of minimising the risk of any potential hydraulic connection to shallow aquifers. However, management decisions require guidelines to assess the need for groundwater investigations relating to CSM extraction.

Coal Seam Methane Extraction Methods

History

The origins of coal seam methane exploration began in the USA in 1979 where AMOCO drilled the first coal seam methane well in the San Juan Basin (Origin Energy, 2002). In Europe, coal seam methane was explored from working and abandoned mines due to the lower cost associated with the exploring coal seams (Modern Power Systems, 2002).

In the 1950's, CSM was considered a hazardous by-product of underground coal mining operations and when encountered it was flared off. Methane gas could seep out of the coal seams and into the atmosphere in the cases where mining operations had ceased. To prevent the methane seeping, the underground mines could be sealed, however the open cut operations would require methane to reach equilibrium in partial pressures. In the late eighties methane was identified as a dangerous greenhouse gas, 21 times more potent than CO_2 (Modern Power Systems $_2$, 2002), therefore it had to be contained.

In recent years, the CSM has been explored as a resource and is captured, manufactured and utilized for power generation.

CSM is currently being produced commercially in the USA, UK, Russia, Australia, Germany, with the active exploration ongoing (Gayer, R. and Harris, I., 1996; Creedy, D. and Tilley, H. 2003).

Methods

Coal seam methane is held within coal under confining pressure and water. The methane is adsorbed to the coal and stored in cleats and fractures. Releasing the methane from the seam involves changing the pressure within the coal seam by dewatering. The potential for methane extraction is dependant on the following properties; the methane saturation level in the coal seam, coal rank and depth, composition of gas, sorption capacity and the hydraulic conductivity of the coal seam.

The most common method of increasing hydraulic conductivity involves the process of induced hydraulic fracturing. In this process a large quantity of sand and water are pumped into the seam under high pressure. This causes the existing coal seam fractures to dilate while the injected sand holds the fractures open thus providing high permeability pathways for the gas to be extracted.

Other methods available for CSM extraction are (Creedy & Tilley, 2003):

- Enhanced coal seam methane (ECSM) – a process where nitrogen or CO_2 is injected into the seam. The injected gas reduces partial pressures of methane and enhances desorption.
- Biotechnology – a process where methanogens are introduced into the seam to microbially increase the methane content of the coal seam as well as enhancing the permeability of the seam by removing pore-clogging waxes

International experience in groundwater assessment for CSM exploration

Collection, handling, treatment, and disposal of waters produced during CSM exploration and the influence of CSM on the local groundwater systems are important, hence if not done properly, can have a lasting negative environmental impact. The USA leads the CSM exploration and production in the world with three large CSM production areas: the San Juan Basin in Colorado and New Mexico, the Black Warrior Basin in Alabama, and in the recent years the Powder Basin in Wyoming and Montana.

The volume and quality of water produced through CSM exploration process depends on the depositional environment, depth, type of coal and permeability of overburden. In the USA, the water produced with CSM is generally sodium, bicarbonate and chloride dominated (USGS, 2000). The salinity of water varies in range from fresh 200mg/L to saline 170,000mg/L (Table 2). The salinity is dependent on the origin of rocks hosting coal seams, residence time, and origin of water entering the coal seams. Overall, the CSM water is of better quality than water produced from conventional oil and gas wells (USGS, 2000).

Table 3 Water production and salinity levels in major CSM producing basins in the USA

Basin	Water production per well (kL/day)	Average salinity (uS/cm)	Major disposal method
Black Warrior	9	NA	Surface discharge
S Powder basin	47	1200	Surface discharge
N Powder basin	47	2500	Surface discharge
Raton	31	3400	Injection
S San Juan	3	29700	Injection
N San Juan	3		Injection
Uinta	25	23400	Injection

Prior to the introduction of Federal regulations in USA in the 1970's, large volumes of CSM production water were directly discharged into rivers, streams, and unlined evaporation ponds. Now, the disposal and reuse are governed by Clean Water Act (1977, with amendments in 2009), the Safe drinking Water Act, and the Resources Conservation and Recovery Act, in addition to particular State regulations. Ongoing studies are undertaken by U.S. Geological Survey (USGS) on all active CSM fields to provide the information on the regional geology and hydrogeology, specific reservoir properties, and water quality.

The USGS, in cooperation with the Wyoming State Engineer's Office (WSEO) and the Bureau of Land Management (BLM), conducted an investigation to enhance the understanding of the characteristics of the aquifers associated with the development of CSM in the Powder River Basin.

Bartos T. and Muller K (2002) found that the groundwater quality in the Powder River Basin, affected by the CSM project most frequently exceeded U.S. Environmental Protection Agency public water-supply standards and State of Wyoming domestic-use standards. Samples collected from wells completed in both the Wasatch aquifer and coal seam aquifers plotted in a wide range of both sodium- and salinity-hazard classes, but most samples clustered in or near the combined medium-sodium-hazard—high-salinity-hazard classes. The Tertiary age coal seams which represent the aquifers are interbedded and overlain by siltstone and sandstone. The deposition occurs in fluvial, lacustrine and swampy environments (Seeland, 1992); therefore the sources of salt are most likely linked to long residence time.

A guide was developed by water specialists in Wyoming, Montana, Colorado, Utah and US EPA to address the resources management issues related to CSM. They found that the following were of most importance related to CSM exploration: impact of water withdrawal on groundwater resources and impact on surface water, soil and vegetation due to discharge of production water (Keith et al, 2003).

In Colorado majority of produced groundwater through CSM process is injected back in the aquifer. In British Columbia (Canada) groundwater produced as a result of CSM must be reinjected into the aquifer or maybe allowed to dispose to surface water if the water quality complies with Waste Management Act. Other methods include treating, discharging into surface water bodies, and using water for irrigation.

The US Bureau of Land Management estimates that one CSM well can lower aquifer levels by 10m within 3m of the well (NPRC, 2001). In the Powder River and San Juan Basins, the level of drinking water wells near CSM development had reportedly dropped by over 60m (WORC, 1999).

The environmental concerns that have been highlighted in existing literature from CSM exploration include the following:

- the potential for groundwater drawdown and depletion of important water supply aquifers
- the effect on beneficial uses for groundwater and surface water users
- the need to dispose of coal seam water and the effect on water quality (surface water and groundwater)
- the release of methane to shallow groundwater.

CSM exploration in Australia

Potential CSM resources have been known in Australia since the 1980's however the development of the resource did not get underway until the mid to late 1990's. Nevertheless, the extraction of CSM to improve mine safety has been well established.

Within Australia the most active areas of exploration and production are in Queensland. CSM has been exploited in the Bowen-Surat Basin for the last decade with the production coming from Permian Coal measures in the basin. The Bowen Basin is the most actively explored basin for CSM, with drilling activity exceeding 80% of Australia's total in 2004 (Geoscience Australia, 2008).

CSM is also being explored in other areas of Australia including South Australia (Gippsland, Willochra and Pedirka basins), Western Australia (Perth, Collie, Wilga and Canning Basins), Victoria (Otway Basin), Tasmania (Tasmania Basin) and NSW.

In New South Wales there are currently two areas of CSM production; Narrabri in the Gunnedah Basin and Camden in the Sydney Basin, with coal mine methane being extracted in several mines in the Southern Coalfields.

CSM related water monitoring legislation Australia

The current legislation covering the CSM exploration and production is governed by separate State legislation. The high salinity of the water associated with majority of the coal seams in the Sydney-Gunnadah-Bowen Basins and the reliance on water resources has meant that a strong emphasis needs to be taken to protect the surface and groundwater resources. It has been recognised however that Federal guidelines are required to assist in the management of this emerging industry, a study by the National Water Commission (NWC, 2009) is currently being undertaken to assess the issues relating to the production and disposal of water from CSM production.

In 2004 the Queensland government developed new legislation called the *Petroleum and Gas Act 2004* which encompassed both the *Petroleum Act 1923* and the *Gas Act 1965* and incorporated clear links to the *Water Act 2000 (Qld)* to ensure that groundwater and surface water resources are protected.

CSM related water monitoring legislation NSW

NSW legislation covering CSM has been developed relative to the pace of CSM exploration. Currently, the exploration and extraction of CSM is operated under the *Petroleum Onshore Act 1991*. The legal requirements for monitoring water assets during the exploration phase of CSM development and the disposal of water from CSM production is covered under the *Water Management Act 2000 (NSW)* and the *Water Act 1912 (NSW)*. Currently, there are no prescriptive guidelines for groundwater monitoring during exploration and production of CSM outside of the NSW water legislation.

Department of Water and Energy (formerly DLWC) developed "Stream/Aquifer Guidelines: Management of Stream/Aquifer Systems in Coal Mining Developments, Hunter Region" The Guidelines were created to assist the coal mining industry in managing the surface water and aquifer features associated with underground coal mining. Although the guidelines were not specifically designed for CSM development they can be adapted to assist in the design of groundwater monitoring process.

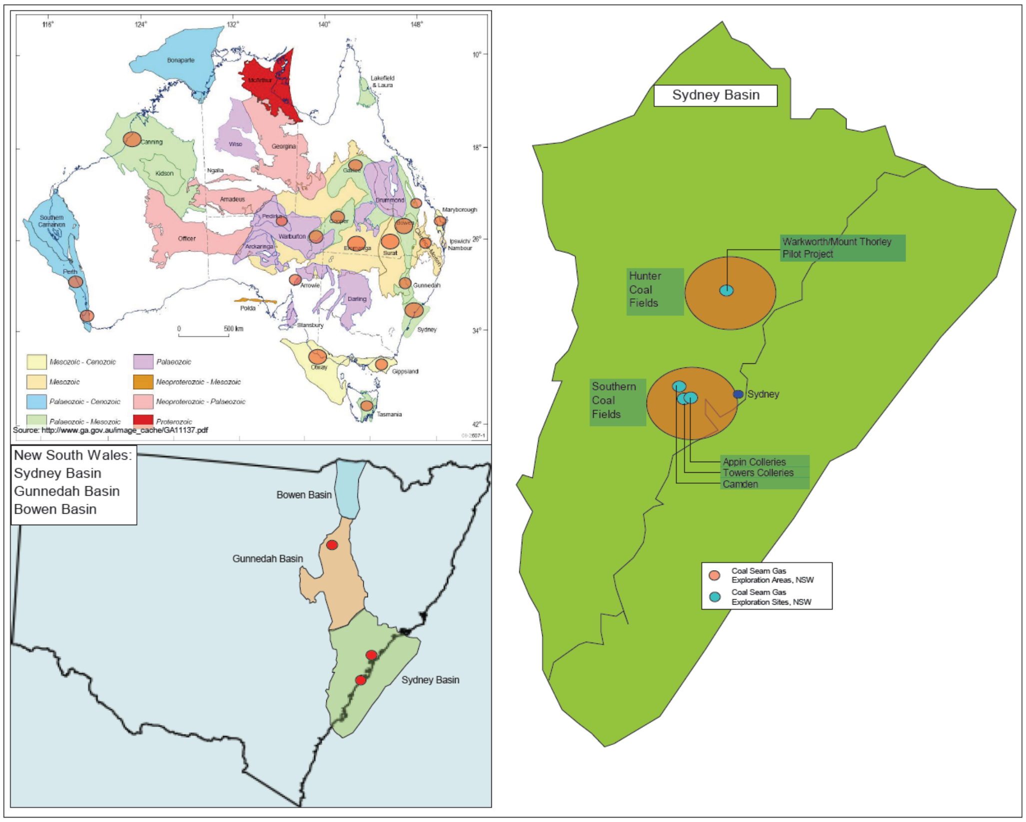
Potential for Coal Seam Methane within Sydney Basin

The Sydney Basin forms the southern part of the Sydney-Gunnadah-Bowen basin. The Sydney Basin is 400km long and 200 km wide with approximately 12% of the basin area extending out to sea along the NSW coast, as far as the continental shelf.

The geology of the Sydney Basin comprises a succession of Permian-Triassic sediments consisting of marine, deltaic and fluvial formations. The coal measures of the Sydney Basin were deposited after the Hunter-Bowen orogeny within a shallow basin which was open to the sea to the south.. A succession of marine transgressions and regressions during the Permian deposited sediments within the basin comprising marine sands, fluvial sands and gravels, deltaic mud and outwash fans and coal seams.

CSM exploration is currently being undertaken at several locations in the Hunter Valley where estimated high yields of CSM exist in the Permian coal measures that extend through the basin. A CSM extraction project is being trialled at Mount Thorley and Warkworth mine in the Hunter Valley to reduce its emissions footprint (Darnbrough, 2008). In Tower, Appin and Tahmoor collieries in the Southern Coalfield the extraction of methane has been ongoing since 1996.

Figure 4 Sydney Basin and location of areas with potential for CSM exploration



Source: http://www.ga.gov.au/image_cache/GA11137.pdf

Groundwater issues for the Sydney Basin

Internationally identified groundwater issues related to CSM exploration and relevant to Sydney Basin include the potential for groundwater drawdown and depletion of shallow aquifers and the release of methane to shallow groundwater.

The geology of the Hunter Valley and Southern Coalfields comprises a sequence of Permian and Triassic conglomerates, sandstones, siltstones, shales and coal seams. The coal seam represent relatively permeable unit generally confined between less permeable layers comprising Permian siltstone/conglomerate/sandstone sequence.

By targeting deeper seams the potential effect on the alluvial aquifers is minimised. This is because the number of confining layers between the coal seam undergoing depressurisation and the alluvial aquifers will increase. This has the effect of minimising the risk of any potential hydraulic connection.

There is need for specific monitoring to determine baseline conditions of aquifers and surface water features associated with CSM exploration. This includes monitoring groundwater levels, and water quality without which it is difficult to determine any changes that may have occurred during exploration. Currently there are no specific guidelines for the length of the baseline monitoring period for coals seam gas exploration. For example, methane is found naturally in groundwater systems associated with organic rich, anoxic sediments. The challenge for monitoring any water systems associated with CSM extraction is to determine the background or natural level of methane present in the water and its origin, and in this way provide the ability to detect changes when production starts.

The water produced during CSM extraction in the northern parts of the Sydney Basin would typically be brackish to saline (DIPNR, 2005; Coal and Allied, 2002, Gates *et al*, 1983)). The salinity of the water is generally high enough (up to 10,000 μS/cm) that it is at the threshold of agricultural use and therefore presents a challenge for disposal. Water Management Act (NSW) guidelines do not allow disposal of saline water into the streams and groundwater bodies. Therefore, treatment may be needed or other beneficial uses need to be explored. The potential effects and advantages and disadvantages of different options are given considering the water quality and current legislation. The water disposal options for CSM produced water are given in Table 2.

Table 2 Various options for discharge of CSM production water

Option	Advantages	Disadvantages	Potential Effects
Discharge to surface waters	-Low operational cost -Environmental benefits	- Land, flood inundation risk, and costs -Treatment cost for high salinity water -Permission for discharge is required - High evaporation can concentrate contaminants	- Surface water - Shallow ground water (leakage from surface structures) - Land inundation/reuse. - Flood inundation areas.

Deep well injection	- No surface discharge -The effect on shallow aquifers is minimised	-Requires permit for groundwater recharge and aquifer interference -Water treatment may be needed -Ongoing monitoring is needed -Increased cost for deep well construction, operation, maintenance, abandonment - Permeability needs to be such to allow injection	- Potential for aquifer degradation
Disposal for beneficial use (irrigation, water for environment)	-Potentially least expensive -Environmental benefits	-Disposal options for high salinity water are limited - Restrictions\cost due to potential treatment	- Land degradation
Closed water system (i.e. water reuse for hydraulic fracturing)	- No/limited surface water storage and discharge	- Complex piping network - Requires permit	- Land (potentially increased water distribution network)
Evaporation ponds	-No surface or groundwater discharge	-Significantly large areas are needed for disposal of water -Need to resolve land ownership and long term environmental liability	-Land degradation -Long term legacy related to salt ponds

Conclusion

The development of CSM throughout the world in the past two decades has resulted in technical progress in exploitation methods and has allowed easier access to the much needed energy source.

The effect of CSM extraction on the natural resources has been recognised early on in the USA, and later followed by other countries. In the USA, the protection of groundwater, surface water and potential land degradation has been managed by State and Federal acts. In recent years, guidelines have been developed in the USA in response to public request to address resource management related to CSM extraction. These guidelines address the effect of CSM exploration on groundwater systems, and the effect of various disposal options on the environment and private property.

Groundwater in the Sydney Basin CSM areas in deep coal seams is generally saline, therefore the groundwater has limited beneficial purposes, but reinjection or disposal to creeks following treatment could be a viable option. Potential groundwater drawdown and depletion of shallow aquifers can be minimised by temporal and spatial monitoring of groundwater and surface water. As methane is naturally occurring in coal seam aquifers the background concentrations of the gas need to be determined within different aquifers prior to gas exploration.. Greater emphasis should be placed in understanding the natural occurrence of methane in groundwater and more specifically suitable monitoring programs need to be implemented prior to any CSM exploration activities.

CSM extraction in the Sydney Basin is relatively young industry. Currently, there are no prescriptive guidelines for groundwater monitoring during exploration and production of CSM outside of the NSW water legislation. General management of surface water and groundwater for CSM extraction is only provided by the Water Management Act 2000 (NSW); however it is not specific. Specific guidelines have been recently developed in Queensland for the CSM industry; for the effective management of groundwater and surface water in NSW, similar legislation needs to be developed.

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Fracture Properties of Hawkesbury Sandstone in the Sydney Region

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Abstract

Geotechnical and hydrogeological data obtained from various infrastructure projects in Sydney were collated to form a database that describes the defects (fracture/discontinuity) properties of the Triassic age Hawkesbury Sandstone. Four investigations across northern, western and southern Sydney involved drilling over 70 boreholes with borehole imaging conducted by RAAX Australia to provide information on subsurface defect characteristics. Statistical analysis, including frequency distribution and distribution weighting, as well as linear regression, were conducted on borehole imaging data. This paper presents the results of the analyses, including the relative proportions of defect dips, spatial distribution of sub-horizontal and sub-vertical defects and defect aperture size with respect to depth. Sub-horizontal defects comprised 68% of the total defects and sub-vertical defects accounted for the remaining 32%. The number of sub-horizontal defects was found to decrease with increasing depth; however, no correlation was found between sub-vertical defect frequency and depth. Few defects possessed a defect dip within the range of 30 to 65 degrees from the horizontal, and the average vertical defect spacing was of the order of 1 m. These findings may assist fracture network representation in conceptual discrete fracture network models

Keywords: borehole imaging, defect characteristics

1. Introduction

Borehole imaging data from four infrastructure projects across Sydney have been analysed in the current study to document defect (fracture/discontinuity) properties of the Hawkesbury Sandstone.

1.1. Regional Stratigraphy

The investigation areas are located within the Sydney Basin where lithologies generally comprise (down the stratigraphic sequence): sediments of varying thickness, Bringelly and Ashfield Shale of the Wianamatta Group, Mittagong Formation, Hawkesbury Sandstone and the Narrabeen Group. Hawkesbury Sandstone is the focus of this study. The geology of the Hawkesbury Sandstone has been described in detail by others, for example Conaghan (1980) and Pells (2002) with respect to engineering geology.

1.2. Subsurface Investigations

In borehole imaging, a video camera is lowered down the borehole and provides a visual image of the borehole wall which is processed and used for interpretation. Borehole imaging was conducted in 74 boreholes at depths ranging from 1.2 to 191.2 m below ground level. In each borehole both open and closed (tight/infilled) defects were logged. Sandstone units of the Hawkesbury Sandstone were the main lithology encountered in the boreholes, with some shale and minor basalt. Defect data for the shale and basalt were not included in the current study.

2. Defect Characteristics

Defects are defined in this study as open dislocations in the rock fabric that are larger than the typical size of intergranular voids present in intact fabric. Defects included bedding plane partings and cross-bedding discontinuities. The defects provide preferential pathways for groundwater flow and are generally referred to as fractures, joints or partings. The dataset analysed comprised a total of 3733 defects which were divided into two main groups:

- Sub-horizontal defects with dip angles less than or equal to 45 degrees.
- Sub-vertical defects with dip angles greater than 45 degrees.

Defect data were analysed for the relative proportions of defect dips, the spatial distribution of sub-horizontal and sub-vertical defects, and defect aperture size with respect to depth. Vertical depth below ground level was corrected for angled boreholes.

2.1. Relative Proportions of Defect Dips

The relative distribution of defect dips for all analysed boreholes is presented in Fig. 1. Since boreholes drilled at near-vertical angles are likely to encounter fewer sub-vertical defects than are present in the rock volume, the population of defect dips was weighted according to borehole and dip direction to account for defects that were not intersected during drilling. This method, developed and utilised by Tammetta & Hewitt (2004), applies a weighting factor to each defect data point which accounts for borehole and dip geometry. The weighting factor, W, is equal to the inverse of the scalar product between a unit vector which is aligned with the borehole, ǔ, and a unit vector normal to the plane of the defect, č:

$$W = \frac{1}{\check{u} \cdot \check{c}} \quad (1)$$

Higher weightings are applied when the line of the borehole is close to lying in the plane of the defect, while lower weightings are applied when the line of the borehole is close to being normal to the plane of the defect. The distribution of dip angles is produced by applying the weighting factor for a given dip angle to all defects in the dataset. The area under the curve in Fig. 1 illustrates that sub-horizontal defects account for 68% of the total defects, sub-vertical defects account for the remaining 32%, and few defects possess a defect dip within the range 30 to 65 degrees from the horizontal.

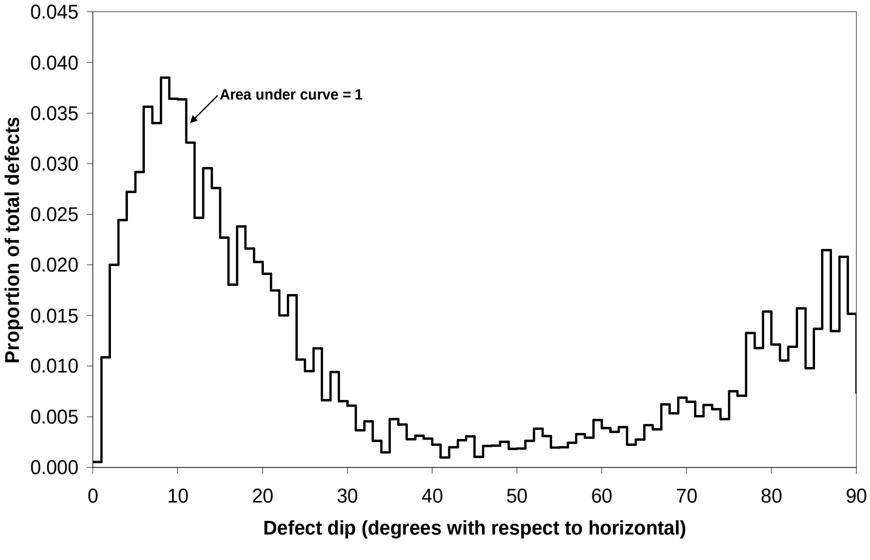

Figure 1 Relative (weighted) proportion of defect dips

2.2. Defect and Aperture Distribution

2.2.1. Available Dataset

The percentage of RAAX imaging data and defect data obtained at specific depth intervals of 1 m is presented in Fig. 2. Note that *N* is the number of data points presented each for dataset in the figure. The figure illustrates that there is a greater number of boreholes covering depths around 25 m and the number of boreholes covering deeper locations progressively decreases. Correspondingly, the number of defects recorded at depths around 25 m is significantly higher than the number recorded at greater depths. This is to be expected, since the greater stress relief at shallower depth allows for increased defect detail. In order to remove this inherent bias of observed defects with depth, the proportion of defect data at each depth interval was weighted according to the proportion of data present in the dataset for that depth interval. The weighted defect distribution with depth is presented in Fig. 3 for sub-horizontal defects and shows a decreased proportion of defects at greater depths. Linear regression demonstrates a correlation between depth and number of sub-horizontal defects. The weighted defect distribution with depth is presented in Fig. 4 for sub-vertical defects and shows no correlation exists between depth and observed number of sub-vertical defects.

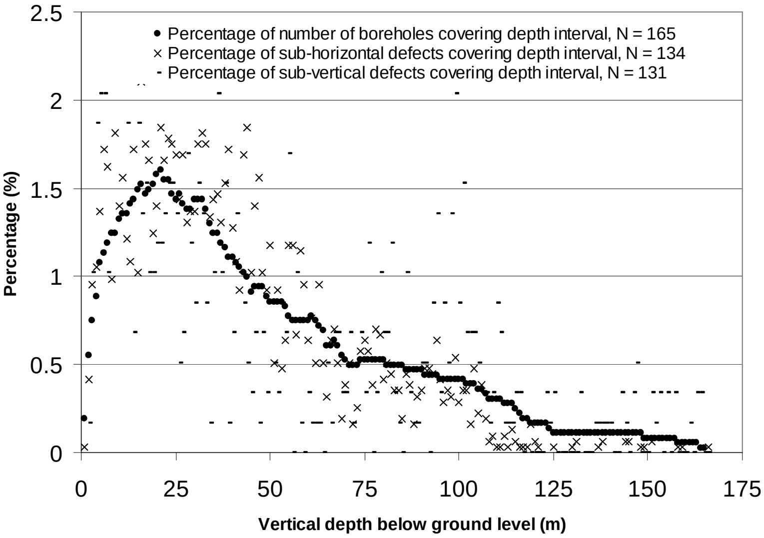

Figure 2 Relative proportion of borehole imaging data and number of defects, aggregated over 1 m intervals

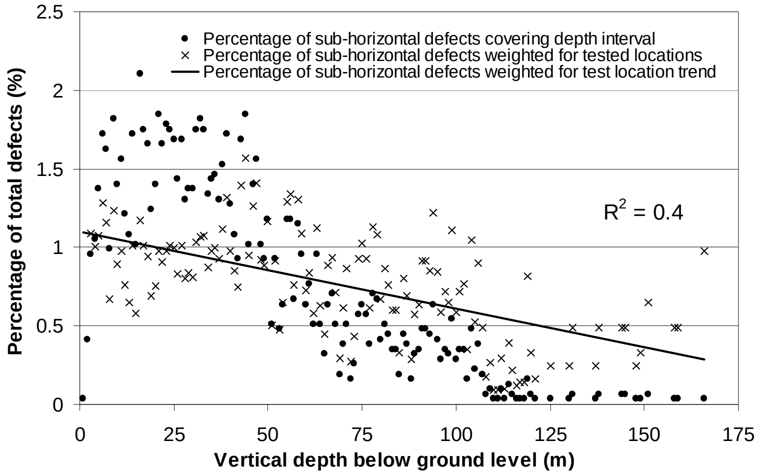

Figure 3 Relative percentage of sub-horizontal defects, aggregated over 1 m intervals, *N* = 134

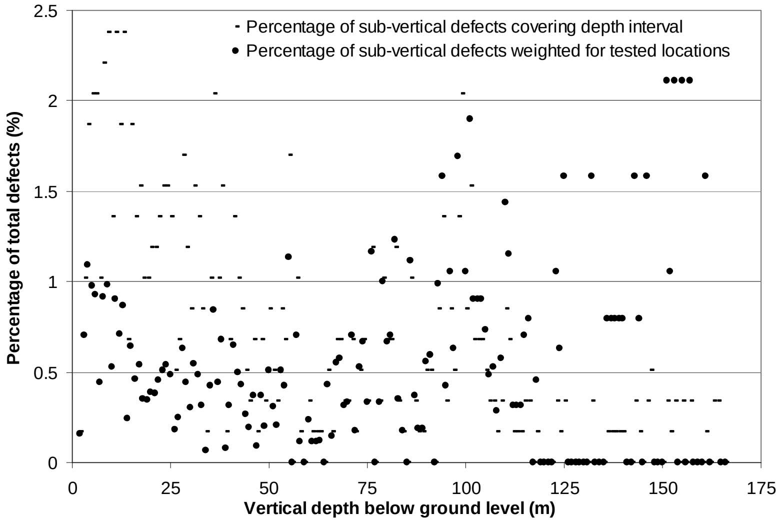

Figure 4 Relative percentage of sub-vertical defects, aggregated over 1 m intervals, *N* = 131

2.2.2. Spatial Distribution

The defect spacing (distance between one defect and the next) and the defect density (number of defects per metre) were calculated for both the sub-horizontal and the sub-vertical defect groups. Defect spacing was determined by calculating the projected vertical or horizontal distance for sub-horizontal and sub-vertical defects respectively, as implied by defect dip angle, between successive defects in a borehole. This approach assumes defects are near-parallel. The vertical spacing between sub-horizontal defects against depth is illustrated in Fig. 5 and predominantly ranges from 0.01 to 10 m for depths of up to 105 m. While the figure suggests a slight increase in defect spacing at depths greater than 105 m, this apparent increase is likely biased due to the lack of data available at deeper locations. The horizontal spacing between sub-vertical defects against depth is illustrated in Fig. 6 and consistently ranges from 0.001 to 10 m for depths of up to 160 m. The 100-point arithmetic moving mean suggests both the vertical spacing between sub-horizontal defects and the horizontal spacing between sub-vertical defects averages in the order of 1 m.

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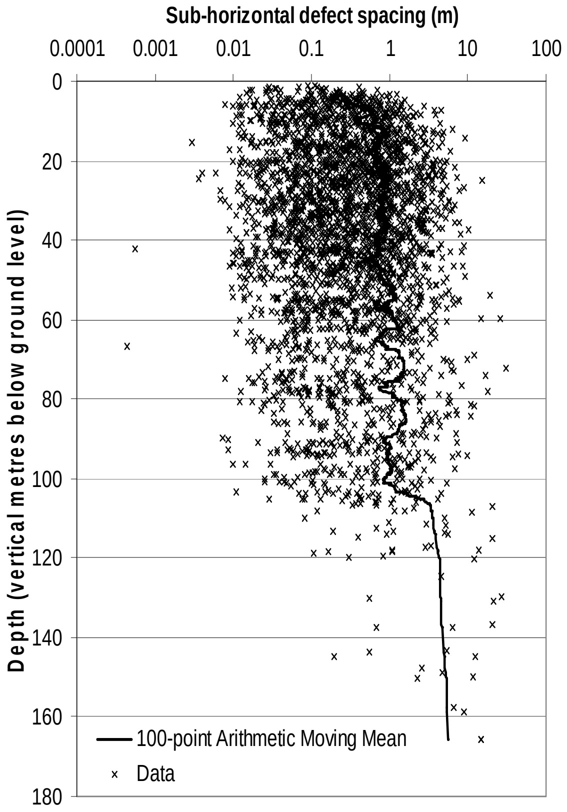

Figure 5 Sub-horizontal defect spacing, *N* = 3073

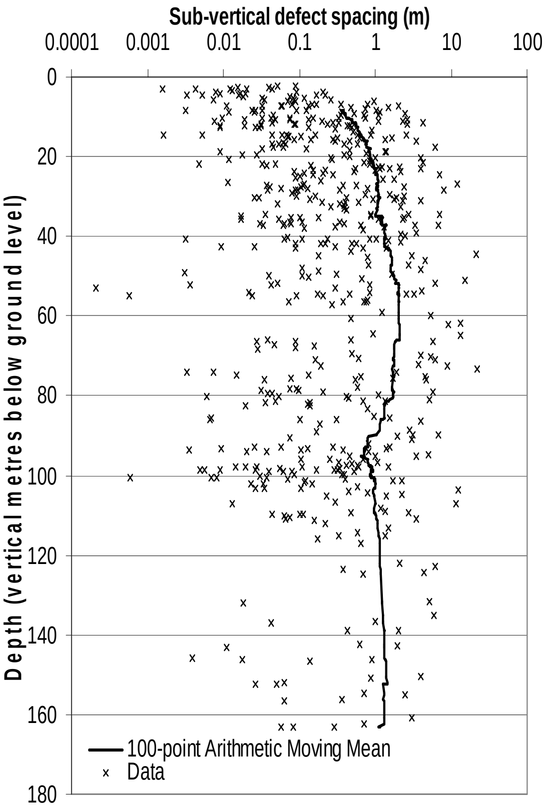

Figure 6 Sub-vertical defect spacing, *N* = 532

The defect densities (number of defects per metre) of sub-horizontal defects considered against depth predominantly range between 0.1 and 100 defects per metre for depths of up to 105 m. The defect densities (number of defects per metre) of sub-vertical defects against depth predominantly range between 0.01 and 100 defects per metre for depths of up to 160 m.

2.2.3. Aperture Size

Hydraulic conductivity is closely related to defect characteristics such as aperture size, frequency, angle, orientation, interconnectivity, defect plane features and filling materials (Hamm et al., 2007). In a study conducted by Hamm et al. (2007) showed that, in fractured granite in the Mt. Geumjeong area, Korea, hydraulic conductivity was more strongly correlated to defect aperture than it was to defect frequency. In a study conducted by Baraka-Lokmane et al. (2003), the predicted hydraulic conductivity from defect geometry (aperture, width and length) measured using an optical method correlated well with independent physical conductivity measurements conducted on fractured sandstone cores.

In the current study the variation in aperture size with respect to depth was explored. Note that the aperture size resolution for RAAX imaging is 0.3 mm. Thus, whilst apertures under 0.3 mm in size are included in the data, they are reported as being 0.3 mm in size. Defects with an aperture size less than or equal to 0.3 mm account for 54% of all sub-horizontal defects and 60% of all sub-vertical defects, and defects with an aperture size of 0.5 mm account for 30% of all sub-horizontal defects and 25% of all sub-vertical defects.

The variation in aperture size with vertical depth for sub-horizontal defects is illustrated in Fig. 7. The data shows significant variation in aperture size over depth, ranging from the minimum RAAX imaging resolution of 0.3 mm to almost 500 mm. Due to the lack of available data it is not possible to determine trends at depths greater than 100 m. However, the data suggests the presence of apertures of all sizes within the range at all depths up to 100 m, with the majority of data in the range of 0.5 mm or smaller. The variation in aperture size with vertical depth for sub-vertical defects is illustrated in Fig. 8. Like the analysis of sub-horizontal defects, although the dataset is smaller, the majority of sub-vertical defects' data are in the range of 0.5 mm or smaller.

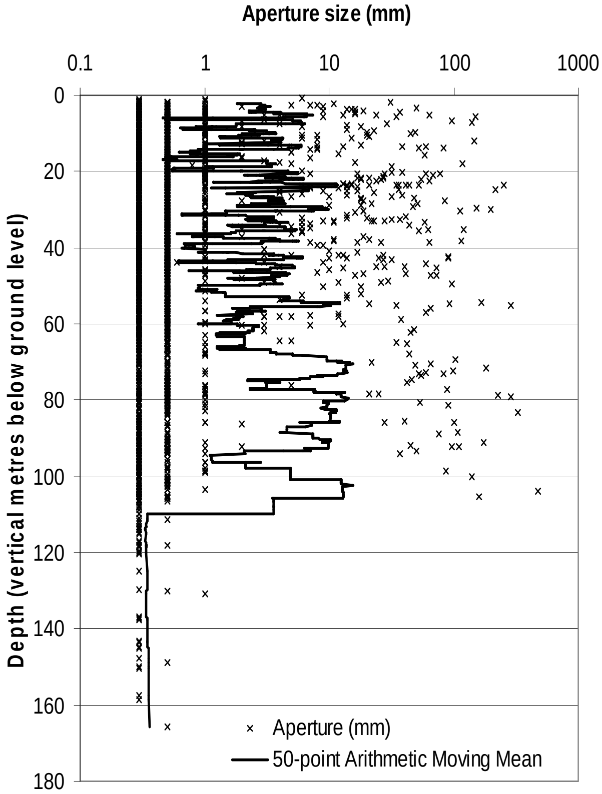

Figure 7 Aperture size for sub-horizontal defects

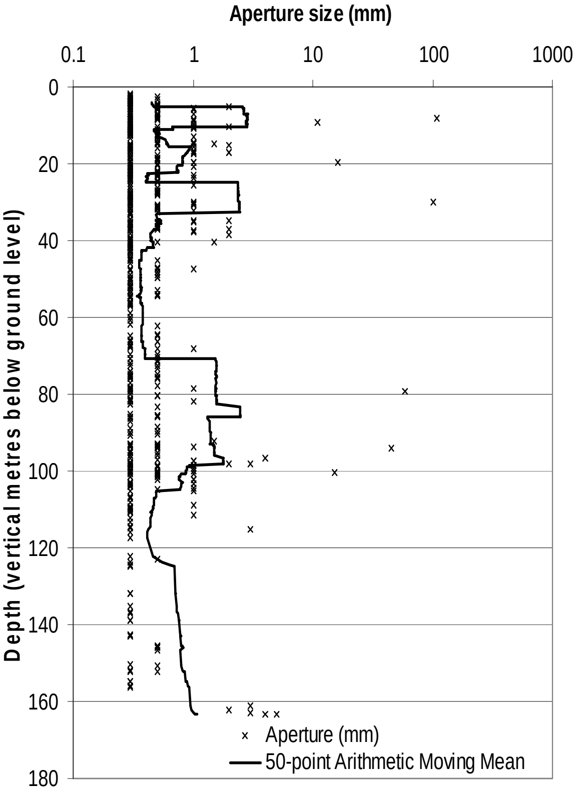

Figure 8 Aperture size for sub-vertical defects

3. Conclusions

From the analysis of the borehole imaging dataset, several observations were made for the defect properties of the Hawkesbury Sandstone in the study area. These are summarised below:

- Sub-horizontal defects comprised 68% of the total defects and sub-vertical defects accounted for the remaining 32%.
- Few defects possess a defect dip within the range of 30 to 65 degrees from the horizontal.
- The number of sub-horizontal defects decreases with increasing depth. No correlation appears to exist between the defect frequency and depth for sub-vertical defects.
- Though there is a large range of vertical spacing between sub-horizontal defects (0.01 to 10 m) and horizontal spacing between sub-vertical defects (0.001 to 10 m), the average spacing for both groups is of the order of 1 m.
- Aperture size shows significant variation ranging from the minimum resolution of 0.3 mm to almost 500 mm for sub-horizontal defects and 0.3 mm to 100 mm for sub-vertical defects. However the majority of the data for both defect groups was in the range

of 0.5 mm or smaller. No correlation appears to exist between aperture size and depth for both defect groups.

- Insufficient data exists in the current study to reliably determine trends at depths greater than approximately 100 m.

This information may assist fracture network representation in conceptual discrete fracture network models. Methods have been developed for building three-dimensional (3-D) fracture networks in rocks surrounding boreholes using image logs, for example the method developed by Wu and Pollard (2002). The method correlates fracture patterns for individual sets of fractures and extrapolates fracture density and connectivity from 1-D in boreholes to 3-D in the surrounding rocks.

Comparative analysis of the current borehole imaging dataset in conjunction with packer test results will provide more insight into characterising the fracture properties of Hawkesbury Sandstone.

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An integrated hydro-geotechnical modelling approach to predicting the impacts of subsidence above longwall coal mines on groundwater and surface water flows in the Hunter Valley (NSW).

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Abstract

Coal mining in the Hunter Valley of the Sydney geological basin co-exists with high value agriculture, horse breeding, viticulture and "lifestyle" rural residential. There is increasing community and regulator concern over impacts on (diversions from) surface water flows – even if "impacts" are only perceived.

Longwall coal mining is a total extraction technique whereby the target seam is extracted in panels up to more than 500 metres wide. Following the extraction of coal, the strata above the panels collapses. Depending on the thickness of the seam, the width of the panel and the height of overburden, subsidence induced fracturing of the overburden can create connected flowpaths which may extend to the ground surface, and any creeks and alluvium located above the extracted panels.

Longwall mining has the potential to impact adversely on shallow groundwater and surface water flows if not managed, and the water regulators in NSW require impacts to be rigorously investigated before approving mining.

An integrated approach to predictions by coupling deformation models with groundwater models has been developed, which enables the required levels of reliability in predictions and the development of impact management strategies, and has allowed longwall coal mines to be approved beneath sensitive surface and groundwater resources.

This paper details the development of the integrated modeling approach and presents some case studies where the modelling has been successfully applied to achieve project approvals.

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The Role of Vegetation in Minimising Deep Drainage: application to mining and waste management industries

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Abstract

Minimising deep drainage (recharge) is an important requirement for the sustainable management of mine sites and landfill waste storage sites. Using vegetation to move water from soil to atmosphere is a viable option but knowledge of the rates of water use and an understanding of what determines the rate of water use by vegetation is critical to successfully minimising recharge. In this paper we describe the application of two models to estimate vegetation water use at a remnant Cumberland Plain woodland in NSW. The first model (a modified Jarvis-Stewart model) is very simple and requires very few inputs and is amenable to industry use. The second is a Soil-Plant-Atmosphere exchange model. This is complex but provides a detailed mechanistic understanding of the processes regulating vegetation water use. It also allows manipulation of key vegetation and climate attributes to investigate “what if” questions about the relationships among climate, vegetation structure and vegetation function (water use).

A key finding of our field study is that the deep clay layer underlying a relatively shallow (< 80 cm) sand layer provides a long-term storage of water that decouples tree water use from changes in the water content of the upper (sandy) soil profile where most of the roots are located. This result is counter-intuitive and not a well documented phenomenon and has significant ramifications for the design of store-release covers for capping mine and waste storage sites.

Keywords: Deep drainage, soil-vegetation-atmosphere models, mining

Introduction

Mining generates a large volume of waste rock and this is often stored above ground in large mounds that cover a large area. If rain percolates through this waste rock dump, leaching of toxic and/or highly acidic material can occur and this causes significant damage to vegetation, streams and groundwater, locally, off-site and regionally. Similarly, the waste management industry has dumped very large volumes of domestic and industrial waste into small and large pits around the world. When rainwater percolates through these waste dumps leaching of toxic material into groundwater and streams can occur.

In order to minimise the deep drainage of leachate from waste rock and waste dumps, there is increasing interest in using vegetation to evapotranspire rainwater. The expectation is that by removing water from soil through the process of transpiration, the amount of deep drainage will be minimised. The use of clay caps, topped with soil and vegetation, to produce "store-release covers" sitting above waste, is of significant interest to the mining and waste management industries.

Vegetation water use is determined by the interaction of four key variables, namely soil moisture content, atmospheric water content, net radiation balance and leaf area index of the vegetation. Consequently the design of an effective store-release cover requires detailed understanding of the interactions amongst these variables and how these interactions determine vegetation water use.

There are two approaches possible to determining the interactions amongst the key driving variables of water flux through plants and there are two approaches to determining vegetation water use. The first approach in each case requires measurements of the four variables (soil moisture, atmospheric moisture, net radiation balance, vegetation water use) at each site of interest. This is time consuming, expensive and impractical. The second approach uses models to investigate the interactions and rates of water use.

There are very many different models that purport to link vegetation water use to climate and soils at a site. Site specific predictive models require parameterisation at each site of interest and are therefore equally time consuming, expensive and impractical as they require many site-specific measurements. More generic models are used to calculate flows using our understanding of the physics of key processes within a hydrological setting. Such models tend to be relatively poor at incorporating the biological component (especially the trees and grasses) of the site. Of course, it is the trees and their responses to the driving variables that determine whether a store-release cap can function effectively. A third type of model, termed soil-vegetation-atmosphere-transfer models (SVAT models) are mechanistic models that include descriptions of both the physics of climate and soils but also incorporate some understanding of plant function. These models may be highly detailed and mechanistic or more empirical and less mechanistic.

The aims of this paper are two-fold. First, this paper describes a significant modification of the Jarvis-Stewart model. This model has the benefits of being simple to formulate, simple to parameterise and, we contend, can be applied to any temperate woody landscape in Australia using a generic set of parameters. As such it allows us to estimate the rate of water use of the trees planted on any store-release cover if we have basic meteorological data. The second aim is to describe the application of a detailed mechanistic SVAT model to a site in NSW. The reason for describing this is because we found that tree water use was independent of soil moisture content to 80 cm depth, a result that was entirely unexpected. However, the SVAT model was able to show the mechanistic reason for how this could occur.

Methods

Basic measurements

Two sites were used in the work described here. The first was a remnant woodland site approximately 70 km south of Tamworth. Sapflow was measured in the two dominant species using Greenspan sapflow sensors for a period of approximately two years. Basic meteorological data were also collected, including solar radiation, vapour pressure deficit and rainfall. Soil moisture content was also measured using theta probes (Delta-T Devices, UK) at 50 cm depth. Leaf index was measured using a LiCor LAI 2000 meter. See Zeppel and Eamus 2008 for a full description of the site and methods. The modified JS model was applied to this site.

The second site was a remnant woodland located on a waste disposal site west of Sydney in NSW. Tree sapflow was measured using a number of HRM sapflow sensors. Sensors were placed in a range of tree sizes for both of the dominant tree species at the site (see Zeppel et al. 2008 for full details of site and measurement techniques). In addition to measuring tree water use, basic meteorological data were collected, including net radiation, vapour pressure deficit and rainfall. Soil moisture content was also measured using theta probes (Delta-T Devices, UK) at 50 cm depth. Leaf index was measured using a digital camera according to the method of MacFarlane et al. (2007). The SVAT model was applied to this site.

A modified Jarvis-Stewart model

The modified Jarvis-Stewart model (see Whitley et al. 2009 for a full description of this model) was used to calculate stand water use, rather than the usual formulation of the JS model in which canopy conductance is calculated and then the Penman-Monteith equation used to calculate water flux. In our modified JS model:

$$E_c^{JS} = E_{c\,max}\, f_1(R_s)\, \hat{f}_2(D)\, f_3(\theta)$$

The three functions for solar radiation (R_S), vapour pressure deficit (D) and soil moisture content (θ) are:

$$f_1(R_S) = \left(\frac{R_s}{1000}\right)\left(\frac{1000 + k_1}{R_s + k_1}\right)$$

$$\hat{f}_2(D) = k_2 D \exp(-k_3 D)$$

$$f_3(\theta) = \begin{cases} 0 & ,\theta < \theta_w \\ \dfrac{\theta - \theta_w}{\theta_c - \theta_w} & ,\theta_w < \theta < \theta_c \\ 1 & ,\theta > \theta_c \end{cases}$$

The model is parameterised by optimising the free parameters E_{max}, k_1, k_2, k_3, θ_w (water content at the wilting point) and θ_c (water content at field capacity) using a non-linear least squares method.

The SVAT model

The SVAT model of Williams (Williams et al. 1996, Zeppel et al. 2008) was used to model the rate of water use and changes in soil moisture for an entire year. The model was parameterised using the field data and additional parameters as described in Zeppel et al. (2008).

Results

The modified JS model performs very well in modelling stand transpiration in both winter and summer (Fig 1). An artificial neural network was also included in the analyses to compare this with the performance of the modified JS and the performance of the P-M equation.

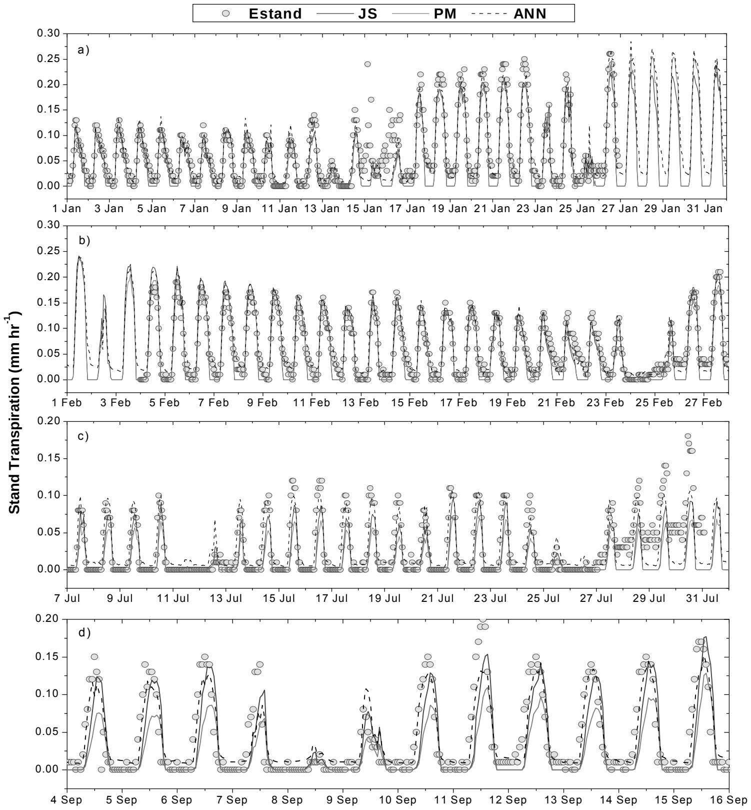

Figure 5 Stand transpiration modelled using a modified JS model, the P-M equation or an artificial neural network model (ANN). Data were obtained at the woodland site south of Tamworth.

It is similarly clear that a regression of modelled daily stand water use and measured daily water use shows a significant ($p < 0.05$) relationship with a slope of almost one (Fig 2).

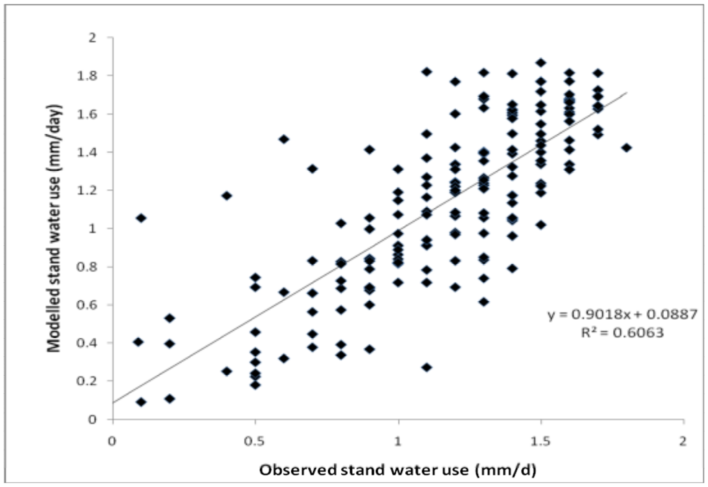

Figure 2 Stand transpiration was modelled using a modified JS model, the P-M equation or an artificial neural network.

The performance of the SVAT model was similarly acceptable, with strong positive correlations between modelled and observed rates of water use in spring and summer (Fig. 3). The mechanistic SVAT model allowed us to examine the relationships among stand water use and soil water content at a number of depths. Stand water use was independent of the water content of the upper (top 80 cm) soil profile (Fig. 4), which fluctuated over a wide range because of rain, especially early in the study. In contrast, the water content of the clay layer (> 100 cm) showed only a slow decline throughout the study period (Fig. 5). The presence of roots in the deeper clay layer (150 cm) was confirmed through trenching to a depth of 1.5 m (Fig. 6).

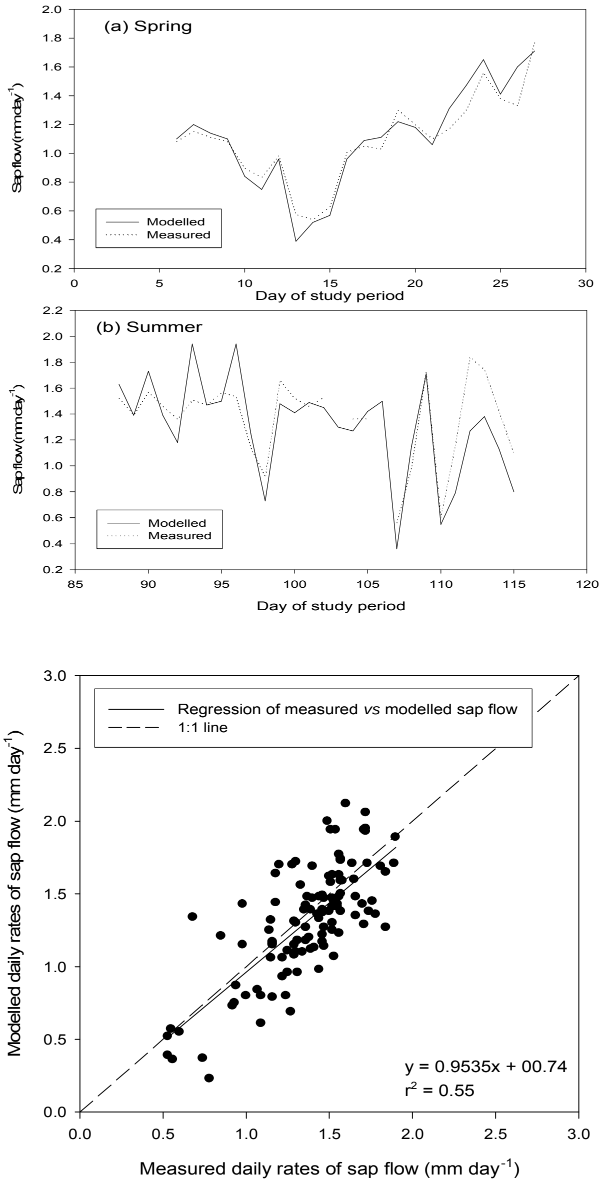

Figure 3a,b,c Modelled and measured rates of stand transpiration show a strong positive correlation across seasons. In this example, a SVAT model was applied (Zeppel et al. 2008) to a remnant woodland located on a waste disposal site.

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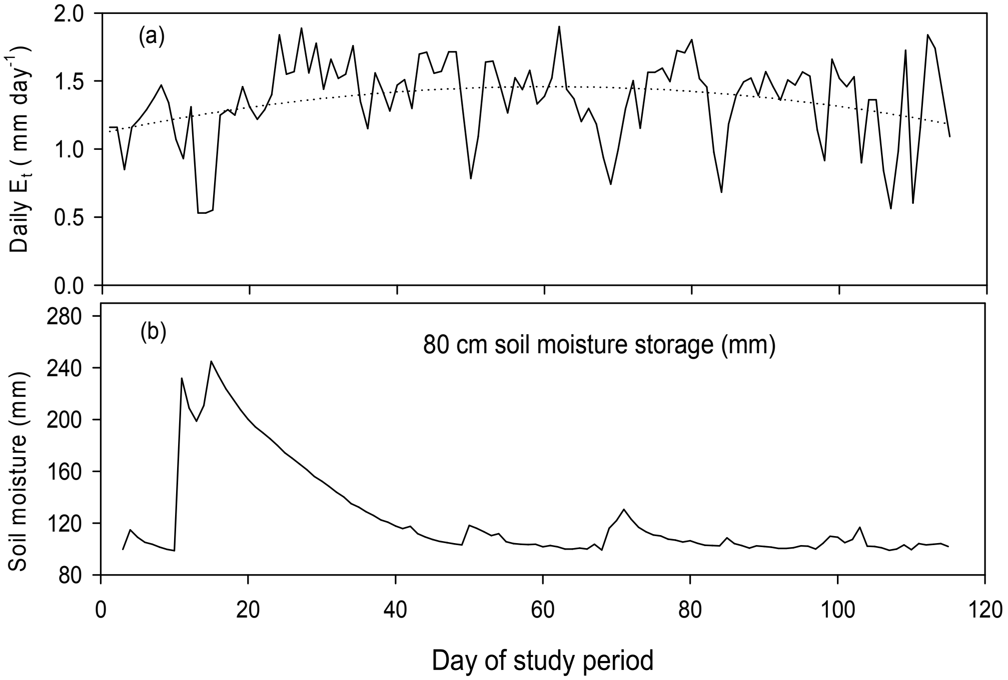

Figure 4 Tree water use (E_t) showed significant daily variation but was found to be independent of the water content of the upper 80 cm of the soil profile. The dotted line is a 5 day running average. Data obtained at the waste site.

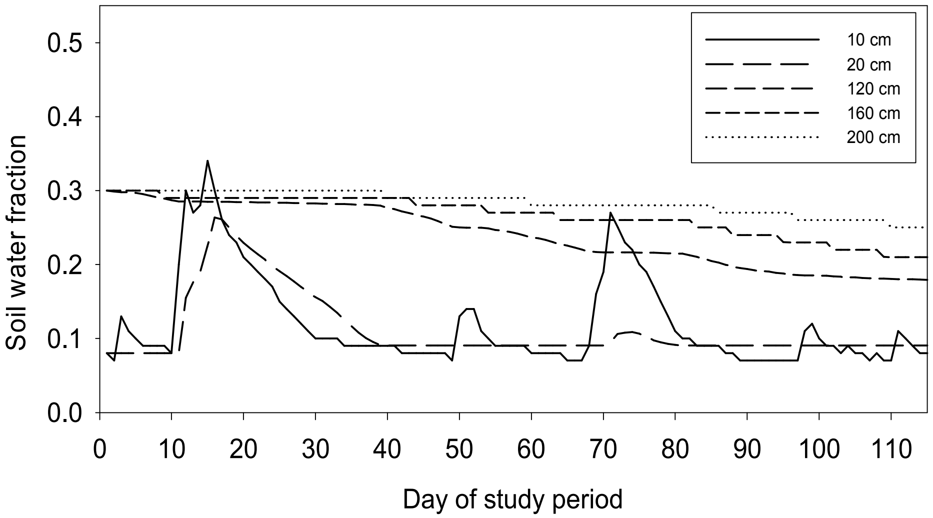

Figure 5 The water content of the upper 20 cm of soil shows large changes in response to rainfall but within the clay layer (below 100 cm depth) only slow changes in water content were observed over

the study period. Data obtained from the waste site. Note that the total store of the top 80 cm of the profile is presented in Fig 4.

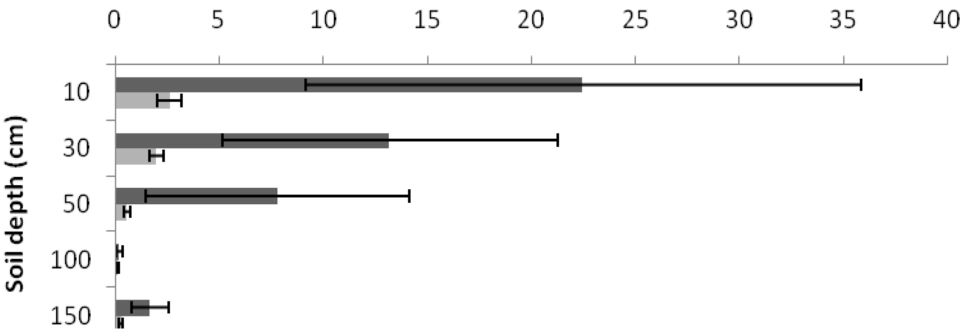

Figure 6 Whilst most of the roots were found in the upper 30 cm of the profile, some root mass was observed in the clay layer at 150 cm depth. Dark bars: coarse roots; light bars, fine roots (data from Macinnis-Ng et al. 2009). Data obtained on the waste site.

Conclusion

The modified JS model is able to accurately represent the rate of water use by a stand of trees from only three simple parameter (R_s, D and θ). This makes it very useful to mine managers, managers of waste storage sites and water resource managers who generally do not have access to the extensive and highly detailed information that is required for mechanistic models.

The detailed SVAT model was able to show that in contrast to expectations, the rate of vegetation water use was independent of the soil moisture content of the upper 80 cm of soil. The reason for this was the presence of a deep wet clay layer that acted as sponge, supplying water to the canopy during dry periods. The SVAT model was able to demonstrate that the upper soil profile was able to dry out independently of the clay layer and that this clay layer showed only small changes in moisture content throughout the 6 month period of study. The presence of roots within this clay layer confirmed this hypothesis.

These two models can be used to examine groundwater-vegetation-climate interactions as part of the sustainable management of water resources. Our study at our waste management site has shown that minimising deep drainage through revegetation is likely to be successful, thereby minimising the potential for polluted leachate to reach the water table.

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A Revised Appraisal of Groundwater in the lower Blue Mountains

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Abstract

The upper Blue Mountains are on the western fringe of the Sydney Basin. A regional monitoring bore network was established in 1997. Over the next 10 years increased demand for groundwater saw entitlements approach the estimated extraction limit for this porous rock aquifer. Concurrently the World Heritage National Park and other nature conservation areas that surround the area have required specific water allocation. Enhancement of the monitoring network was required to manage the competing uses resulting in the installation of 31 monitoring bores at 13 sites in the lower Blue Mountains. These sites fall generally in a triangular area between Springwood, Richmond and Penrith. The bore sites are situated within three groundwater management units, namely the Blue Mountains and Richmond Sandstones and the Sydney Basin Central unit.

The aquifer systems targeted by this monitoring enhancement project occur predominantly within the Triassic Hawkesbury Sandstone sequence in the lower Blue Mountains and in the Richmond area. The aquifers are recharged along the plateau areas of the Blue Mountains and the ridgelines around Richmond and Windsor, with discharge occurring along the escarpments, cliffs and the lower lying river valleys. Initial groundwater level observations suggest the potential for significant groundwater-supported baseflow discharge to streams and ecosystems in the valleys.

Air lift bore yields up to 32 litres per second (L/s) were encountered during piezometer construction. The groundwater associated with the Hawkesbury Sandstone was generally low salinity (less than 1,000 mg/L total dissolved solids; TDS) whilst that associated with the shale was saline (over 10,000 mg/L TDS). The limited intersections of sandstone under the shale indicate the likely downward diffusion of salt. In the lower-lying areas around the Hawkesbury River this has occurred against an upward hydraulic gradient.

This paper describes the aquifer framework, the groundwater flow patterns and the impact of current development on the baseflow of stream and environmental assets of the Blue Mountains and the associated foot hills.

Keywords: Groundwater, Blue Mountains

Introduction

The Sydney Basin Blue Mountains & Richmond Sandstone groundwater management units (GMU) are located on the western fringe of Sydney as shown in Figure 1.

- The Sydney Basin - Blue Mountains Sandstones GMU (Blue Mountain Sandstones) forms a plateau that rises up to over 1,000m above the coastal plain at Katoomba. To the east the sandstone plateau drops down in elevation and it is cut by the north-south trending Hawkesbury – Nepean River. The northern extent of this management area is defined by the Grose River and the abutting Sydney Basin - Richmond Sandstones GMU. The western boundary is defined by the Sydney Basin Cox's River GMU.

- The Sydney Basin - Richmond Sandstones GMU (Richmond Sandstones) is located north of the Blue Mountains Sandstones and the Grose River. To the north of the Richmond GWMA is the Sydney Basin North. To the east the Hawkesbury - Nepean River marks the boundary between the Richmond Sandstones and the Sydney Basin - Central GMU. The western boundary is defined by the Sydney Basin Cox's River GMU.
- The Sydney Basin - Central GMU is located adjacent to both the Blue Mountains Sandstones and Richmond Sandstones with the boundary marked by the Hawkesbury - Nepean River. Further to the south is the Sydney Basin Nepean Groundwater Management area and it is bounded to the east by the coast.
- The Hawkesbury Alluvium is located along the Hawkesbury - Nepean River and it overlies the Blue Mountains Sandstones, Richmond Sandstones and Sydney Basin Central sandstone aquifers.

The Blue Mountains and Richmond Sandstones which are the main focus of this paper, cover an area of about 3,238 km^2 of which 2,375 km^2 is National Park as shown in Figure 1.

The rainfall varies considerably across the project area because of the diverse range of elevations from high plateau at Katoomba with an annual average rainfall of 1,391 mm/year to less than 780 mm/year at Windsor on the floodplain of the Hawkesbury River.

This paper focuses on a series of additional monitoring bores installed in the Blue Mountain Sandstones during 2008 and the Richmond Sandstones in 2009.

Groundwater management

The Sydney Metropolitan Surface Water and Groundwater Sharing Plan is currently being developed by the NSW Department of Water and Energy in preparation for the repeal of the *Water Act 1912*.

Only where water sharing plans are in place does the *Water Management Act 2000* apply and replace the *Water Act 1912*. Under both Acts, the rights to the control, use and flow of all water in aquifers are vested in the State. The acts provide the direction to the statutory process to allow individuals and other entities access to the resource by way of licences and approvals. Water sharing plans establish the rules for sharing water between the environment and water users and between competing consumptive water users. The water sharing plans, once finalised and gazetted under the *Water Management Act 2000*, have legal effect for 10 years.

Regional geology

The geology of the study area can be summarised into three main stratigraphic types:

1. The Hawkesbury Sandstone, which is the focus of these groundwater investigations, is dominantly a medium to coarse grained sandstone, but varies from fine to very coarse grained (Herbert 1983). This unit forms the high plateaux and spectacular gorges in the lower Blue Mountains. The formation thickens eastwards with maximum

thickness of approximately 230 m. Shale lenses are irregularly spaced throughout the unit. Two contrasting sandstone facies have been distinguished as “sheet sandstone facies” and “massive sandstone facies” (Conaghan 1980). The sheet sandstones consist of crossbeds, usually 0.1 to 5 m in thickness. The “massive sandstones facies” are more friable in weathered exposure, contain large amounts of clay, have generally lower primary porosity and smaller proportions of cementing agents. These massive facies sandstones are up to 15 to 20 m thick and extend over several kilometres. Numerous mudstone units occur within these sandstone units.

2. The Wianamatta Group rocks consist of a minor sandstone horizon sandwiched between two major shale units. It is generally less than 150 m thick in the study area. The marine origin of these rocks has resulted in the incorporation of a high proportion of soluble salts into the rock matrix, creating a significant connate salt store available for dissolution, leaching and mobilisation. On weathering, the Wianamatta Group produces heavy clays, prone to piping and water logging. These heavy surficial soils have implications for the generation of urban salinity where the natural drainage is impeded or diverted.

3. Hawkesbury Alluvium. The alluvium associated with the Hawkesbury River tends to be an admixture of clean quartz sand and cobbles with thin interbeds of yellow clay. The sequence is up to 20 m thick. It is distinguished from the higher level Tertiary alluvium which has a significant clay content.

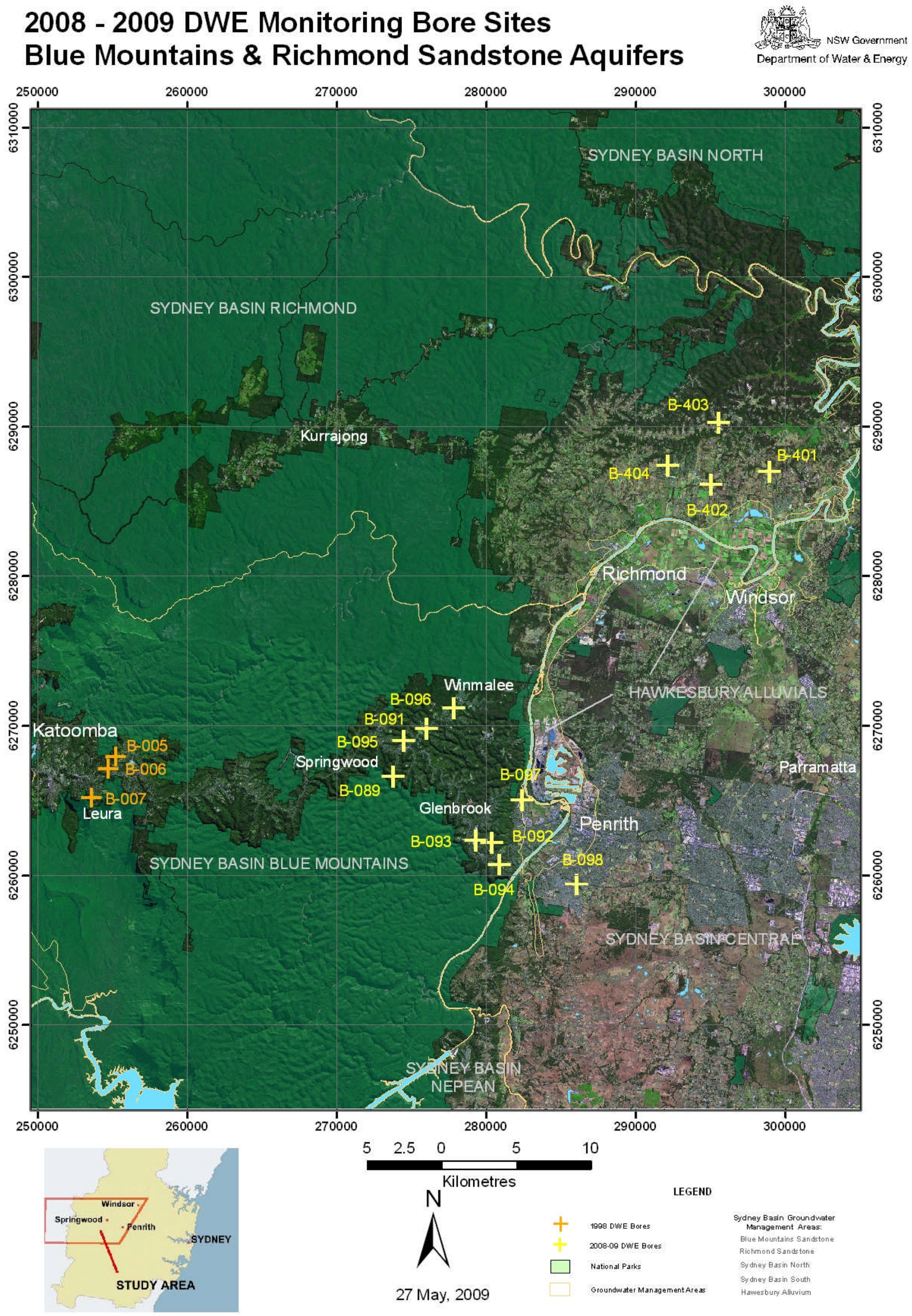

Figure 6 Location of the Department of Water & Energy Monitoring Bore Sites in the Sydney Basin: Blue Mountains, Richmond and Sydney Basin Central Sandstone GMUs.

There has been significant structural movement in the study area with most aquifers exhibiting some secondary porosity characteristics. The Lapstone Monocline is a major geological structure that cuts the project area. The deposition of Permian and Triassic rocks occurred, where the eastern area sank faster than to the west, so that rock units became thicker to the east. The rocks along the hinge lines were progressively bent in a north south direction and preserved as monoclines (Pickett & Alder 1997). There is significant faulting around the monocline, just west of the Lapstone Monocline at Glenbrook where a large vertical fault in the rock occurs with a 50m displacement to the west. A similar fault is also noted at Kurrajong.

Monitoring bore drilling programme

In the current program the Department drilled and installed 31 monitoring bores at 13 key sites in the Sydney Basin aquifers. The location of the sites is given in Figure 1.

The bores were drilled in a sequence to assess a series of north-south and east-west sections through the Sydney sandstones. Monitoring bores were drilled at key locations from July to November 2008 around the lower Blue Mountains at Springwood, Glenbrook and the Penrith area. Drilling recommenced north of Richmond and Windsor from February until March 2009 with the installation of another 4 key sites.

Details of this drilling are described for the Blue Mountains in DWE (2008) and Richmond in DWE (2009), with the earlier work at Leura discussed by Rumpf (1997).

At many key sites multilevel bores have been installed to assess the characteristics of the multilayered aquifers. They were constructed in separate bore holes.

The drilling method of rotary air hammer was used to install the monitoring bores, but the hammered rock chip samples limited the amount of geological interpretation. Down hole geophysics of all bore sites was used to further assess the geology.

Hydrogeology

The study identified three main groundwater systems in the sandstone plateau sequence of the Blue Mountains

(i.) A shallow unconfined aquifer in the upper sandstone porous rock aquifer. Local-scale groundwater movement is topographically driven, discharging as hill-slope springs, valley seepages and baseflow to the upper sandstone plateau streams.

(ii.) Intermediate low yield aquifers intersected in some monitoring bores are assumed to be perched by less permeable siltstones, mudstones and shale lenses that form part of the Hawkesbury Sandstone sequence. These aquifers are likely to discharge to mid-level valleys within the sandstone plateau. Their responsiveness to recharge will be assessed following the installation of continuous groundwater level loggers.

(iii.) Deeper intermediate-scale aquifers in the interlayered and fractured horizons within the coarser grained porous sandstone aquifer. These aquifers become semi-confined to confined and discharge at lower levels in the landscape, such as the Glenbrook Creek near Springwood and to the Hawkesbury - Nepean River at Penrith. Artesian groundwater heads have been encountered east of the Blue Mountains Sandstone Plateau at Penrith which have very high yields. The aquifer has a dual porosity and the secondary porosity is likely to be influencing the bore yields at Emu Heights, as it is close to the base of the Monocline which contains fault systems.

Relatively thick sequences of massive shales, siltstones and mudstone sequences can restrict vertical movement of groundwater to depth.

The hydrogeological section at Springwood shown in Figure 2. provides the generalised relationship between the aquifer intervals. A perpendicular section from Winmalee to Glenmore Park near Penrith shown in Figure 3, exibits the deep aquifer flow from the sandstone plateau down to below the monocline.

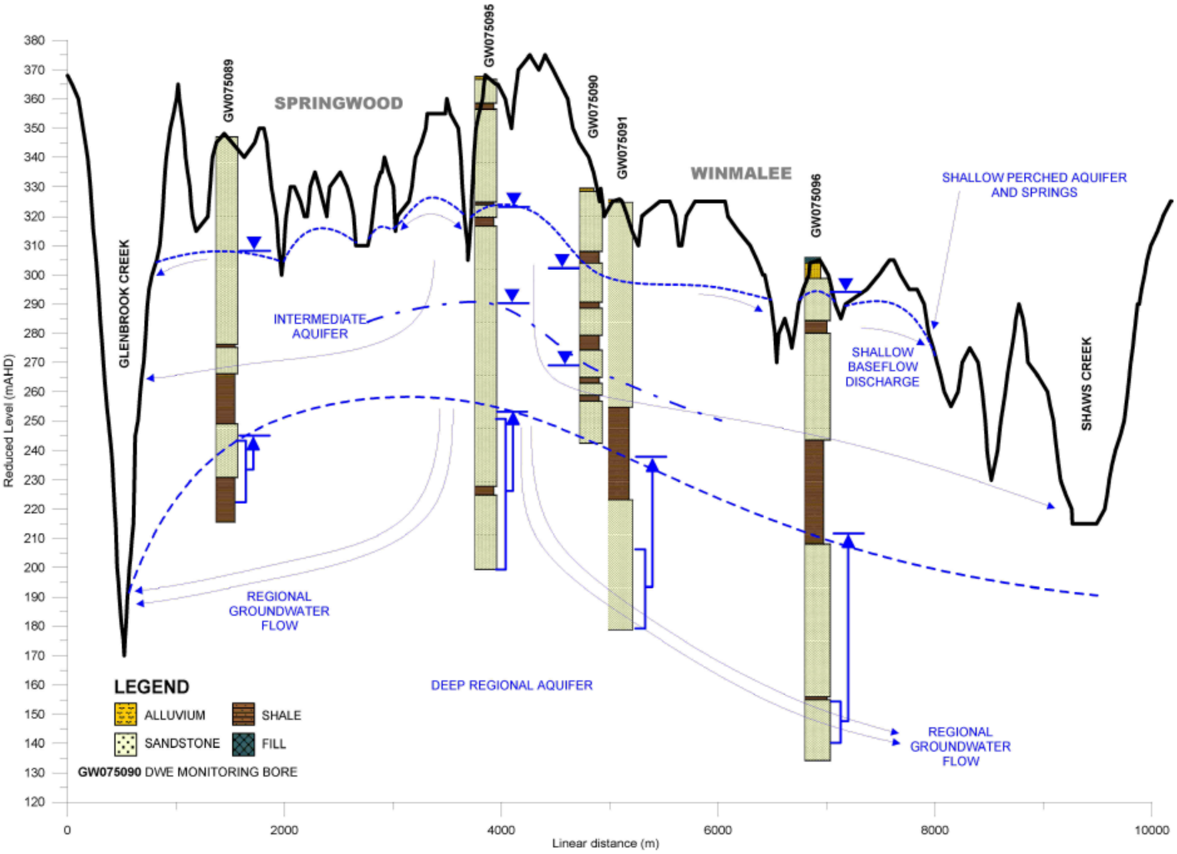

Figure 7 Springwood cross section (NE-SW) showing the multilayer shallow and deep groundwater levels at monitoring bores.

Conclusions

Hydrogeological investigations have shown that complex multi-layered sandstone aquifers occur within the Blue Mountains Sandstone GMU and there is a high degree of connectivity with surface water systems. The shallow and intermediate aquifers are critical to spring flow and to stream baseflow in the upper plateau rivers. These aquifers will be typically the ones that support groundwater dependent ecosystems, such as wetlands and hanging swamps. The deep regional aquifer system appears to be flowing towards the deep incised valley rivers such as Glenbrook Creek and across the Monocline at Glenbrook into the Hawkesbury - Nepean River at the base of the plateau. The deep aquifer appears to have a large positive pressure head, which may indicate groundwater from the lower Blue Mountains is pressurised in the Hawkesbury Sandstone and flowing under the Hawkesbury - Nepean River out further east to the coast. Further work to assess the flow dynamics is warranted to assess if this observation is correct or not.

The installation of continuous groundwater level loggers and data recorders will greatly increase the understanding the aquifer flow dynamics and allow further detailed assessment of these aquifers. A detailed understanding of hydrogeological processes and ecosystem dependencies is crucial for managing such aquifers so that there are clear rules and guidelines for those stakeholders using groundwater. This work will also assist government in assessing the potential extraction impacts on groundwater dependent ecosystems for groundwater trading and thus allow an informed decision-making process, in order to maintain important ecosystems into the future.

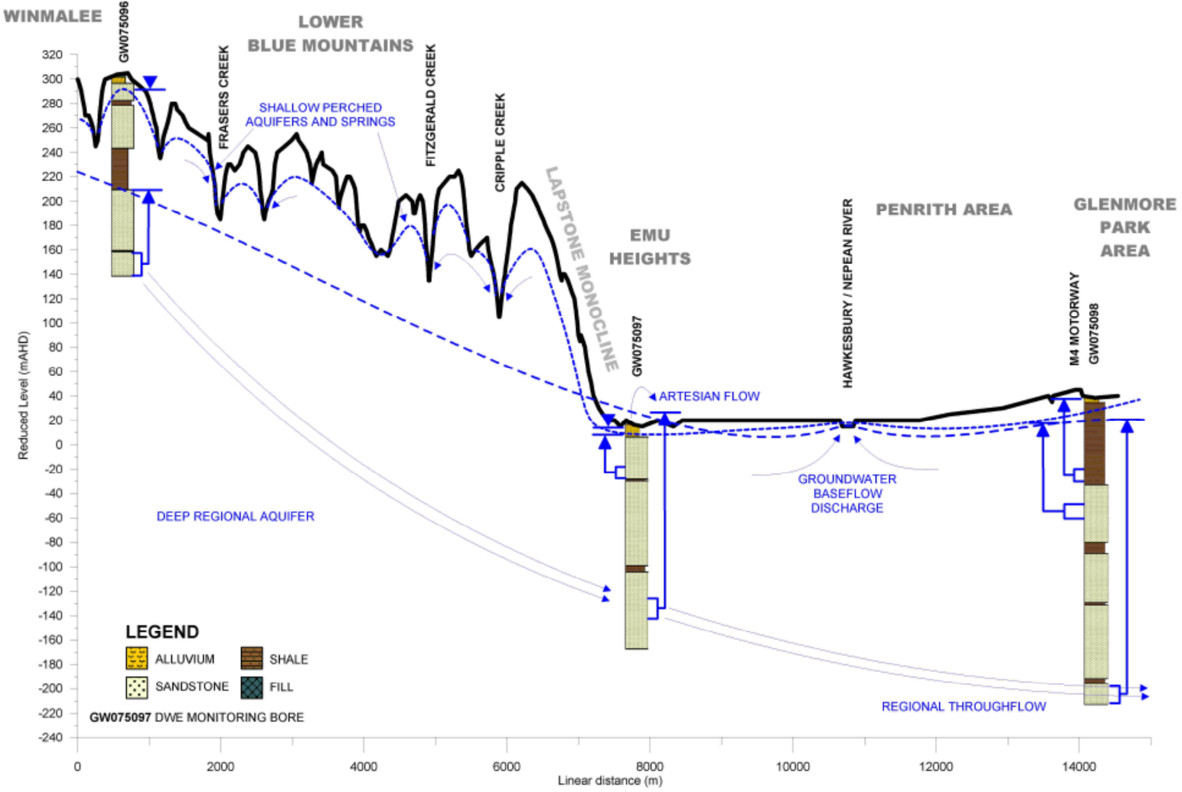

Figure 3 Winmalee to Glenmore Park cross section (NW-SE) showing the shallow and deep groundwater levels that have a large positive pressure head, with artesian flow at Emu Heights.

Acknowledgements

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The dynamics of groundwater invertebrate communities in alluvial aquifers during and following drought

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Abstract

Many alluvial aquifers in eastern Australia are inhabited by diverse communities of groundwater invertebrates. Often, the alluvial aquifers are hydrologically connected to streams and rivers, which supply oxygen and organic matter to groundwater food webs. However, in periods of prolonged drought many rivers cease to flow, severing the connection with the aquifer. This lost connectivity potentially changes the trophic dynamics of the aquifer, affecting invertebrate community structure. To assess changes in stygofauna community during and following drought, 8 sites in the Hunter Valley were monitored seasonally for two drought years and one post-drought year from 2005 to 2008. Water level, water quality parameters, and nutrients (nitrates, soluble reactive phosphorous, dissolved organic carbon) were also recorded, as were other potential sources of organic matter such as phreatophytic trees, infiltrating rainfall, and surface flow. Preliminary analysis indicates that lower depths to water tables following drought initially dilute faunal densities. Higher invertebrate densities and community richness coincided with proximity to phreatophytic trees, suggesting that tree roots potentially offer food or habitat to stygofauna in alluvial aquifers as they do in cave streams. Communities further from rivers appeared to be less diverse, but more stable than those closer to rivers, probably because near-river communities contained higher proportions of stygoxenes. In periods of drought, exacerbating drawdown through pumping could not only lead to the loss of phreatophytic trees, but also to the stygofaunal communities that they potentially support. These impacts may be further amplified in highly fragmented landscapes where clusters of tree roots become isolated. These results are particularly

relevant to sustainable water-use in the Sydney basin, where groundwater is being considered as a supplementary water supply during periods of water shortage.

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Hydrogeological resource investigations – to supplement Sydney's water supply at Leonay, western Sydney, NSW, Australia

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Abstract

Despite being close to Australia's largest urban population, remarkably little groundwater resource investigative work has been conducted until the 21st century. Leonay is an outer urban area located approximately 60 km west of Sydney, at the foothills of the Blue Mountains and was selected as one of seven priority sites to conduct groundwater investigations. These investigations were undertaken by the Sydney Catchment Authority (SCA) as part of the NSW Government's Metropolitan Water Plan (MWP). Drilling, to depths in excess of 300 metres, targeted the Triassic Hawkesbury Sandstone associated with the Lapstone Monocline. This geological structure is a major regional feature which is known to have increased the fracturing and thus consequent permeability of the sandstone aquifer.

The groundwater potential of the Hawkesbury Sandstone is largely influenced by its dual porosity nature, that is, the primary intergranular pore space is overprinted by secondary fracturing of the strata.. The secondary porosity has both horizontal and vertical components. Intense flexural fracturing associated with the development of the Lapstone Monocline has caused a series of water bearing fractures and faults that have been targeted by the drilling program, resulting in the development of high yielding test production bores. Cainozoic alluvium and higher level river terraces deposited across the Nepean River floodplain overlies much of the secondary fracturing. Groundwater recharge to the Hawkesbury Sandstone occurs up gradient in the lower Blue Mountains where the sandstone outcrops and flow is eastwards towards the Nepean and Parramatta Rivers.

Drilling, geophysical logging, test pumping of multiple test production and monitoring bores were conducted to characterise the geology and hydrogeology of the study area and assess the groundwater resource potential. Boreholes were constructed that fully and partially penetrate the Hawkesbury Sandstone to assess aquifer parameters, resource potential, possible interaction between surface water (Nepean River) and groundwater, and recharge/discharge characteristics. A number of multidisciplinary approaches were undertaken to characterise the groundwater resource and to quantify potential extraction rates. This included a 60-day pumping trial, multiple pumping tests using a variety of test pumping analytical techniques, and water sampling for hydrochemical studies and radionuclear isotopic analysis to assess recharge mechanisms and groundwater residence times.

Keywords: groundwater, resource investigation, Hawkesbury Sandstone, pumping trial

Introduction

The primary objective of the groundwater investigation program was to assess and characterize the geology and hydrogeology of the Leonay-Emu Plains area and to confirm the presence of a groundwater resource suitable for drought water supply. The following activities were undertaken to achieve these outcomes:

- Identification of the probable groundwater resource area;
- Assessment of the quality of groundwater within the Hawkesbury Sandstone;
- Interpretation of geological, geophysical, pump test, settlement and hydrogeochemical data to assess potential borefield impacts;
- Initial quantification of the resource potential of developing the Hawkesbury Sandstone and the potential for borefield development.

Groundwater investigations at Leonay commenced in February 2006 with the construction of two test production bores and two observation bores at Leonay Oval. Following favourable results, a more detailed groundwater investigation was undertaken between September 2006 and November 2007. This investigation included the construction of 18 additional boreholes including eight test production bores followed by test pumping and hydrogeochemical sampling.

Background

Leonay is located approximately 60 km west of Sydney, at the foothills of the Blue Mountains, next to the Nepean River (Fig. 1). The investigation area is in an urban environment consisting largely of residential dwellings and parkland. To the west, the investigation is flanked by ribbon urban development of the lower Blue Mountains and natural bushland of the Blue Mountains National Park. Council owned parkland and open public spaces were selected to locate test production boreholes.

The investigation covered an area of approximately 20 km^2. Structurally the study area is located within the central portion of the Sydney Basin. The target aquifer for this investigation is the mid Triassic Hawkesbury Sandstone, the most widespread regional aquifer within the Sydney Basin. The main geological feature in the Leonay area is the north-south oriented Lapstone Monocline that is aligned north-south along the foothills of the Blue Mountains. The Hawkesbury Sandstone is overlain by Quaternary alluvium, the Ashfield Shale and the Mittagong Formation and underlain by Early Triassic Narrabeen Group sediments.

Groundwater within the investigation area is present within both alluvial sediments and the hard bedrock formations. Minor good quality water is associated with the shallow alluvial deposits however the majority of good quality groundwater is located at depth within the Hawkesbury Sandstone. At Leonay the Wianamatta Shale underlies the alluvial sediments and forms an aquitard. Water within the shale is of generally poor quality and there is some saline leakage into the underlying Hawkesbury Sandstone.

The Hawkesbury Sandstone is a semi-confined dual porosity regional aquifer system that extends across most of Sydney Basin and it contains water of generally good quality. Groundwater flow is highly variable and it is generally dominated by secondary porosity and fracture flow associated structures such as faults and fracture zones. The primary porosity of the rock matrix within the Hawkesbury Sandstone is low and a bore that does not intercept major fractures or fissures is likely to yield less than 5 Litres per second (L/s). However, a bore in the Hawkesbury Sandstone that intercepts major fractures and fissures can yield in excess of 40 L/s.

Investigation bore sites were selected on the basis of locations along the inferred alignment of the Lapstone Monocline and the suitability of public open spaces away from the main residential areas within the suburbs of Leonay and Emu Plains. Observation bores were constructed up-gradient in Lapstone and Emu Heights and down-gradient across the Nepean River in Regentville. Sites were generally located more than one kilometre apart to obtain a broad appreciation of the extent and characteristics of the sandstone groundwater resource.

Geophysical logging was conducted at the completion of each borehole to complement the geological log, to further refine the stratigraphy and to identify significant fracturing and other structural features where possible.

An extended pumping trial was conducted by pumping four test production bores simultaneously over 57 days and measuring drawdown and recovery in the network of observation bores. Throughout the test pumping program groundwater was collected and analysed for major ions, iron and manganese, nutrients and environmental isotopes primarily to characterize the groundwater.

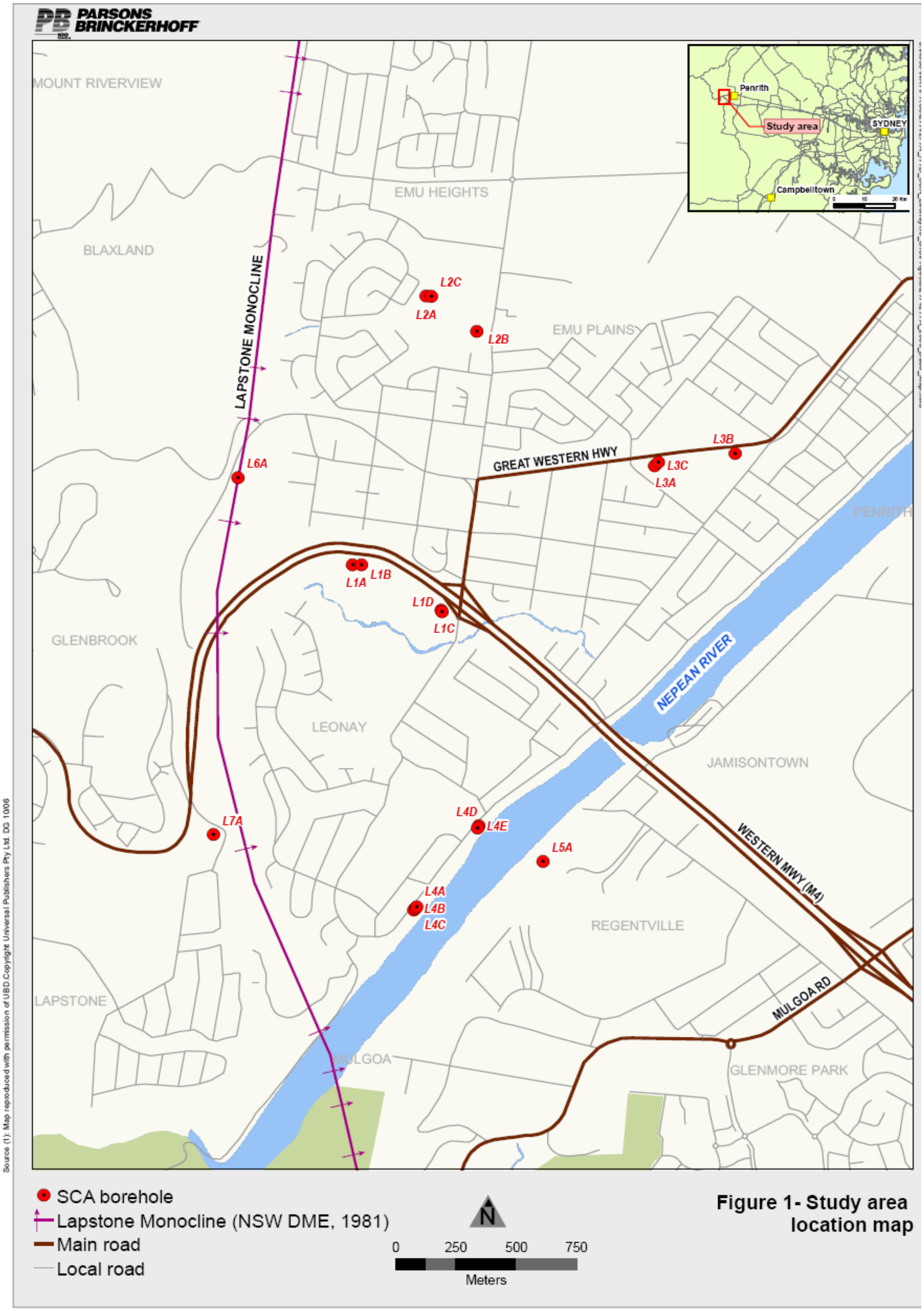

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Figure 1- Study area location map

Figure 8 Location of test bores and test production bores in the Leonay study area

Discussion of Results

Drilling and bore construction program

The drilling program was designed to drill through alluvium and shale (where present) and into the underlying confined sandstones. Multiple bores were constructed to monitor the impact of pumping on separate aquifers within the Hawkesbury Sandstone at seven sites.

Borehole construction details are presented in Table 1. The Hawkesbury Sandstone aquifer can be separated into two groupings based on lithological and hydrogeochemical parameters, although this separation is not as evident in the geophysical logs. The upper most part of the Hawkesbury Sandstone (upper 100 m) is partly interbedded with shale lenses and contains mudstone and nodules and a higher clay content than the lower Hawkesbury Sandstone. In contrast the lower Hawkesbury Sandstone is a cleaner medium to coarse grained white to grey quartzose more competent unit.

Table 4 Borehole construction details and extended pumping trial results

Location	**Bore ID**	**Total Depth (m)**	**Screen / Open Interval (m)**	**Aquifer Sampled ***	**Maximum Airlift yield (L/s)**	**Standing Wat Level (mbgl) 27 July 2007**	**Drawdown at End of the Pumping trial (m)**	**Electrical Conductivity µS/cm**
Leonay Oval	L1A	174	48-174	H	68	19.19	18.98	481
	L1B	311	160-311	H B BW	21	17.83	14.54	366
	L1C	300	173-300	H B BW	43	12.47	10.27	376
	L1D	175	47-175	H	9	5.15	8.78	494
Koloona Reserve	L2A	264	90-264	H B	33	7.7	57.81	317
	L2B	276	84-276	H B BW	50	6.24	20.46	293
	L2C	14.5	11.5-14.4	CF	2.5	7.58	-0.12	589
Darcy Smith Oval	L3A	301	84-301	H B BW	46	4.14	6.21	310
	L3B	300	84-300	H B	12	2.57	4.91	326
	L3C	14	11-14	CF	0.5	8.98	0.23	969
River Road Reserve South	L4A	290	84-290	H B	50	10.98	22.22	377
	L4B	78	30-78	H	30	12.04	4.72	912
	L4C	15	9-15	CF	0.5	10.51	0.32	-
	L4D	290	84-290	H B	35	11.42	1.39	353
	L4E	84	15.5-84	H	25	10.88	2.42	1817
Tench Reserve	L5A	283	96-283	H B	9	8.26	3.74	593
John Whitton	L6A	300	84-300	H B	20	46.48	4.79	317
Skarret Park	L7A	289	90-289	H B BW	12	94.8	3.7	250

Note: Aquifers H – Hawkesbury Sandstone CF – Cranebrook Formation B – Burralow Formation BW – Banks Wall Sandstone
- not measured

Groundwater quality assessment

Typically groundwater from the Hawkesbury Sandstone is slightly acidic ranging from pH 4 to 6.5. Groundwater quality within the Hawkesbury Sandstone aquifers is variable ranging from fresh to brackish in the upper aquifers and becoming better quality with depth. Increased salinity in the upper Hawkesbury Sandstone aquifers is attributed to leakage of saline groundwater from the overlying Ashfield Shale. Characterization of the groundwater within the upper Hawkesbury Sandstone aquifers indicates the groundwater is dominated by sodium, magnesium and chloride. Dominance of chloride rather than bicarbonate in the upper aquifers is in part due to leakage from the overlying Ashfield Shale where connate sodium chloride (Na-Cl) salts are present because of its marine depositional environment. Groundwater quality from this investigation is discussed in more detail in McLean and Ross, 2009.

In contrast the chemical composition within the lower Hawkesbury Sandstone aquifers is dominated by bicarbonate rather than chloride, chemically evolving along the flow path and increasing in alkalinity. The increase in alkalinity is attributed to the dissolution of carbonate minerals including calcite (calcium carbonate $CaCO_3$) and siderite (iron carbonate, $FeCO_3$). Concentrations of potassium and sulphate are typically low in the upper and lower aquifers.

Groundwater from the Hawkesbury Sandstone typically has elevated concentrations of iron and manganese (McKibbin and Smith, 2000). Dissolved iron concentrations sampled during test pumping ranged from 13 mg/L to 48 mg/L. The most likely source for these elevated iron concentrations is mineralization within the rock matrix including siderite, iron oxyhydroxides and oxides and pyrite (iron sulphide, FeS_2). Dissolved manganese concentrations within the Hawkesbury Sandstone ranged from 0.5 mg/L to 2.2 mg/L. The concentration of these dissolved species is related to availability/reactivity of minerals and chemical processes in the sandstone aquifer and dictated by pH, redox conditions and the distribution of iron and manganese bearing minerals in the rock matrix.

Throughout the pumping trial, the chemical composition of the groundwater changed little. Transient water quality data from the pumping trial suggests that during extended pumping at individual sites groundwater quality is unlikely to change significantly with a few exceptions. Sites close to the Nepean River slightly decreased in salinity due to the influence the Nepean River. Sites further away from the river in areas capped by Ashfield Shale slightly increased in salinity due to seepage from the shale.

Isotope hydrology

Stable isotope data (Oxygen-18 and Deuterium) for groundwater samples collected throughout the investigation indicate the groundwater is of meteoric origin. Changes measured in the isotopic signature throughout the extended pumping trial is due to groundwater of different isotopic signatures being drawn into the pumping bores from different fractures and/or sandstone matrix as pumping progressed.

Radiocarbon dating (Carbon-13 and Carbon-14) was used to give some indication of the age of groundwater in the sandstone aquifers, and some insight into recharge processes operating in the Leonay area. Corrected groundwater ages measured at the end of the pumping trial ranged from an average 2300 years BP (L1A) to 8500 years BP (L4A) suggesting variable residency times. There is generally an increase in groundwater residence time in the Hawkesbury Sandstone aquifer along the flow path (west to east). Groundwater age also increases with depth. This is consistent with up gradient recharge areas in the lower Blue Mountains and down gradient discharge areas.

Throughout the test pumping program groundwater ages decreased slightly in production bores L1A, L2A and L4A. The decrease in groundwater age is due to either younger water being drawn laterally from upgradient or leakage from the overlying alluvium. The younger water in the vicinity of the Nepean River could be derived from leakage from the alluvium and indirectly the Nepean River.

Extended pumping trial

A series of test pumping programs were initiated throughout this investigation to assess the performance of the Hawkesbury Sandstone, calculate aquifer hydraulic parameters and assess bore spacings and groundwater interference at various sites. An extended pumping trial was conducted for 57 days between 27 July and 18 September 2007 in production bores L1A (19.9 L/s), L2A (17.4 L/s), L4A (17.9 L/s) and L4B (24.1 L/s). A total pumped volume of 398 ML was discharged to local stormwater drains and the Nepean River. Groundwater drawdown and recovery was measured in fourteen monitoring bores and four test production bores over the duration of the trial. Maximum groundwater drawdown is presented in Table 1.

At the completion of the pumping trial groundwater drawdown was greatest at L2A at Koloona Reserve and decreased in other production bores down hydraulic gradient. Drawdown and recovery data was used to estimate values of transmissivity, hydraulic conductivity (k) and storativity. The results indicate the deeper Hawkesbury Sandstone is of low to moderate permeability ($0.15 < k < 3.3$ m/day) and has water transmitting properties consistent with a medium to coarse grained fractured rock aquifer. Storativity values (10^{-5} to 10^{-4}) suggest a semi-confined to confined aquifer system. Bores located nearest to the Nepean River and open to the shallower Hawkesbury Sandstone exhibited hydraulic conductivities one order of magnitude greater than other bores ($14.8 < k < 73.2$m/day).

Safe yields were calculated for test production bores (L2A, L4A and L4B) using average aquifer parameters calculated from pumping test data. Safe yields were capped at 18 L/s (L2A), 19 L/s (L4A) and 30 L/s (L4B) based on the analysis results and testing programs. These estimates are conservative and could be increased if pumping tests at slightly higher rates were undertaken.

A comparison of groundwater elevations between the Hawkesbury Sandstone and the shallow alluvium indicates an upward vertical flux under non pumping conditions at most sites. Water levels in the Hawkesbury Sandstone were higher at all investigation sites except in the close proximity of the Penrith weir pool (in the Nepean River).

Borefield development

An assessment of interference drawdown and bore spacing based on the earlier pumping tests and the pumping trial indicated that interference drawdown at the spacing adopted for this pumping trial would not be an impediment to borefield performance.

Interference drawdowns would appear to be tolerable at distances of 1 to 1.5 km however groundwater modelling is required to optimise production bore locations and spacings.

Conclusions

These hydrogeological investigations beneath Sydney indicate that a prospective aquifer exists in the Hawkesbury Sandstone for drought water supply along the Lapstone Monocline structural feature.

Acknowledgements

We thank the Sydney Catchment Authority for permission to publish the results of this groundwater investigation. The experience and professionalism of our subcontractors also contributed to the success of this investigation, namely Highland Drilling (drilling contractors), Alpha Geoscience (geophysical contractors) and Ted Wilson & Sons (pumping contractors). We also gratefully acknowledge the efforts of SCA project manager Joseph Ross and PB hydrogeologists Liz Webb, Dr Wendy McLean, Dr Elizabeth Cohen, Tim Wilkinson and Joshua Lloyd.

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Stygofauna of fractured rock aquifers in the Sydney Region

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Abstract

Long considered devoid of life, fractured rock aquifers in the Sydney region are being recognised as biodiverse ecosystems that support a unique stygofauna. Sampling in the Kangaloon and Kulnura fractured sandstone aquifers has identified diverse, crustacean-dominated fauna in each. The stygofauna assemblages at each location include syncarids, mites, copepods, and amphipods, making them structurally similar at a coarse taxonomic level, but each location contains a unique suite of species. Furthermore, there is apparent taxonomic differentiation even among similar taxa within these locations.

Stygofauna assemblages are characterised by spatial and temporal heterogeneity of fauna with little apparent relationship to physico-chemical attributes of the sampling bores. At both locations, large scale groundwater extraction is ongoing or planned, so understanding the spatial and temporal patterns in stygofauna distribution, and the response of fauna to water abstraction should be priorities for future research on these ecosystems.

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Keynote Paper

Hydrological Changes due to Longwall Mining in the Southern Coalfield, New South Wales, Australia

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Abstract

Longwall mining may impact surface water and groundwater as a consequence of mining-induced subsidence, which includes the vertical and horizontal deformations and displacement of the ground mass. As a result of fracturing riverbeds and rockbars, surface flow is diverted to subsurface routes and surface water-groundwater connectivity is enhanced. The interaction between surface water and groundwater can occur laterally and longitudinally to a stream. Several types of interactions are possible based on the extent of fracturing in the aquifer; from a single recharge-discharge zone to multiple recharge-discharge zones. A reduction in streamflow may not only be the result of fracturing streambeds and rockbars in the main stream overlying an active longwall mine; mining-induced fracturing can extend across the catchment and its tributaries, generally bounded by the limit of subsidence. Increased fracturing allows rainfall to infiltrate and recharge fractured aquifers, reducing runoff available for recharging streams. Although rainfall recharge to the shallow aquifers can increase, groundwater levels can also decline due to the mining-induced fracturing of the rock mass, causing the dewatering of shallow aquifers and reducing baseflow discharge. Fracturing of the banks of streams and tributaries can also reduce streamflow during high flow conditions. Streamflow reduction is also an effect of the spatial distribution and density of fracture networks, changes in porosity and permeability of the subsurface rock mass, changes in groundwater storage capacity, modification to baseflow discharge and alteration of the hydraulic gradient near the streams.

Keywords: Longwall mining, surface water-groundwater interaction, streamflow loss, fractured aquifer

Introduction

Streamflow reduction, including streamflow loss, is a net flow reduction along a stream that can be associated with natural or anthropogenic hydrological conditions. In catchments with longwall mining activities, the reduction in streamflow can be the result of complex hydrological processes that affect the catchment water balance due to mining-induced fracturing and subsidence. This subsidence can result in the fracturing of streambeds and rockbars, alteration of the connectivity between surface water and groundwater, reduction in baseflow discharge to streams and reversal of the hydraulic gradient.

Concern over the potential impact on water supplies and the maintenance of stream function has increased following the observed surface water-groundwater connectivity in areas where mining-induced subsidence has led to declines in baseflow discharge to streams. There have been various studies undertaken above active longwall mines, providing some insight into mining-induced subsidence on the temporary or permanent loss of streamflow and the increase in surface water-groundwater interaction.

Streamflow depletion associated with longwall mining was observed and detailed analysis provided for the Appalachian Coalfield, USA (Carver & Rauch, 1994; Dixon & Rauch, 1988, 1990; Tieman et al., 1987, 1992); Utah Coalfield, USA (Slaughter et al., 1995) and East Midlands, England (Shepley et al., 2008). A reduction in streamflow has also been identified in a Southern Coalfield catchment of NSW, Australia, where mining induced-subsidence has caused the enlargement of existing fractures, the development of new fractures (including the fracturing of streambeds and rockbars), the separation of bedding planes and changes in channel geometry. These changes have lead to a diversion of surface water to the subsurface, dry streambeds and disconnection between surface water and groundwater (Jankowski, 2007; Jankowski & Spies, 2007; Jankowski et al., 2008; Kay et al., 2006).

Conceptual surface water-groundwater interaction

According to Larkin & Sharp (1992), the stream-aquifer system can be classified based on the predominant regional groundwater flow component: (1) underflow-component dominated, with groundwater flow longitudinally to a stream and in the same direction as stream flow; (2) baseflow-component dominated, with groundwater flow moving laterally to or from a stream depending on whether the stream is gaining or losing; or (3) a combination of both. These flow paths into the stream create 3D physico-chemical patterns controlled by the groundwater flow pattern (Brunke & Gonser, 1997). The stream-aquifer classification was determined for alluvial aquifers, however it is generally transferable to shallow fractured rock aquifers impacted by mining, where intensive fracturing produces a similar flow pattern. The above three groundwater flow types are postulated in a Southern Coalfield catchment impacted by longwall mining, through the development of new fractures, enlargement of existing fractures, separation of bedding planes and the modification of stream topography (Jankowski, 2007).

Streamflow may be permanent or temporary based on the following scenarios:

- Permanent flow occurs when the:
    - stream is connected-gaining and there are baseflow contributions from regional aquifers;
    - size and distribution of the surface fracture network is small, limiting surface water infiltration;
    - capacity of the subsurface system to store water is lower than the streamflow infiltration rate.
- Temporary flow occurs when the:
    - baseflow contribution is small and unreliable;
    - size and distribution of the surface fracture network is large, allowing increased surface water infiltration;
    - capacity of the subsurface system to store water is higher than the streamflow infiltration rate.

In the Southern Coalfield, for example, observed maximum subsidence may be up to 2.2 m (Dendrobium Colliery Area 2) (BHP Billiton, 2008) and observed maximum upsidence may be up to 197 mm (Waratah Rivulet, Metropolitan Colliery) (HCPL, 2006).

Mining–induced subsidence causes topographic and structural modifications to streambeds and the drainage basin, generally bounded by the angle of draw (subsidence to 20 mm). Fracturing of streambeds (Fig. 1) and rockbars (Fig. 2) causes surface water to divert to subsurface routes and interact with groundwater. In the Southern Coalfield, surface water typically flows vertically through fractures and horizontally through bedding planes. Recharge to the shallow sandstone aquifer also occurs through joints, veins and large cavities, with baseflow discharge occurring through fractures (flow is often under artesian pressure) and bedding planes.

Depending on the connectivity between the fracture network and bedding planes, a complex groundwater flow system can develop in the sandstone aquifer. In natural incised sandstone valleys, groundwater flows towards a stream and surface water-groundwater interaction represents a connected-gaining system. Mining impacts can cause streamflow losses along sections of streams, with surface flow diverted into the subsurface and the potential for a net reduction in flow at the end of the hydrological flow system. This enhanced surface water-groundwater connectivity along streams can result in the system changing from connected-gaining, to connected-losing and to disconnected-losing. Lateral and longitudinal flow around and along a stream and the location of recharge and discharge zones are modified with subsidence impacts on streambeds.

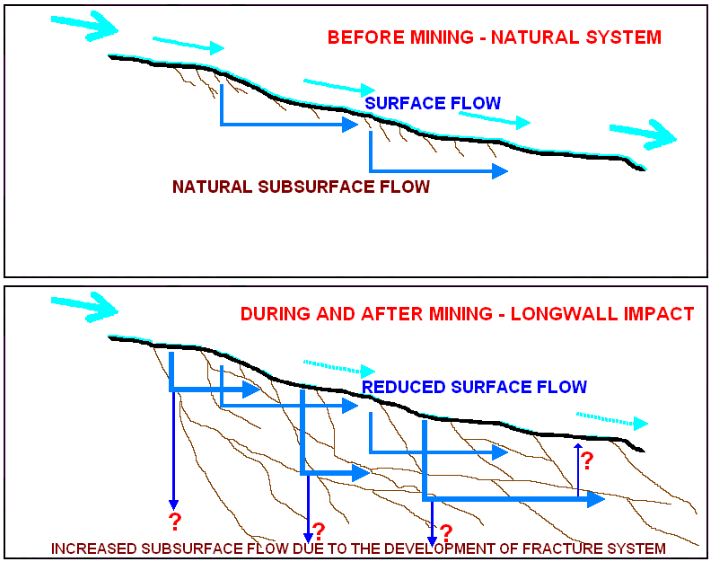

Figure 1 Diversion of surface flow into the subsurface due to fracturing of streambeds – natural versus impacted systems

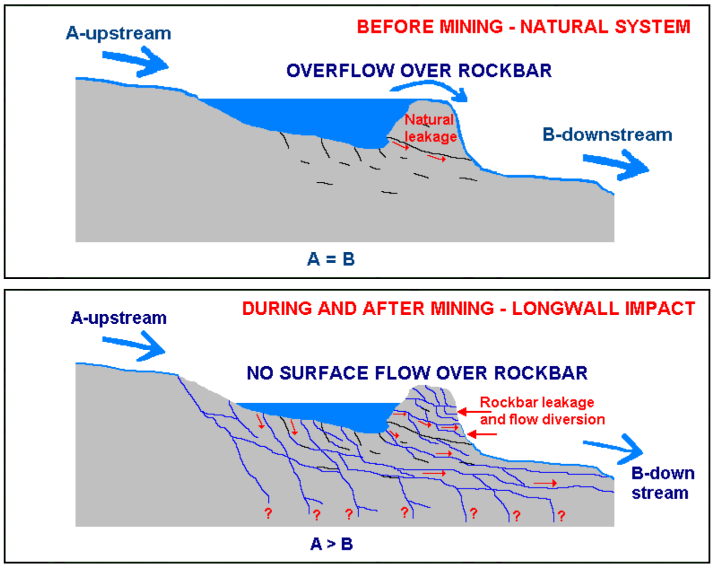

Figure 2 Diversion of surface flow into the subsurface due to fracturing of rockbars – natural versus impacted systems

Several conceptual scenarios have been identified by Jankowski (2007) to describe surface water-groundwater connectivity, subsurface flow pattern, recharge/discharge zones and mixing between surface water and groundwater. These scenarios, based on lateral and longitudinal surface water-groundwater flow, are discussed below.

Lateral surface water-groundwater flow in a longwall mining impacted catchment depends on the hydraulic gradient. 3D groundwater flow patterns depend on the number of aquifers and aquitards, distribution and connectivity of fractures and bedding planes, and can include the following scenarios:

- Before mining groundwater flow is typically towards the stream with a steep hydraulic gradient and baseflow discharge – connected-gaining stream.
- During mining there may be impacts to the wider catchment, with groundwater flow towards the stream yet the hydraulic gradient is flatter and baseflow discharge is reduced – connected-gaining stream but with potential for reduced gains.
- During mining there is a flat water table and/or slightly changing hydraulic gradient and a possibility of groundwater flow through a stream.
- During mining there may be a reversal of the hydraulic gradient, where surface water recharges the subsurface and groundwater flows away from the stream – connected-losing stream.
- Part of a stream is above an extracted longwall panel and part of the stream in an unmined area, potentially causing a reversal of the hydraulic gradient in the mined area and the hydraulic gradient to slope towards the stream in the unmined area – connected-gaining and connected-losing or flow through a stream.
- During mining there may be significant mining impact with fracturing of streambeds, fracturing of the strata over a substantial thickness and impact to the wider catchment, resulting in the groundwater table lowering below the streambed, a lack of surface flow or reduced surface flow during dry

periods, and reduced surface flow during rainfall due to increased groundwater recharge – disconnected-losing stream-aquifer system.

Longitudinal surface water-groundwater flow can have several recharge-discharge zones present along the streambed causing surface flow to recharge the subsurface and potentially discharge downstream.

The flow systems which can result can include the following scenarios:

- A simple shallow flow system along a stream with multiple separate subsurface flow paths, developed along preferential bedding plane(s) and fracture(s).
- A simple deeper flow system along a stream with multiple separate subsurface flow paths developed along preferential bedding plane(s) and fracture(s).
- Complex surface water-groundwater interaction with shallow and deeper subsurface flow paths, developed along preferential bedding planes and fractures with many locations of surface water and groundwater mixing zones.
- Complex surface water-groundwater interaction with multiple recharge-discharge and mixing zones, where flow occurs along a single preferential bedding plane and number of fractures.
- Complex surface water-groundwater interactions with multiple recharge and mixing zones and a single discharge zone, where the flow travels along a single preferential bedding plane and a number of fractures.
- Complex surface water-groundwater interaction with a single recharge zone and multiple discharge zones, where the flow travels along a single preferential bedding plane and number of fractures.
- Complex 3D surface water-groundwater interaction with multiple recharge and mixing zones, and flow travelling along several bedding planes and fractures. No discharge zone is locally present; groundwater may leave the catchment as regional flow or flow to a lower aquifer system.

Streamflow reduction

Evidence from surface flow

A lack of detailed baseline hydrological monitoring data is the main obstacle to adequately assessing the impact of mining on catchment hydrology, however a range of methods have been used to assess streamflow. Figure 3 shows the streamflow data from the main stream in a Southern Coalfield catchment impacted by longwall mining. Although there is no pre-mining data, one method used for assessing the streamflow data is based on subtracting the upstream streamflow from downstream streamflow, which has been used by others, such as Tieman et al. (1987).

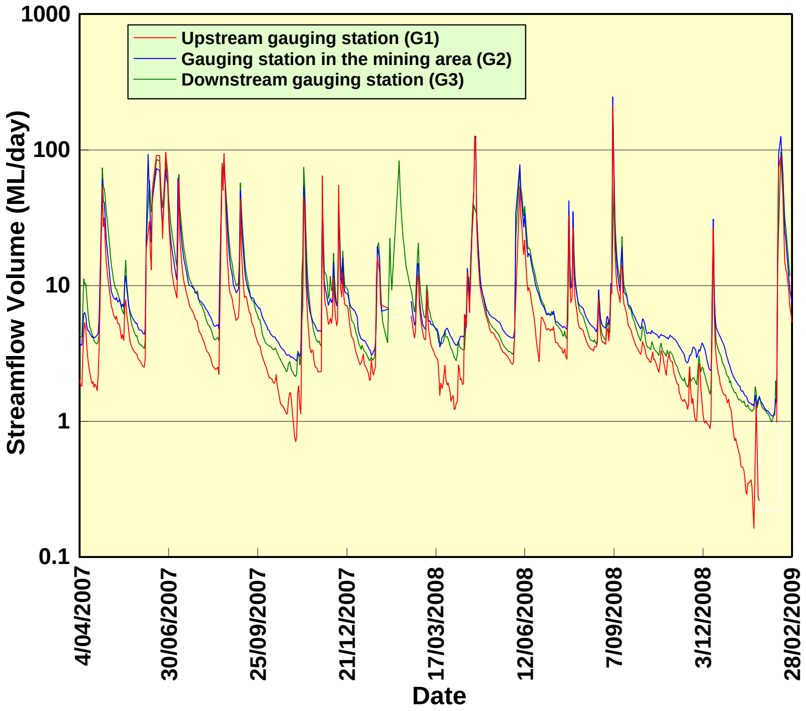

Figure 3 Comparison of streamflow upstream (G1), in the mining area (G2) and downstream of the mining area (G3)

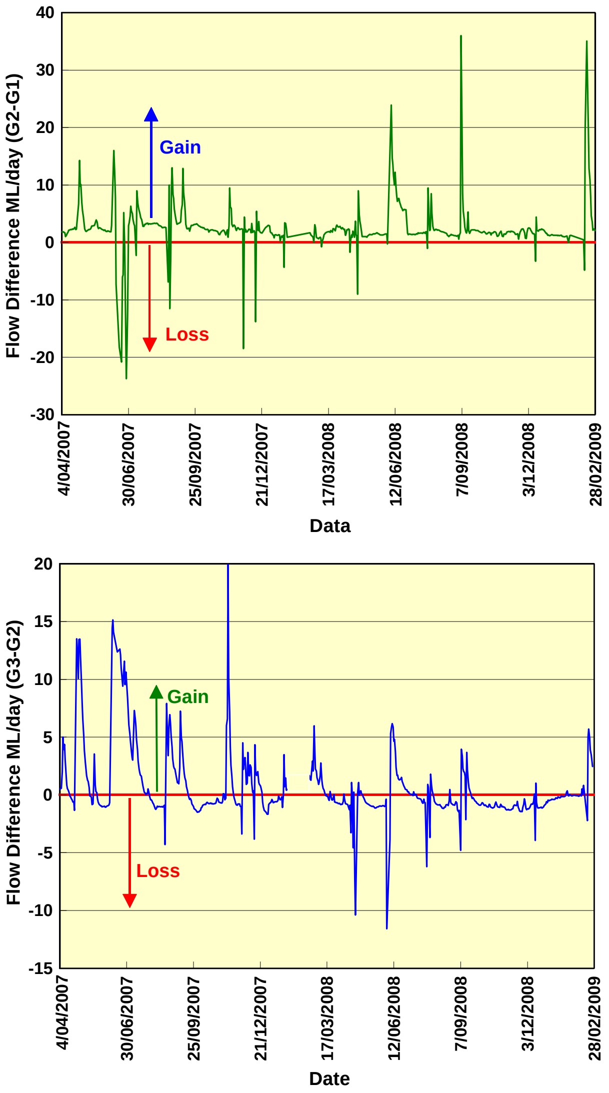

Figure 4 Flow difference between mining area (G2) and upstream (G1) gauging stations (left), flow difference between downstream (G3) and mining area (G2) gauging stations (right)

As shown in Figure 3, the upstream gauging station (G1), which is located on the upstream edge of the mining affected area and is likely to represent close to natural flow conditions, has lower flow during dry periods compared to the other gauging stations (G2 is located on the downstream edge of the mining area and G3 is located downstream of the mining area). This lower flow is expected, as the catchment area increases downstream and there is likely to be increased volume contribution to G2 and G3 from additional runoff, flow from tributary creeks and baseflow discharge. During periods of prolonged dry weather, the reduction in surface flow becomes visually evident as streamflow is diverted into the subsurface and there are sections of the stream which are dry.

When the flow data from G1 is subtracted from the flow data from G2, it appears that typically the low flows at G2 are higher than the low flows at G1 (Fig. 4). Increasing flow downstream is due to incremental contributions from the catchment and baseflow discharge to some or the entire stream length between these two gauging stations. When the flow data from G2 is subtracted from the flow data from G3, the volume of water at the downstream location is lower than the volume of water at the upstream location (Fig. 4).

The sharp losses shown in Figure 4 typically occur: just before large rainfall events and may represent a lag in travel time; and during high flow conditions and may represent errors with the data (rating curves appear to be less reliable during these conditions). Although no data was collected prior to the commencement of mining, the monitoring data available indicates there is a loss of surface flow.

Evidence from shallow groundwater

Groundwater level data obtained from shallow piezometers along the stream is shown in Figure 5. The groundwater levels at six locations representing the upstream (mined in 2003-2004) (GW5 and GW6), mining area (GW3 and GW4) and downstream (edge of mining above the rib zone) (GW1 and GW2) conditions were compared with the streambed elevation and indicate the connectivity between surface water and shallow groundwater (Jankowski et al., 2008). GW5 and GW6 shows the disconnected-losing part of the stream, where the groundwater level is below the lowest streambed elevation. This area was mined in the past and currently represents a nearly recovered part of the hydrological system.

Fractures, joints and bedding planes still provide pathways for subsurface flow, however the openings are smaller than they would be above the active mining panel. There is usually surface flow in the stream at this location, however surface flow also recharges the subsurface system with a relatively fast infiltration rate, indicating a high hydraulic conductivity of the aquifer. It is expected that lateral flow dominates natural rainfall recharge of the aquifer, whereas longitudinal flow is expected to dominate subsurface flow.

At GW3 and GW4 the stream is usually connected-gaining, with the groundwater level above the lowest stream bed elevation. It is expected that this part of the stream is in the compressional phase of subsidence, where fractures have partially re-closed, there is limited vertical and horizontal extension of fractures and bedding planes, the groundwater level has partially recovered and groundwater discharges through vertical fractures under pressure. However, this area appears to be undergoing some fracturing and incremental impact by subsequent longwall panels.

During low streamflow conditions in January-February 2009, the stream become connected-losing as the groundwater level went below the streambed elevation. This may be associated with the relatively low rainfall conditions that prevailed in the end of 2008 and early 2009 as well as an incremental effect of longwall panels LW15 and LW16 on the catchment surface water and groundwater. At GW1 and GW2, the groundwater level remained below the lowest streambed elevation, indicating a disconnected-losing part of the stream. Longwall mining has not occurred at this location, however the piezometers are located over the headings at the edge of an extracted longwall panel and is within the rib area covered by a 35^o angle of draw. This part of the stream is disconnected-losing, as subsidence is likely to have developed significant openings with a high capacity to allow the inflow of surface water.

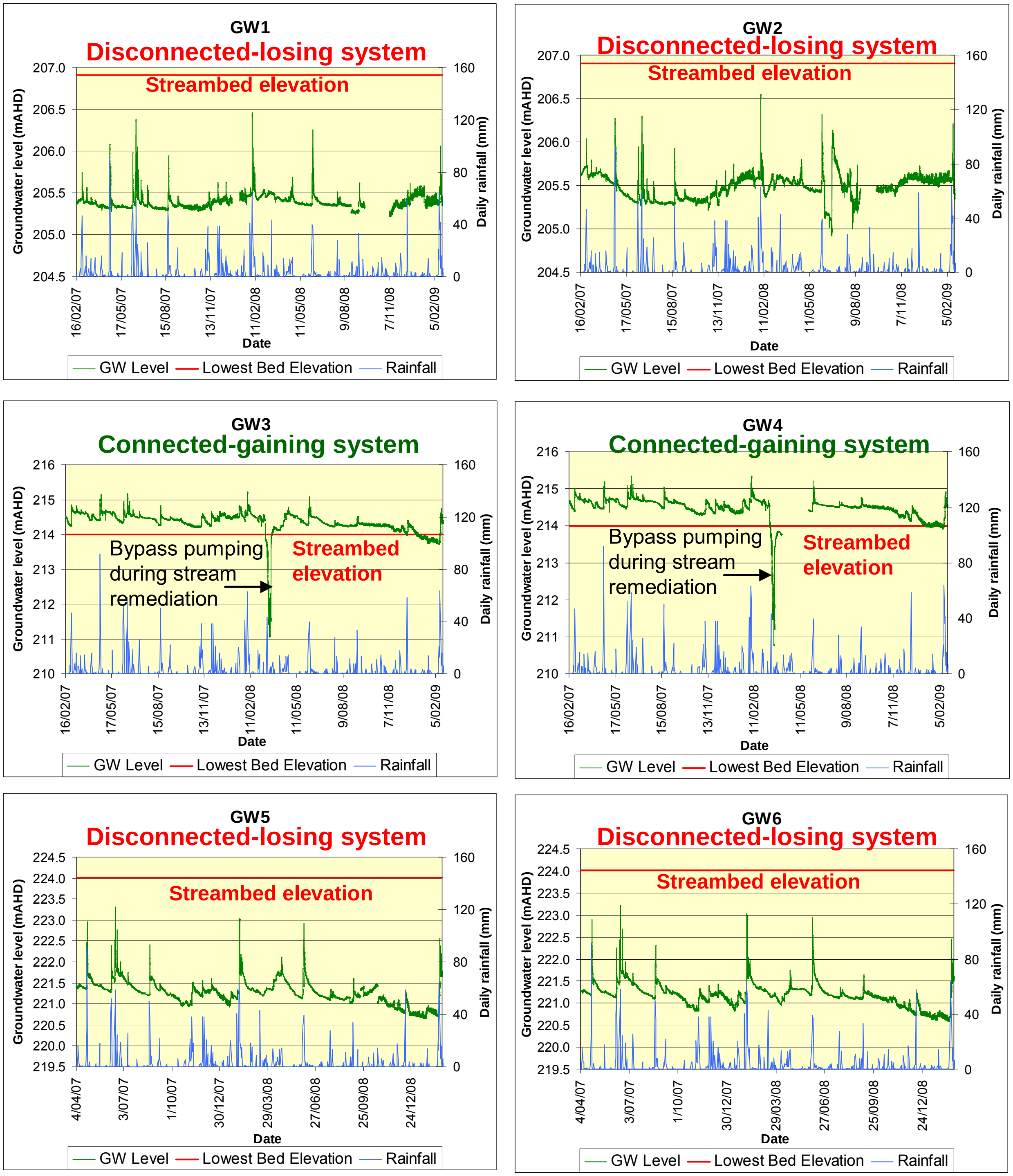

Figure 5 Groundwater levels upstream (GW5 and GW6), in mining area (GW3 and GW4) and downstream (GW1 and GW2) (modified from Jankowski et al. 2008)

Conclusions

The method used of subtracting the upstream streamflow from downstream streamflow is appropriate for providing an initial indication on whether or not there is streamflow loss. However, in mining impacted catchments in particular, the method is a simplification, due to the complex hydrological processes that occur. The complexity of the hydrology results in difficulties in assessing stream flow losses, as there can be decreases in surface runoff, reduction in baseflow discharge to tributary creeks and streams, and leakage from the shallow aquifer to deeper regional aquifers. This system, dominated by surface water-groundwater interaction, is very difficult to monitor. Vertical and horizontal ground movements result in the development of new fractures and the enlargement of existing fractures and bedding planes. Pathways are created, allowing surface water to recharge the shallow subsurface, causing a reduction in streamflow and decreased baseflow discharge to the main stream. Losses to deeper regional aquifer have not been monitored or accessed. Reduction in streamflow depends on surface fracturing and the hydraulic connectivity between surface flow, shallow aquifers and deeper regional aquifers. Shallow piezometers located near the stream indicate that shallow groundwater close to the stream is affected by subsidence, causing the majority of groundwater levels to be below the streambed, causing the stream to be disconnected-losing with the diversion of surface water into subsurface voids. If the shallow aquifer becomes connected to the deeper regional aquifer, it is possible that this water will be lost from the immediate catchment.

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The Design of Hydrological and Hydrogeological Monitoring Programs to Assess the Impact of Longwall Mining on Water Resources

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Abstract

Longwall mining activities under water resource catchments can cause impacts due to subsidence and rock deformations above the extracted coal seam. Impacts can include a temporary or permanent loss of surface flow, water quality changes, groundwater level declines and loss of swamps. Monitoring programs must be adequately designed and implemented to determine the baseline conditions prior to longwall mining, the extent of hydrological and hydrogeological alterations during mining, and whether the hydrologic and hydrogeologic systems recover following mining. The selection of appropriate surface water, groundwater and water quality monitoring locations should be based on an integrated holistic approach to assess and interpret changes in time and space. The question “how much monitoring is enough?” depends on site-specific conditions and predicted subsidence, while regulatory requirements must also be considered. Monitoring programs in catchments where longwall mining occurs need to ensure sufficient representative and defensible data is collected to confidently interpret changes to the hydrologic and hydrogeologic systems as mining progress. Designing monitoring programs in catchments where longwall mining is proposed can be challenging, as mining results in progressive changes in fracture patterns and then rock porosity and permeability. Consequently, for example, the fracturing of riverbeds can change the location of recharge-discharge zones and the shearing of the rock mass can result in the destruction of piezometers. This paper discusses the monitoring challenges and needs identified by the Sydney Catchment Authority, through its experience in assessing mining reports and data, and in its development of guidelines for hydrological and hydrogeological monitoring programs suitable for assessing the impact of longwall mining across the SCA’s Special Areas.

Keywords: Monitoring, longwall mining, surface water, groundwater

Introduction

Monitoring programs are often designed to identify and quantify potential impacts of human activities, such as loss of surface water flow, decline in groundwater levels, changes to water quality and enhanced surface water-groundwater interaction. Determining what to monitor, how long to monitor and in what detail, is often guided by the budget, timeframe, and nature of the development and its potential impact. Equally important, the monitoring program needs to reflect a robust experimental design and the selection of analytical methods.

The SCA is required to provide a sustainable supply of good quality water to Sydney, Shoalhaven and Southern Highlands, the Blue Mountains and the Illawarra, with the SCA's role, functions and objectives further defined in the SWCM Act (1998). Special Areas protect the water supply by limiting development and associated pollutant generation in close proximity to the storages. They are areas of bushland with numerous plant and animal species, including threatened plants and animals, and contain evidence of Aboriginal occupation and non-Aboriginal exploration and early settlement (SCA, 2008). Some of the SCA's storages and Special Areas are at risk from longwall mining operations and associated subsidence impacts and environmental consequences including the potential to reduce the yield and water quality of the storages, as well as cause deterioration in the terrestrial and aquatic environments.

There are several documents which discuss the potential impacts from underground coal mining and associated activities in the SCA area of operations including CSIRO (2002), Dendrobium Commission of Inquiry (2001), Holla & Barclay (2000), ACARP (2001, 2002), Williams (2004), HNRMF (2004) and DECC (2008). Various environmental consequences have been observed to date including diversion of surface flow to subsurface flow, cracking of the beds of various creeks and rivers (such as Wongawilli Creek, Native Dog Creek, Cataract River and Waratah Rivulet), reduction in water quality, adverse impacts on ecosystems, drying up of permanent pools and the release of methane gas into surface water bodies. Potentially, other impacts may include loss of upland swamps and leakage of surface water and shallow groundwater to deeper aquifers and mines, permanent loss of streamflow and reduction in catchment yield.

Mining companies are required under the conditions of their development approvals to devise and implement monitoring programs to assess subsidence impacts and environmental consequences, and to report on the monitoring undertaken in annual environmental management plans. Other documents, such as subsidence management plans and end of panel reports also include an analysis of monitoring data. Historically baseline monitoring has been negligible and ongoing monitoring has often been inadequate in duration or spatial density to support the available evaluation techniques. Site access is often difficult and compromises on sites are sometimes required. For this reason the SCA has been developing guidelines for hydrological and hydrogeological monitoring programs which will be suitable for assessing the impact of longwall mining across the SCA's Special Areas (SCA, 2007 & 2009). This has built upon the experience obtained through the assessment of various mining reports and the data collected by mining companies.

Objectives of monitoring programs

Monitoring locations (rainfall stations, stream gauging stations, pool level loggers, water quality sampling sites and piezometers) and the data and accuracy required must be consistent with the monitoring objectives. The objectives of the hydrological and hydrogeological monitoring programs in SCA's Special Areas with longwall mining proposed or being undertaken include the following:

- To obtain accurate and representative monitoring data to assess and understand the environmental consequences of subsidence impacts on water resources (surface water and groundwater).

- To quantify if there is any net loss of surface flow or water quality deterioration at the end of the hydrological flow system.
- To determine the extent of any groundwater level declines and whether groundwater flow paths have changed.
- To determine the extent of any impact, laterally and with depth.
- To determine whether the hydrological and hydrogeological systems will return to baseline (pre-mining) conditions and the rate of that recovery.
- To evaluate the immediate and long-term effectiveness of remediation techniques.

A monitoring program should be supported by the rigorous analysis and interpretation of the data. The detailed interpretation may be aided by the use of advanced research techniques (e.g. isotopes and tracers), subsidence modelling and numerical modelling to better understand the hydrological and hydrogeological systems and the changes with mining.

Monitoring program design

The design of a monitoring program seeking to assess the impact of longwall mining must be rigorous, comprehensive, defensible and appropriate for assessing the changes during and immediately post mining and the degree of recovery of the hydrological and hydrogeological systems following the cessation of mining. Monitoring programs should be developed in consultation with the land and water managers, such as the SCA, and should address a range of factors including the:

- location and significance of streams
- distance to reservoirs
- location of springs and baseflow areas
- location, size and significance of swamps
- resource potential of aquifers
- groundwater development in the area
- number, dimension and location of longwall panels
- expected progress of mining
- predicted subsidence
- depth of mining
- local geology
- topography
- catchment shape and area
- variability of climatic conditions
- accessibility
- potential impacts on water resources.

The SCA has identified a number of key challenges in the design of a monitoring program including:

- What is the pre-mining nature of the groundwater-surface water connection in the proposed mining area and how might this change during and post mining? Streams generally fall into four categories; connected gaining, connected losing, disconnected losing or bank storage (Winter et al., 1998). It is important to ascertain which conditions prevail prior to the commencement of mining and this requires a network of shallow/deep piezometers close to the streams. This should also be complemented by a stream gauging network which can distinguish between those reaches which are dominated by baseflow and those which are characterised by naturally high transmission losses. Once mining has commenced these networks should be maintained to monitor subsequent changes in the status of those stream reaches.

- How will any changes to streamflow volume be evaluated and is the diversion of surface flow to the subsurface likely to result in a temporary or permanent loss of surface water? To determine this, the monitoring program will need a network design that extends below the mined area to identify whether any of the surface flow diverted to the subsurface returns further downstream. There are a number of possible methods available for evaluating the change in streamflow; however, all methods are complicated by the high degree of natural variability typical of these streams on the Woronora and Illawarra Plateau areas. The available methods generally fall into three groups:
    - Comparison of pre- versus post mining streamflow data. Where possible the SCA requires two years of pre-mining data in order to ensure that the data covers a reasonable range of climatic conditions. In practice this is often difficult to ensure as mining may commence sooner than two years after the development approval is granted or previous mining has already impacted the current approval area. It is also necessary to demonstrate that there is no statistically significant difference in rainfall in the before and after periods.
    - Comparison of streamflows above and below the mining area. This approach assumes that the natural flow increases downstream due to increased contributions from the catchment and groundwater (baseflow) discharges. Runoff depth can be calculated by dividing the daily runoff volume at each gauging station by the subcatchment area enabling a comparison of yield between subcatchments of different catchment areas. If runoff depth is less at the stations downstream than at those above the mined area this may indicate a loss of streamflow. Similarly subcatchment runoff coefficients may be calculated by plotting a linear regression of cumulative rainfall depth and cumulative runoff depth for each gauging station. The differences in the runoff coefficients may indicate a reduction in catchment yield that cannot be explained by climate variability. There are however a number of problems with this approach; it is often difficult to find a reliable gauging site above the influence of the subsidence zone and the streams may be small or ill defined through in-valley swamps. In some cases there may also be a problem with finding a suitable location downstream of the mining area particularly if mining is to extend up to or beneath a downstream reservoir.
    - Comparison to an unimpacted ‘control’ catchment. This approach is predicated on the assumption that catchments are identical and the hydrological responses of the control catchments will remain stable over time while the hydrological response of the mined catchment will change as a result of subsidence. If available, the analysis would use the full time series of data from pre-mining to post mining. If pre-mining data is not available, a hydrologic model may be applied to the mined catchment, calibrated to the post mining gauging record, and then run for the whole period (pre-mining,

during and post mining). The comparison with the observed record in the control catchments (a BACI test of impact) may then indicate a statistically significant change from before to after mining activity, providing there is no statistically significant difference in the control catchments from before to after mining.

- What is the impact on the groundwater system; does the mining cause the shallow groundwater to leak into the regional groundwater flow, the deep aquifers and/or the mine? Longwall mining causes surface subsidence, strata deformation and movement, which alters groundwater systems, hydraulic gradients and can result in groundwater level declines, altered groundwater flow paths and baseflow reduction. Groundwater assessment is essential to determine impacts to the deeper groundwater systems. This will necessitate a network of multilevel piezometers monitoring across the stratigraphic units. The uppermost units are the most important for assessing water resource impacts.
- What impact on water quality is caused by surface water-groundwater interaction? Subsidence creates new fracture networks, which when exposed to infiltrating surface water and groundwater, undergo chemical reactions. As a result, water discharging to streams can contain elevated ion concentrations, such as iron and manganese. Shallow piezometers near streams and surface water monitoring sites are required to determine the water quality during pre-mining, and post mining periods.

Both hydrological and hydrogeological monitoring should be continuous over all three phases of the mining activity:

- Pre-mining (baseline) – for a minimum of two years to obtain background information during varying climate conditions. Two years of baseline data was also recommended by the strategic review of the impacts of underground coal mining on natural features in the Southern Coalfield (NSW Department of Planning, 2008).
- During mining – for the duration of mining to obtain data and information about whether or not there has been impacts, and the extent of impact, on water resources.
- Post-mining – for a minimum of three years following the cessation of all mining activities. Monitoring may be required for a longer period of time if recovery is slow and the hydrological/hydrogeological system has not returned to pre-mining conditions in respect to flow, water level and water quality.

Hydrological and hydrogeological monitoring programs must have a sufficient number of locations for monitoring surface water flow, pool levels, surface water quality, springs, groundwater levels (perched, shallow and deep) and groundwater quality, in order to support rigorous scientific analysis. Figure 1 is a hypothetical catchment showing the indicative locations for hydrological and hydrogeological monitoring sites.

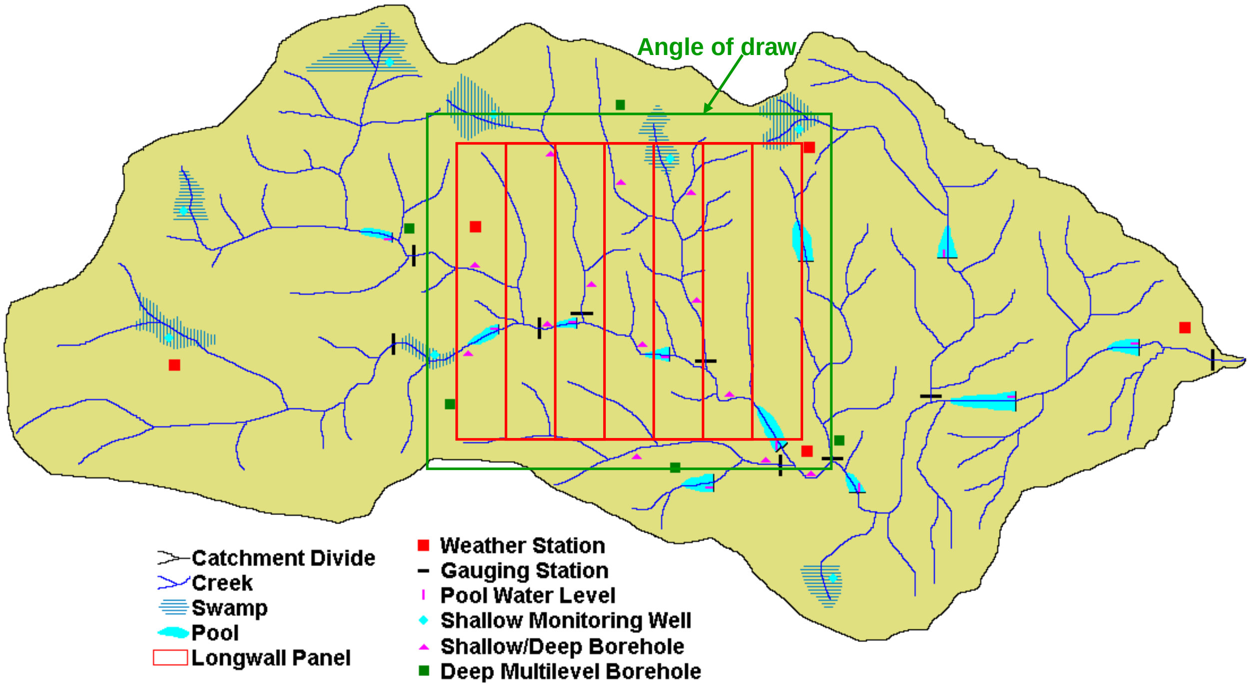

Fig. 1 Monitoring site locations in a hypothetical catchment

The monitoring program should be undertaken inside (inner zone) and outside (outer zone) the area defined by the angle of draw (subsidence up to 20 mm). A broader area, up-gradient and down-gradient of the proposed mining, is required to assess the water quantity and quality changes away from mining. The up-gradient monitoring sites are not expected to be impacted by mining, and therefore may be useful as control sites for assessing the natural characteristics and for comparison with monitoring sites within the mining area. Specifically, the following should be evaluated:

- fracturing of streambeds and rockbars
- changes to surface water flow and changes to pool levels
- diversion of surface water to the subsurface
- migration of water in the subsurface
- modified or enhanced surface water-groundwater interaction, including increased rates of chemical reactions during water-rock interaction
- changes to surface water and groundwater quality
- increased vertical and horizontal subsurface flow
- decreased groundwater levels
- changes to the groundwater flow direction, including changes to the hydraulic gradient near streams
- increased fracture porosity and permeability
- enhanced connectivity and leakage between aquifers.

Conclusions

An appropriate and rigorous monitoring program must be developed and implemented by companies mining in the SCA’s Special Areas if catchment yield and water resources are to be protected. The program must be comprehensive and able to provide the data required to determine potential impacts on water resources and to assess the impact predictions made by mining companies. The monitoring programs should address the pre-mining, during mining and post-mining phases, and should clearly define the monitoring locations, parameters, frequency, duration, and the accuracy and detection level of data. The monitoring programs need to be tailored to the local conditions, environmental objectives and mining activities, and therefore the monitoring programs should be devised in consultation with agencies such as the SCA and other regulatory agencies. The SCA continues to refine its guidelines for monitoring and evaluation of longwall mining and is currently reviewing the available analytical tools including integrated surface water and groundwater models, advanced statistical techniques, and advanced research techniques such as isotopes and tracers.

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Why is Wybong Creek salty?

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Abstract

Wybong Creek is a 90 km long tributary of the Goulburn River, in the upper Hunter Valley of New South Wales. Previous research identified Na-Cl concentrations in Wybong Creek at levels which decrease the water quality of the Goulburn River and impact agriculture. This study aimed at identifying the origin of solutes in the Wybong Creek catchment and the processes which caused salinisation, in order to identify salinity mitigation measures.

Surface water was sampled at ten sites along Wybong Creek. Ground water was sampled from most bores occurring in the valley. Major ion analyses indicated that saline, Na-Cl dominated water arose abruptly in the mid-catchment area, with surface and ground water in the upper catchment being dominated by fresher, Na-Mg-HCO_3 type water. Based on these findings, more intensive research including soil sampling and piezometer installation was conducted in the mid-catchment area.

Results from research in the mid-catchment area showed only slightly saline soils with up to 2185 mg TDS kg^{-1} soil occurring within a salt scald. Ground water samples, however, had 4500-6300 mg TDS L^{-1}. This ground water was found to arise at the break of slope, before it flowed to the salt scald. Smectite produced by weathering of basalt in the floodplain of Wybong Creek appears to be impeding this saline ground water from flowing further down its flow path, causing groundwater to mound and evapoconcentrate near the ground surface at the salt scald. Point source increases of salinity in Wybong Creek and saline ground water seeps from fractures in the bedrock indicate that though smectite impedes some of the ground water flow from the salt scald through the regolith, saline groundwater enters Wybong Creek through fractures in this mid-catchment area. Element to Cl and Br/Cl ratios indicated that either marine water or an evaporite deposit within the Permian strata was the source of saline ground water in the mid-catchment area.

Keywords: Salinisation, groundwater, soil, regolith.

Introduction

The Wybong Creek catchment has been identified as a priority saline sub-catchment of the Hunter river for detailed study (Fig. 1). This was due to Wybong Creek delivering significant salt loads to the Goulburn River. Salts from Wybong Creek were also dominated by Na-Cl, which is anomalous with other rivers in the Hunter Catchment (Creelman, 1994).

The 800 km^2 catchment is bordered in the north by the basalt capped sandstone of the Liverpool Ranges. Relief in the catchment ranges from gently undulating to extremely steep, with the Triassic Narrabeen Sandstone group cropping out as sandstone escarpments throughout

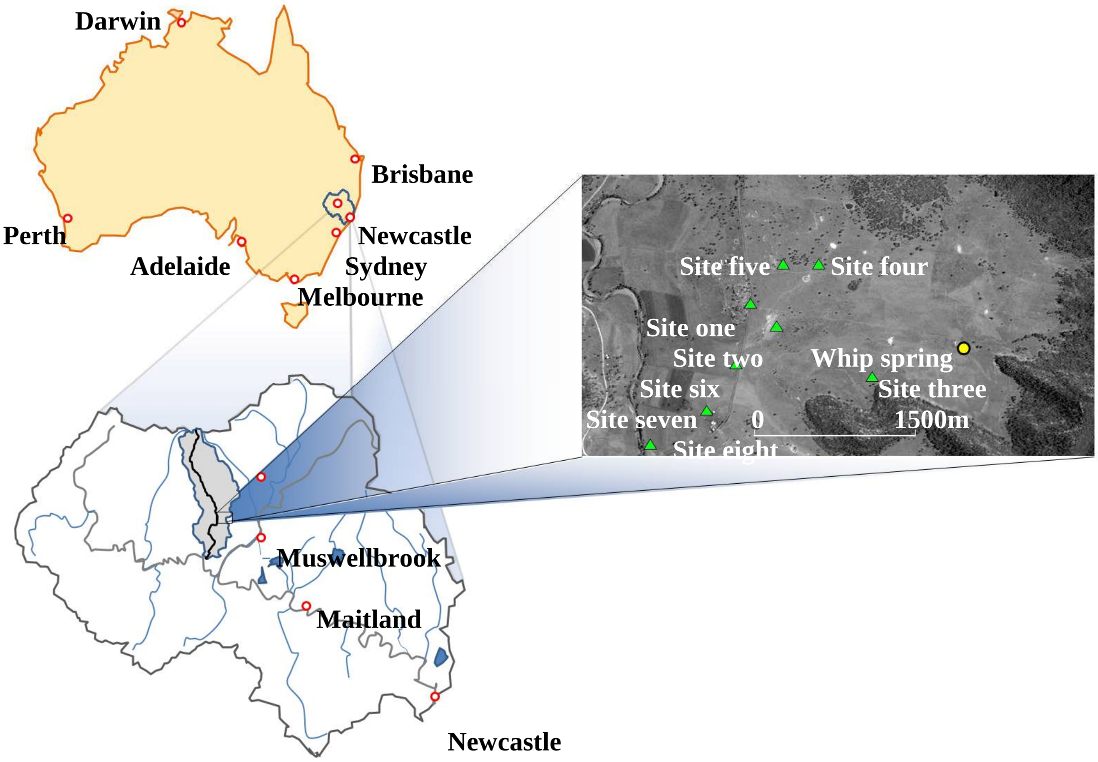

Figure 1. Location of the Hunter Valley within Australia, with detail of the Hunter River Catchment. The Wybong Creek catchment is illustrated in grey, with detail showing piezometer locations within the Manobalai field site.

the catchment. Previous work shows that saline regolith (sodosols) occurs within alluvial landforms in the mid-lower Wybong Creek catchment (Kovac & Lawrie, 1991). North of the Liverpool Ranges, salinisation in the Namoi River catchment and Liverpool Plains has been identified as dryland salinity. Aeolian salts deposited during the arid Pleistocene have been mobilised from the smectitic Narrabri formation and brought to the land surface as a result of increased groundwater pressure (Ringose-Voase et al., 2003). A number of salinisation processes are possible in the Hunter catchment, including dryland salinity (Beale et al., 2000), irrigation (Healthy Rivers Commission, 2002), and input from coal and associated formations (Creelman, 1994). As part of research into salinity in the Wybong Creek catchment, surface water samples were collected from the length of Wybong Creek and ground water from as many bores as possible. In addition, a field site containing a salt scald at the locality of Manobalai was selected for regolith sampling and piezometer installation.

Methods

Water

Water samples were collected from ten sites down the length of Wybong Creek, from as many bores as possible, and from piezometers at the field site. Samples were filtered on site. Samples for cation analyses were acidified using 2 mL 50% HNO_3. Water quality parameters were measured in unfiltered water samples at the time of sampling using Orion Gel-Filled pH and Eh electrodes and pH and Eh meters and an Orion DuraProbe™ 4-electrode conductivity cell and conductivity meter. Alkalinity was measured in the field by titration, using filtered water, a Hach digital titrator, HCl and methyl orange. Samples were analysed for major cations using ICP-AES, and IC was used for anions.

Soil

Regolith samples were collected on the 8th and 9th of January 2008 and the 25th and 26th of March 2009. Sites one to five within the Manobalai area were selected for sampling according to landform, with sites one, three and five located at the breaks of slope, four in a drainage depression and two within the salt scald (Fig. 1.). In order to further understand the evolution of ground water between sites one to five and Wybong Creek, samples from sites six to eight were collected. Piezometers were installed in all holes after drilling.

Soil salinity was initially investigated by analysing 1:5 soil:water extracts for electrical conductivity (EC). A range of samples including the most saline, the least saline and a number with average salinity were selected for ion analyses according to the findings of $EC_{1:5}$ results. Selected samples were analysed for cations using an ICP-MS and for anions using an IC at the Research School of Earth Sciences, Australian National University.

3. Results and discussion

Water

Surface water samples collected from along the length of Wybong Creek had salinities of between 517 – 5270 µS cm^{-1}, with salinities doubling on some sampling dates between the 55 and 60 km sampling points in the mid-catchment area. Above the 55 km sampling point, samples were dominated by Na-Mg-HCO$_3$ type water. Below this point, Na-Mg-Cl type waters occurred. Saline ground water seeps arising from weaknesses in the Narrabeen sandstone were observed at the 60 km sampling point.

The same pattern was seen in ground water samples as that seen in surface water samples above and below the mid-catchment area, with salinities of up to 33,000 µS cm^{-1} in ground water from the lower catchment. In order to elucidate where Cl dominated water was arising, holes were drilled in the mid-catchment area, soil samples were collected and piezometers were installed at sites one to eight (Fig. 1).

Samples from site two and three were the most saline, and were both dominated by Na-Cl (Table 1). These samples had similar chemistry to the ground water monitoring bore GW080944 within the field site, which was 30 m deep and screened within fractured Narrabeen Sandstone. Samples from sites two and three contained more salt than was contained in the soil on a per weight basis (Table 1). Samples from site four and whip well were the freshest samples collected, though these were also collected from alluvium adjacent to the Narrabeen Sandstone escarpments. Samples collected from sites six and eight were much fresher than those from sites two and three, despite being down gradient of sites one – five. The hydraulic head within site two was also significantly higher than that at site six, 370 m down gradient (Table 1). In addition, salinity was more than four times higher at site two than site six. Ground water flowed from the break of slope at site three to site two below. The smectite dominated soils of sites six – eight then impeded saline ground water flow through the regolith below this point. Saline water was seen to enter Wybong Creek from weaknesses in the bedrock, however, with this water found to be similar to that within sites two, three and GW080944.

Soils

Regolith sampled from sites two and four in the valley floor was texturally highly heterogenous throughout the core. Regolith was 16 m deep. Lateral heterogeneity was exemplified by cores from site two, which despite being collected from within two metres of each other, had different textures throughout the cores. Lack of profile development and heterogeneity in these cores indicated the regolith within the valley floor was alluvium (Walker & Butler, 1989), and possibly analogous to the Gunnedah formation in the Liverpool Plains

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Table 1. Ground water and soil chemistry of samples from the Manobalai field site. Mean ion concentrations in ground water ± standard deviations are presented in mg kg^{-1} water, while the range of ion concentrations is presented for soil samples in mg kg^{-1} soil. N/A indicates analyses not yet complete. BDL indicates one of the two ions presented as ratios was below detection limit. *Indicates that Br in at least one sample was below detection limit and not able to be presented as a ratio.

Media	Site	*n*	pH	SWL (RHD)	EC (µS cm^{-1})	TDS (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	K (mg kg^{-1})	Na (mg kg^{-1})	Cl (mg kg^{-1})	SO_4 (mg kg^{-1})	HCO_3 (mg kg^{-1})	Cl/Br	Na/Cl
Ground water	Whip Spring	1	6.5	224	190	223	5	7.4	3.7	66	88	19	43		
	One	2	7.6 ± 0.5	186 ± 0.6	1685 ± 233	1182 ±382	24 ± 12	27 ± 6	3.0 ± 0.2	345 ±120	475 ±191	30 ± 8	266 ± 41	730 ± 47	1.0 ± 0.1
	Two shallow	3	7.1 ± 0.1	178.7 ± 0.7	10410 ± 1669	6250 ± 1004	235 ± 35	460 ± 85	31 ± 4	1330 ± 184	3200 ± 566	185 ± 21	786 ± 107	947 ± 5	0.7 ± 0.1
	Two deep	3	7.1 ± 0.1	178.7 ±1.1	7855 ± 1138	4895 ± 611	180 ± 14	375 ± 35	25 ± 3	1010 ± 127	2550 ± 354	140 ± 28	589 ± 50	959 ± 88	0.6 ± 0.0
	Three	2	7.0 ±0.7	188.5 ± 0.4	9890 ± 1739	6066 ± 1713	144 ± 136	370 ± 255	36 ± 4	1460 ± 85	3250 ± 778	227 ± 103	541 ± 573	790	0.7
	Four	2	7.4 ± 0.6	183.9 ±3.3	466 ± 136	303 ± 90	4 ± 1	9 ± 0.5	7 ± 2	64 ± 28	61 ± 49	20 ± 16	126 ± 16	714	1.6 ± 0.7
	GW080-944	2	7.0 ±0.1	164.5 ± 2.5	9890 ± 1259	5667 ± 655	69 ± 6	302 ± 69	37 ± 6	1575 ± 177	2965 ± 474	30 ± 18	672 ± 100	744	0.8 ± 0.0
	Six	1	8.4	168.5	2785	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Eight shallow	1	8.3	158.8	4740	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Eight fractured	1	7.7	158.7	4070	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
															%NaCl
Soil	Two shallow		6.4-7.2		60 – 752	272 – 2054	0 – 30	9 – 93	6 – 28	57 – 609	9 – 1136	0 – 81	40 – 324	*886 – 1025	0.00 – 0.11
	Two deep		6.1-7.2		37 – 668	459 – 1646	1 – 26	23 – 65	14 – 32	22 – 472	12 – 942	21 – 87	40 – 115	*989 - 1153	0.01 – 0.17
	Three		5.6-8.1		68	829	19	68	25	77	19	37	342	BDL	0.01
	Four		6.7-8.5		17 – 859	101 – 2185	0 – 24	3 – 282	2 – 91	16 – 670	6 – 1210	3 – 121	0 – 69	*911 – 1156	0.00 – 0.19
	Five		6.7-9.4			87 - 1518	0 – 30	0 – 189	11 – 55	4 – 244	0 – 98	5 – 13	36 – 376	BDL	0.01 – 0.03

(Dyce & Richardson, 1997). Cores from sites one, three and five contained horizons, indicating pedological development. All cores from sites one to five contained coloured quartzite that were weathering products from the Narrabeen Sandstone Group that surrounds the Manobalai field site. This is in contrast with sites six to eight which were highly homogenous black smectite, produced from the weathering of basalt (Kovac & Lawrie, 1991), possibly analogous to the Narrabri formation in the Liverpool Plains (Dyce & Richardson, 1997). None of the samples from sites one – five were saline on an $EC_{1:5}$ basis, with the most saline sample occurring within the alluvium. Percent Na-Cl indicated that alluvial samples were slightly saline, with Na-Cl making up 0.00 – 0.19 % of the soils weight (Table 1.; Northcote & Skene, 1972). Cores showing pedological development were dominated by HCO_3, SO_4, Na and Mg. Ion distributions within these cores were consistent with element deposition from above and leaching through the soil profile (Johnston, 1987), or alternatively input of Na-Cl rich ground water laterally or from below. No indication of salt bulges or monotonic increases in elements occurred within the soil profile at sites within the alluvium. The dominance of Na-Cl within these samples, heterogeneity between cores from site two, a lack of Ca-SO_4 in surface samples, and absence of a saline sub-soil in these samples indicated that rather than acquiring salts from aeolian deposition, ground water arising at the break of slope and possibly from fractures was the source of salt to the regolith, including the salt scald, and surface water in the mid-catchment area. This is in contrast to salinity north of Wybong Creek where fresh ground water occurs within sand and gravel rich Gunnedah formation, and acquires salts from the Narrabri formation above (Ringose-Voase et al., 2003).

Origins of salinity to Wybong Creek

Chloride dominated water occurs due to weathering of Cl containing evaporite deposits and/or fractionation of salts during evapoconcentration of water, such as rain water, which is ultimately sourced from the sea (Drever, 1997; Eugster, 1984). Site four had higher proportions of HCO_3, SO_4, Na and TDS to Cl than ground water from site two. Evaporites such as gypsum, anhydrite, or carbonate minerals were not observed in the field nor detected in the soil by XRD analyses, indicating differences in element to Cl ratios were not due to fractionation during evapoconcentration. Instead the abrupt increase in ground water salinity between sites four and two; the absence of saline water or scalding at sites four, whip well and other areas north of the salt scald; and the abrupt increase in salinity in Wybong Creek between the 55 and 60 km sampling points indicated saline, Cl dominated ground water moved into the Manobalai field site through fractures in the rock.

Sodium to chloride ratio's of 0.6 – 1.6, and intermediate Cl/Br ratio's of 714 – 959 indicated that ground water in Manobalai sourced from the mixing of fresher water with water from either marine or evaporite sources (Cartwright et al., 2004; Davis et al., 1998). Collection of aeolian salts in rock formations throughout the Tertiary has been hypothesised as a source of salt to ground water in fractured rock (Gunn & Richardson, 1979). Such a deposit cannot be the source of salinity to the Wybong Creek catchment, as the Triassic Narrabeen Sandstone unit is ubiquitous, and gradual rather than abrupt increases of salinity down catchment would occur if this unit was the source of salts. Marine strata within the Wittingham Coal Measures has been identified as a possible source of solute by some authors (e.g., Creelman, 1994; Kellett et al., 1987), with saline brines occurring in sedimentary basins across the world (Bottomley et al., 1994; Fontes & Matray, 1993; Martel et al., 2001; Möller et al., 2005). Ground water is hypothesised to carry salt from these marine strata into catchments via fractures in the Hunter Valley (Kellet et al., 1987), and it is possible saline water may originate from sedimentary brines also. Little deep (<400 m) drilling has occurred in the Sydney Basin, with sedimentary brines and/or saline aquifers only implied from hydrogeochemical data (Kellett et al., 1987; Patchett & Langford, 2005). Whether Na-Cl dominated groundwater in the Wybong Creek catchment is sourced from evaporites, marine incursion or evapoconcentrated rain water in strata older than the Tertiary is not clear from data presented in this study. Further research using stable isotopes such as $^{87}Sr/^{86}Sr$, $\delta^{18}0$, and $\delta^{2}H$ would help to elucidate sources of solutes.

4. Conclusion

Salt stores were not found within the subsoil of the Manobalai field site. Saline groundwater was instead found to arise at the break of slope within the field site, and within the fractured sandstone beneath the alluvium. Ground water flow from the salt scald to Wybong Creek was impeded by 12 m deep smectite in the Wybong Creek flood plain, with ground water moving into Wybong Creek via weaknesses in the Narrabeen Sandstone, causing abrupt increases in Cl and EC to Wybong Creek in the mid-catchment area. Ground water was saline before it entered the alluvium, in contrast to catchments on the other side of the Liverpool Ranges. Element to Cl and Cl to Br ratios indicated either an evaporite deposit or marine water as the source of salt to the saline ground water in the mid-lower Wybong Creek catchment, with work involving stable and radiometric isotopes required in order to further resolve the source of the salt.

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Groundwater and water balance estimates for the Sydney LPG Cavern, Port Botany, New South Wales

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Abstract

The Sydney LPG Cavern is located at Port Botany, New South Wales. The cavern is an unlined rock storage cavern mined out of the Hawkesbury Sandstone and located at a depth of approximately 124 metres below ground for storing LPG. A ‘water curtain’ was constructed approximately 15 metres above the top of the storage galleries to maintain saturation and to ensure permanent groundwater flow towards the mined cavern.

The LPG cavern has been operational for nine years and during earlier years, seepage inflows to the cavern were becoming more saline. This trend has now been partially reversed with the injection of large volumes of fresh water into the water curtain above the cavern.

The initial step to optimize future injection volumes into the water curtain and to minimize saline intrusion is to develop a good conceptual model and to estimate water balances particularly the volumes of different groundwater inflows and outflows at the site. Preliminary groundwater and water balance estimates have been determined for the site for pre and post cavern development scenarios.

Estimates were made using the site hydraulic conductivity, the hydraulic gradient and the cross-sectional area of the cavern. The regional hydraulic gradient (away from the Port Botany area) was estimated from private bores and groundwater levels from the DWE bore database.

Keywords: groundwater balance, unlined rock storage cavern, water curtain

1. Introduction

The Sydney LPG Cavern is located at Port Botany, New South Wales (Fig. 1). The cavern is an unlined rock storage cavern mined out of the Hawkesbury Sandstone and located at a depth of approximately 124 metres below ground for storing LPG. A ‘water curtain’ was constructed approximately 15 metres above the top of the storage galleries to maintain saturation to ensure permanent groundwater flow towards the mined cavern.

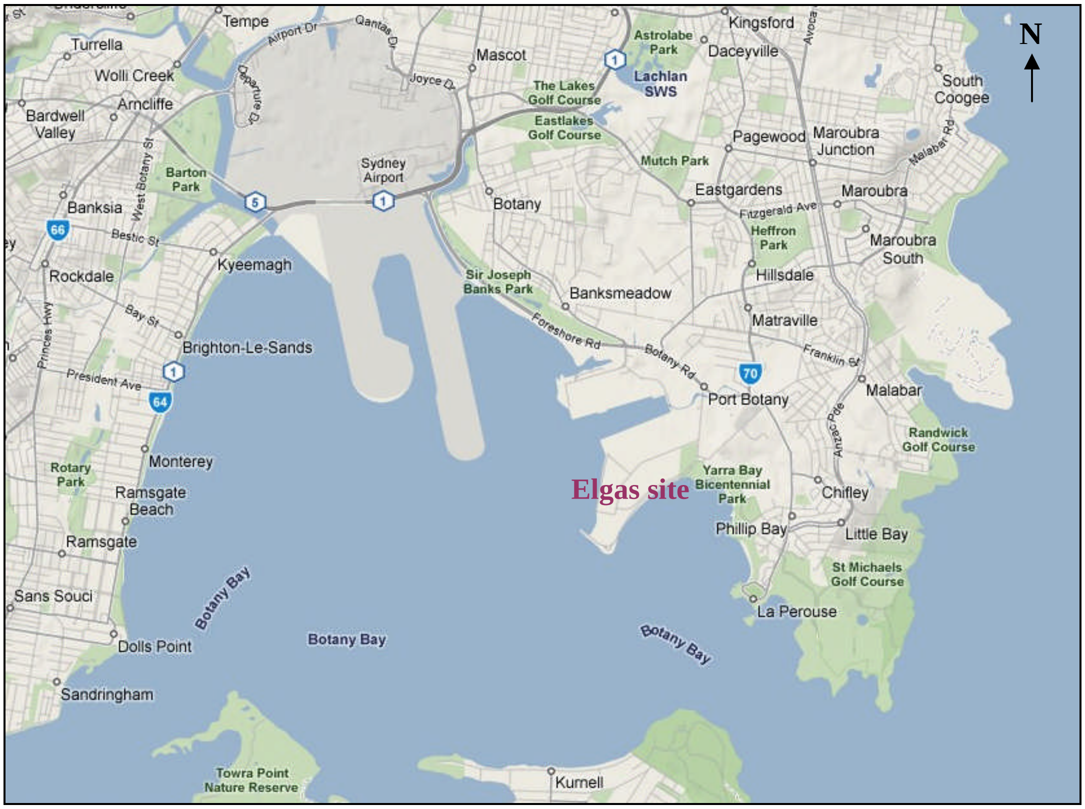
Conceptually there are two aquifer systems present at the site: the unconfined aquifer in the dredged sand/Botany Sands unit that forms the whole of Port Botany, and the underlying leaky confined aquifers within the Hawkesbury Sandstone. Pre-development, the recharge of these deep sandstone aquifers was from rainfall on the eastern exposed sandstone along the coastline, with groundwater flow to the west/south west and water discharging to Botany Bay through the Botany Sands.

However, post-development of the cavern these natural groundwater flow patterns have changed. From the start of monitoring in March 2001 to December 2004 a decrease in groundwater levels and an increase in salinity have been observed. To counteract these trends in recent years, additional potable water has been injected into the water curtain above the cavern. This has resulted in an overall increase in groundwater levels and slight decrease in salinities in the pumped cavern seepage water since December 2004.

Future water management practices at the site are critical to maintaining the cavern infrastructure and minimising the volume of brackish water produced from groundwater seepage into the cavern.

The initial step to optimize future injection volumes and to minimize saline intrusion is to estimate water balances particularly the volumes of different groundwater inflows and outflows at the site. Preliminary groundwater and water balance estimates have been determined for the site for pre and post cavern development scenarios.

Figure 9 Location of Sydney LPG Cavern at Port Botany (Google maps 2009)



2. Geology

The local geology comprises Hawkesbury Sandstone, which is Mid Triassic in age (225-330 million years). The Hawkesbury Sandstone dominates the landscape within a 100 kilometre radius of Sydney. It is flat-lying sandstone, which extends 20,000 square kilometres in area and can be up to 250 metres thick. The sandstone is a hard and durable rock composed of very fine to coarse quartz sand grains (although mostly medium grained) cemented with silica, clay and iron oxides or carbonates to form massive sandstone. Occasional shale bands occur within the sandstone, and at the cavern site there is a fairly continuous shale layer around 10 metres in thickness, occurring between approximately minus 90 and minus 100 metres Australian Height Datum (mAHD). This shale lens is present beneath most of the site, but is thin or absent on the eastern side of the cavern (Parsons Brinckerhoff 2008).

Unconsolidated sand deposits (Botany Sands) overlie the Hawkesbury Sandstone, and at this location, dredged sand from Botany Bay has been used to reclaim the Port

Botany site. The sand is up to 40 metres thick across the site, and comprises dredged material to around 14 metres depth, with a variable thickness of Botany Sands (9 to 30 metres thick). The base of the unconsolidated sand sequence is at around minus 17 mAHD on the southern boundary of the site, and around minus 40 mAHD on the northern site boundary (Parsons Brinckerhoff 2008).

3. Hydrogeology

Conceptually there are two aquifer systems present at the Elgas site: the unconfined aquifer in the dredged sand/Botany Sands unit, and the underlying leaky confined aquifers within the Hawkesbury Sandstone.

The shallow water table aquifer system within the fill and sand material is dominated by saline water, but a thin near-surface, fresh water lens is likely to develop after rainfall events. The water table is only a few metres below ground level and there is a strong tidal influence. Locally the main recharge of the shallow sand aquifer is from rainfall and the reinjection of (treated) cavern seepage water, leading to natural discharge to Botany Bay. The salinity of this shallow aquifer is approximately 50,000 µS/cm.

Very little is known about the characteristics of the regional Hawkesbury Sandstone aquifers in this part of the Sydney Basin apart from the extensive testing carried out at this site prior to and since construction. The current Hawkesbury Sandstone water levels range from around 0 to -7 mAHD (upper sandstone) and from about -10 to -30 mAHD (lower sandstone). The main influence on water levels and piezometric heads is tidal movements for the shallow sandstone aquifer, and cavern pressure and water curtain injection for the deep sandstone aquifer. The current salinity of the upper sandstone aquifer ranges between 10,000-20,000 µS/cm. The lower sandstone aquifer has a salinity of less than 2,000 µS/cm on average (upgradient of the cavern), increasing to approximately 5,000-10,000 µS/cm (downgradient of the cavern on the Botany Bay side).

Naturally (pre-development), the recharge of these deep groundwater aquifers is from the eastern exposed sandstone along the coastline, with water discharging to Botany Bay through the Botany Sands. Aquifer permeabilities and flow velocities are expected to be low (site geotechnical and groundwater studies have not been reviewed). The natural flow direction is expected to be predominantly from north-east to south-west. Locally, the construction and operation of the LPG Cavern has changed these natural velocities and flow directions (Parsons Brinckerhoff 2008).

Previous groundwater bore searches identified that deep sandstone groundwater bores were constructed at three locations in the general area (Parsons Brinckerhoff 2008). These are at Kingsford Smith Airport (heliport area), approximately five kilometres to the north-west; New South Wales Golf Course, 3.5 kilometres to the south-east; and St Michaels Golf Course, 3.3 kilometres to the east-southeast. The identified bores with pre-development groundwater level data available are summarised in Table 1.

Pre-development groundwater levels in the Hawkesbury Sandstone ranged between 2.1 and 9.6m below ground level.

Table 5 Existing Hawkesbury Sandstone bores

Location	Bore Number	Date Completed	Depth (metres)	Standing Water Level (metres)	Yield (litres per second)
Airport	GW103951	21/06/1995	148	6.0	2
NSW Golf Club	GW069143	28/08/1992	95	9.6	1.9
NSW Golf Course	GW100005	05/08/1992	112	6.98	1.24
Domestic bore	GW028573	01/11/1966	13.3	2.1	1.52

4. Cavern Construction and Operation

The Sydney LPG Cavern is an unlined rock storage cavern mined out of the Hawkesbury Sandstone. It has a storage capacity of 65,000 tonnes (approximately 140,000 cubic metres) of liquefied propane (LPG), stored under pressure. The natural stability of the bedrock beneath Botany Bay and the large pressure exerted by the water in the saturated rock mass ensures the containment of LPG and keeps it in liquid phase.

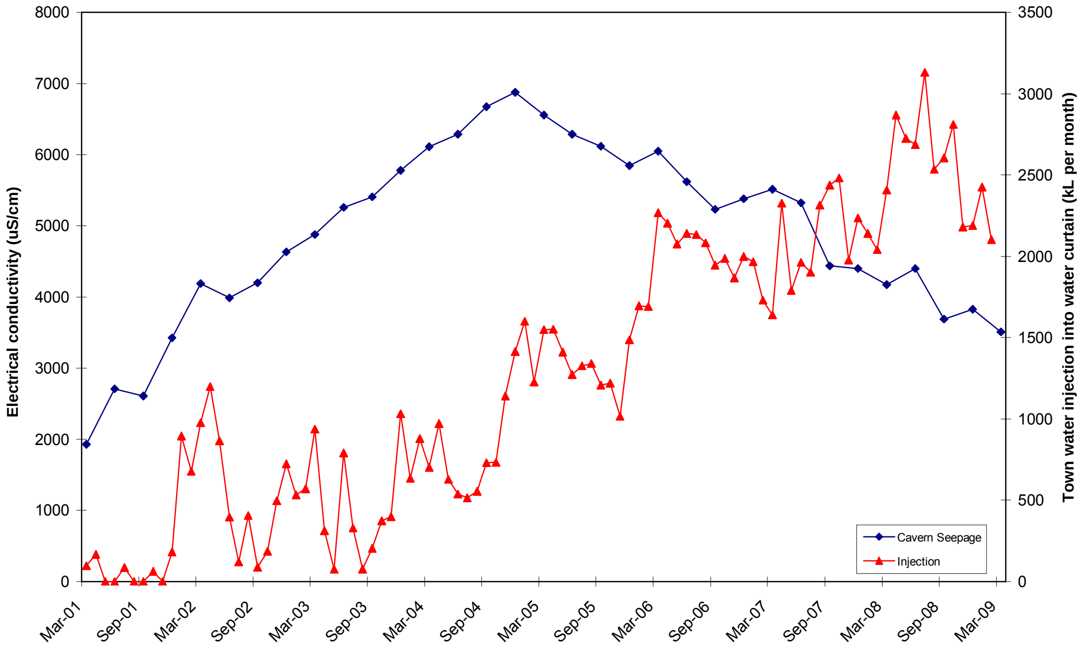
The cavern was excavated with a top elevation of approximately -124 mAHD, so that the pressure of the surrounding groundwater will remain in excess of the gas pressure in the cavern, thus ensuring containment of propane. The cavern volume is obtained by four parallel, unlined galleries, which are 14 metres wide, 11 metres high and about 230 metres in length. They are interconnected at the upper and lower level by smaller connection galleries (5.5 metres by 5.5 metres) so as to allow the interconnection of the vapour and liquid phase of the LPG (Geostock 2000).

A ‘water curtain’ was constructed approximately 15 metres above the top of the storage galleries to maintain saturation to help ensure permanent groundwater flow towards the storage, thus helping to retain the LPG within the caverns. It is made up of small tunnels and boreholes drilled into the surrounding rock. Town water is injected into the water curtain via a pipe in the Access Shaft.

The cavern is makes use of hydraulic containment to prevent migration or escape of stored LPG. When the hydraulic margin (a measure of the inward hydraulic gradient in the Hawkesbury Sandstone) drops below an acceptable level, the piezometric pressure in the sandstone surrounding the cavern is raised by the injection of potable water into the water curtain.

Potable water has been injected into the cavern since the start of operations in 2000, with higher volumes injected since December 2004 (Fig. 2). The salinity of the cavern seepage water increased until December 2004 (from approximately 2000 to 6600 µS/cm) when the injection volumes into the water curtain were substantially increased. Salinity levels have been mostly in decline for the last four years.

Figure 10 Town water injection and increasing EC in Water Curtain and Cavern Seepage

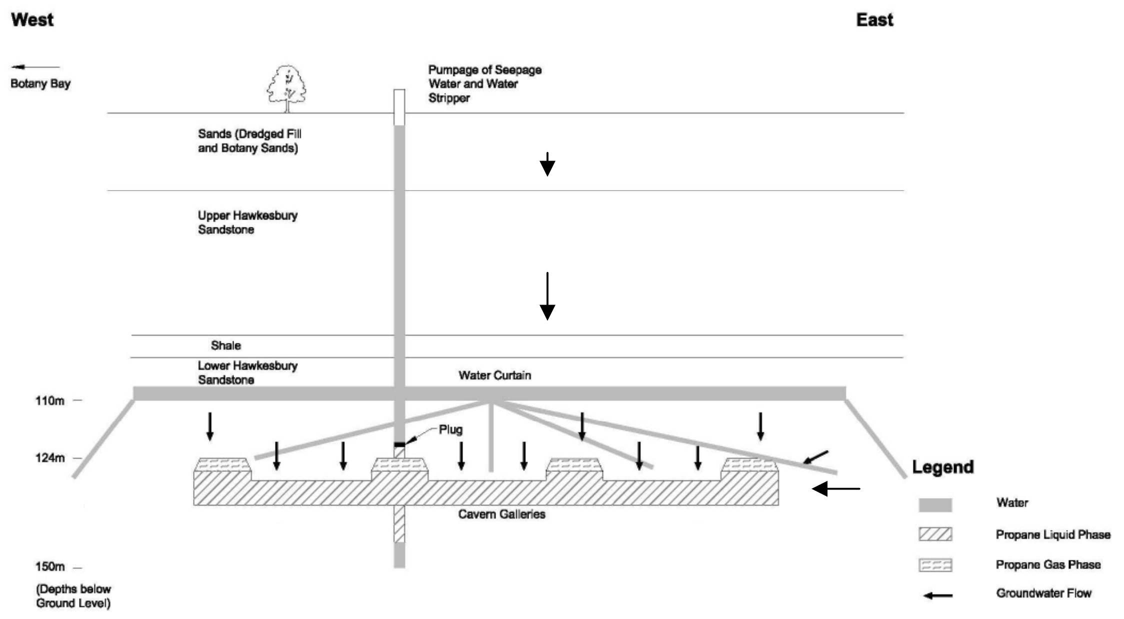


5. Conceptual model

Figure 3 shows a simplified conceptual groundwater model for the cavern. The Botany Sands overlie the Hawkesbury Sandstone. A shale layer separates the Upper and Lower Hawkesbury Sandstone units occurring between approximately minus 90 and minus 100 metres Australian Height Datum (mAHD). The water curtain has been constructed below the shale lens. Groundwater from the Botany Sands (and Botany Bay) flows downward into the upper Hawkesbury Sandstone. Groundwater in the upper Hawkesbury Sandstone also flows laterally and vertically to the lower Hawkesbury Sandstone. Groundwater flow in the lower Hawkesbury Sandstone (on the upgradient side of the cavern) is mainly horizontal towards Botany Bay (southwest). However the flow in this part of the sandstone has now been interrupted by the cavern and some groundwater from this unit now flows into the cavern laterally.

With the substantially lower pressure levels in the sandstone aquifers in the vicinity of the cavern, local groundwater gradients have changed and natural discharge to Botany Bay is no longer thought to occur. Instead, leakage of saline water from Botany Bay is assumed.

Figure 11 Conceptual groundwater model for cavern



6. Groundwater balance estimates

Initial water balance estimates were made using site hydraulic conductivity, the hydraulic gradient and the cross-sectional area of the cavern. The regional hydraulic gradient (away from the Port Botany area) was estimated using groundwater levels from the DWE groundwater database and there are a number of underlying assumptions (such as all water injected into the water curtain flows into the cavern).

6.1. Pre-development conditions

Using Darcy's Law, the following equations were used to estimate the volume of groundwater that could flow from the lower Hawkesbury Sandstone aquifer into an area equal to that of the cavern today under pre-development conditions:

$$Q = kiA \qquad (1)$$

Hydraulic conductivity (k)

Previous hydraulic testing at the study site showed that hydraulic conductivities for the lower Hawkesbury Sandstone ranged between 0.003-0.012 metres per day (m/d) (Parsons Brinckerhoff 2005). A value of 0.012m/d has been used in these estimates as a worst case scenario (highest flow velocity).

Hydraulic gradient (i)

Groundwater levels for DWE bores in the Hawkesbury Sandstone ranged from approximately 28 mAHD in the east (Long Bay) to approximately 1 mAHD (DWR 1994) at the site under pre-development conditions. The difference in groundwater level (27 m) is divided by the distance (3500 m) to calculate the hydraulic gradient. Using equation 2 the hydraulic gradient is estimated to be 0.0077. It should be noted that sandstone aquifer level information is very limited in the area and this is a best estimate only.

$$i = \Delta h / l \tag{2}$$

Cross-sectional area of the cavern (A)

The cross-sectional area of the cavern is estimated to be represented by the north-eastern wall of the cavern, which is where groundwater would enter the cavern primarily. The length of this wall is 230 m and height is 11 m. Using equation 3 the cross-sectional area is calculated to be 2,530 m^2.

$$A = lh \tag{3}$$

By multiplying these three components, an estimate can be made of the monthly groundwater inflow in kilolitres (kL) into the cavern area under pre-development conditions using equation 1. Calculations suggest that the estimated (pre-development) groundwater flow through the Hawkesbury Sandstone at the depth of the cavern was 7 kL per month.

6.2. Operational conditions

Under operational conditions, it is assumed that the natural flow path has been truncated by the cavern and that the groundwater seepage into the cavern is in accordance with the conceptual model. The following equations were used to provide coarse estimates of the total groundwater inflow and outflow for the cavern:

$$Q_{\text{in (cavern)}} = Q_{\text{in (HS lower)}} + (Q_{\text{in (HS upper)}} + Q_{\text{in (Botany Sands)}} + Q_{\text{in (Botany Bay)}}) + Q_{\text{in (water curtain)}} \tag{4}$$

$$Q_{\text{in (cavern)}} = Q_{\text{out (cavern)}} \tag{5}$$

Groundwater inflow from Lower Hawkesbury Sandstone ($Q_{in\ (HS\ deep)}$)

The groundwater inflow into the cavern from the lower Hawkesbury Sandstone is calculated using equation 1. The difference between the pre-development and operational conditions is that the hydraulic gradient is steeper for operational conditions. Groundwater levels have fallen approximately 20 m compared to pre-development conditions. Using equation 2, the new difference in water groundwater levels (Δh) is 47 m, resulting in a hydraulic gradient of 0.013. Using equation 1, the groundwater inflow from the lower Hawkesbury Sandstone is estimated to be 12.2 kL/month.

Water inflow from water curtain ($Q_{in\ (water\ curtain)}$)

The water inflow from the water curtain varies between 1,500 and 3,000 kL per month. For the period December 2004-May 2008, the average volume of water going into the cavern was approximately 1,870 kL/month (Geostock 2008). At the higher injection rates the water levels in the sandstone aquifer rise, and with lower rates they fall slightly. The rate of 1,870 kL/month is considered reasonable to assume reasonably static pressure levels in the sandstone aquifers adjacent to the cavern.

Water outflow pumped to water stripper ($Q_{out\ (cavern)}$)

The volume of water that is pumped to the water stripper and then injected into rubble stockpile and the Botany Sands also varies monthly. For the period December 2004-May 2008, the average volume of water being pumped out of the cavern was approximately 3,040 kL/month (Geostock 2008).

Groundwater inflow from Botany Sands, Botany Bay and Upper Hawkesbury Sandstone ($Q_{in\ (HS\ upper)}$ + ($Q_{in\ (Botany\ Sands)}$ + $Q_{in\ (Botany\ Bay)}$)

This component of the water balance is the main unknown (and is the main source of the brackish/saline water that is reporting to the cavern) and it is impossible to separate between the three sources without the use of a numerical model.

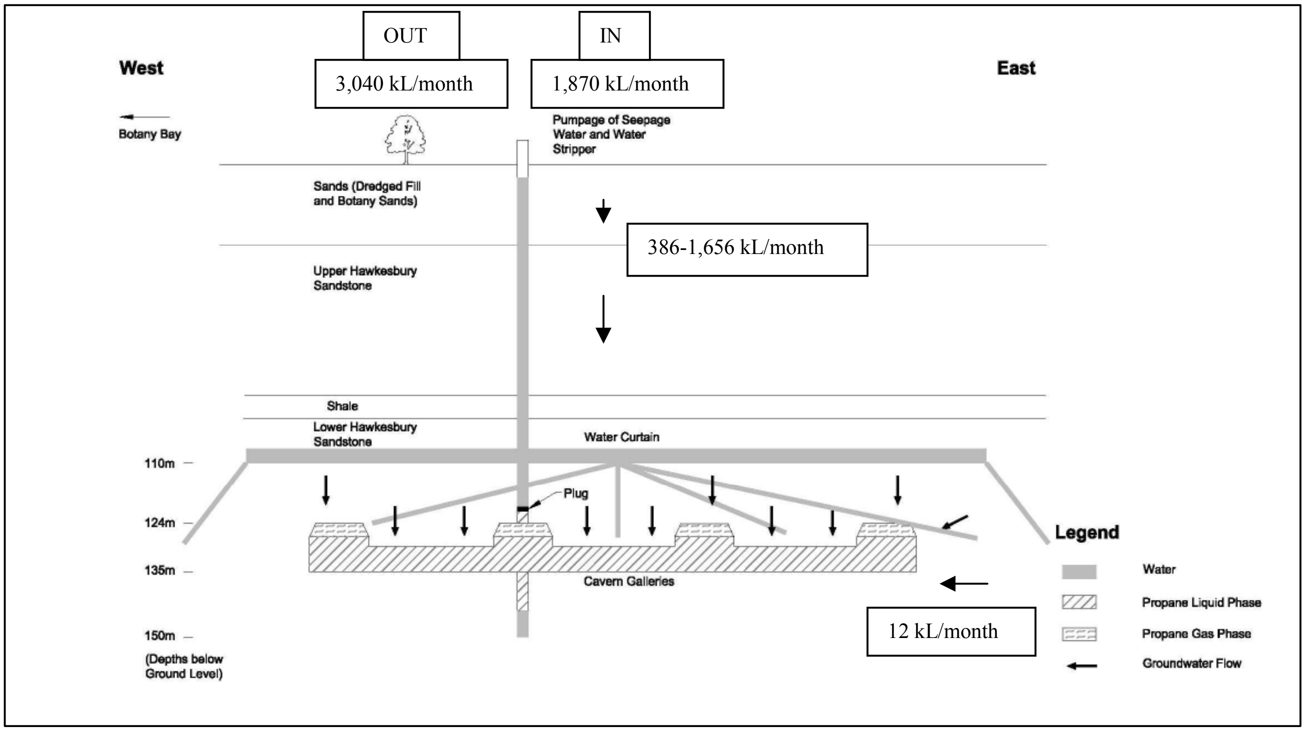
Using equations 4 and 5, and the average estimates for current groundwater inflows and water curtain volumes, the total of these three other sources is estimated to be 1158 kL/month. This estimate can be compared against the following calculated estimate.

Using equation 1, a groundwater volume can be estimated for the three terms as a whole. The hydraulic conductivity (k) is likely to be an order of magnitude lower for vertical groundwater flow, resulting in a value of say 0.0012m/d. The hydraulic gradient (i) is assumed to be 1 (ie. entirely vertical with $\Delta h = 1$). The cross-sectional area (A) is likely to be greater than that of the four ceilings of the cavern (14*230*4) which comprise an area of 12,880 m^2, since the cone of depression is likely to extend somewhat beyond the cavern area. The main area of influence and groundwater capture could be as large as 46,000 m^2 (estimate of the approximate rectangular surface area of the entire cavern).

By inserting these values in equation 1, a groundwater inflow of 386 kL/month is estimated from the Botany Sands, Botany Bay and Upper Hawkesbury Sandstone for the smaller (ceiling only) area. By using the larger water curtain area, a groundwater inflow of 1,656 kL/month is estimated.

The first estimate of 1,158 kL/month is in good agreement with the other calculated water balance estimates of between 386 kL/month and 1,656 kL/month.

Figure 12 Conceptual groundwater model for cavern with water balance estimates



7. Discussion

The salinity of the pumped cavern seepage water has increased from the year 2000 when the LPG cavern started operations, although the most recent trends since December 2004 are decreasing due to high potable water injection rates (see Fig. 2). The historical increasing salinity trend in the cavern seepage to December 2004 is believed to be due to a number of construction and post construction reasons including; sea water intrusion (from Botany Bay), saline intrusion from shallow and sand aquifers, leakage of saline groundwater from the Operation and Access Shafts and cross contamination from the original piezometer network (now eliminated).

Injection of high volumes of water (greater than 2,000 kL/month) has increased water levels in the lower sandstone aquifer, and a decline in salinity has been observed in a down gradient piezometer and cavern seepage (but there is still saline water above which is increasing and will ultimately flow into to the cavern as saline seepage). At the present time increasing volumes of potable water need to be injected to maintain water levels and to maintain the slight rate of decline in salinity levels.

8. Conclusions

Water balance calculations using two different equations indicate that the volume of groundwater flowing into the cavern from the Botany Sands, Botany Bay and Upper

Hawkesbury Sandstone is of the order of 1000 to 1200 kL/month. Using a slightly different approach, similar coarse estimates have been obtained (estimated to be between 386 and 1,656 kL/month). Without a more detailed data analysis and numerical modelling tools to better simulate and estimate contributions from individual saltwater sources, it is difficult to provide more certainty about salinity trends, the individual sources or their relative contributions.

Numerical groundwater modelling could be used to quantify the effects of water injection on hydraulic head and groundwater salinity.

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Regional Hydrostratigraphic Analysis of the Hawkesbury Sandstone

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Abstract

Stratigraphic analysis of the Hawkesbury Sandstone, utilising deep groundwater investigation bores and petroleum exploration wells has enabled a stratigraphic reference for the subdivision of the massive sequence of Triassic sandstones characterised by fluvial deposition. Basin-wide continuity of the sequence within the subsurface and areas of mapped outcrop has been established by geophysical well logging from which lithostratigraphic controls have been identified, principally from gamma ray log signatures. Three informal sub-units of the Hawkesbury Sandstone sequence, Units ‘A’, ‘B’ and ‘C’ provide for a practical assignment of the clastic quartz sandstone and clayey sandstone sub-units to their relevant economic groundwater associations.

Regional cross sections, detailed local stratigraphic correlations and inter-relationships with the bounding sequences reveal a greatly improved understanding of the structural, depositional and stratigraphic controls which focus groundwater recharge and distribution of aquifers having both confined and unconfined characteristics. Resultant stratigraphic resolution has enabled extensive areas of Hawkesbury Sandstone outcrop to be redefined, particularly in the Lower Blue Mountains and Bilpin region, where assignment to the Narrabeen Formation by earlier workers is thought to be incorrect.

Sandstone sequences associated with Units ‘A’ and ‘C’, assigned to the lower and upper parts respectively of the Hawkesbury Sandstone, are characterized by medium to coarse grained sandstones having fair to excellent groundwater potential. Moderate to high-yielding aquifers associated with primary porosity, enhanced by secondary fractures are principally within Unit ‘A’. Unit ‘B’, comprising the middle part of the Hawkesbury Sandstone is dominated by silty to clayey sandstone, siltstone and shale having a disconformable relationship with the underlying Unit ‘A’. The clay-dominated Unit ‘B’ has poor groundwater potential and is recognised as an aquitard in some areas. The sequence was deposited in response to a basin-wide epeiric sea level rise which generated an excellent marker event in the basin.

Keywords: Hawkesbury Sandstone, groundwater, geophysical logs, hydrostratigraphy

Introduction

The Hawkesbury Sandstone is a relatively massive Triassic-aged, dominantly fluviatile sedimentary sequence which extends over a wide area of the Sydney Basin (Fig.1). The sequence is associated with groundwater resources that provide the most productive source of groundwater within the basin, principally associated with porous sandstone sequences, enhanced by fracturing, jointing and faulting. The sandstone is well-recognised as outcrop in the Sydney region, but until recently, was poorly understood on a regional scale. The economic significance of the sequence for its groundwater potential has generated the need to refine understanding of the distribution, variation, and lithological controls to assist in the definition and management of the associated resource. A predictive exploration model has consequently been developed, having a high level of confidence, and success in its application, with the identification of significant groundwater resources.

Studies to gain an improved stratigraphic understanding of the Hawkesbury Sandstone and its relationships with overlying and underlying sequences have been an on-going groundwater resource-based research project by *Hydroilex* since 1997. Since this time, an extensive number of bores (>200) have been investigated by detailed borehole geophysics, resulting in the development of a relatively simple stratigraphic model, principally associated with the definition of three lithostratigraphic sandstone units which comprise the Hawkesbury Sandstone. Prior to this work, the Hawkesbury Sandstone was considered to be a massive undifferentiated sequence of sandstones and siltstones with minor shale, without any recognised vertical stratigraphic resolution. The traditional understanding was based on field outcrop mapping, without significant use of applied geophysical methods and subsurface analysis of borehole data.

Investigations in the central and southern parts of the Sydney Basin have provided the key to developing the stratigraphic model. Complete sequences of the Hawkesbury Sandstone are only recorded in the subsurface, and the recognition of subtle formational variations in clay content, depositional environment and sandstone characteristics has been possible by gamma-ray log signatures. Units ‘A’, ‘B’ and ‘C’ of the Hawkesbury Sandstone have predictive formational porosity and permeability characteristics that are reflected by their associated groundwater yields.

Recent deep borehole data on the Central Coast and Blue Mountains region has been successfully tied-in to regional correlations.

In this summary paper, an outline of the stratigraphic model is provided, accompanied by regional correlations and concepts being developed in the Blue Mountains region.

REGIONAL GEOLOGICAL SETTING

The Hawkesbury Sandstone of the Sydney Basin is an early Middle Triassic (Anisian) alluvial formation which crops out over an area of approximately 20,000 km^2, extending from the Southern Highlands to the Putty area in the north, and to the lower Blue Mountains (Figure 1). The formation crops out extensively along the Sydney coastline, and continues a short distance offshore. The original area of deposition is likely to have been significantly greater. The preserved area of distribution is elongate in form, with the depocentral area being within the Macdonald Trough and Fairfield Basin, close to the central part of Sydney. The provenance of Hawkesbury Sandstone sedimentation was principally from the southwest (Standard, 1964; Jones and Rust, 1983). The sequence ranges in thickness from approximately 160 m in the Mittagong region to approximately 250 m in the Sydney region. In the depocentral part of the basin, the Hawkesbury Sandstone is overlain by the 300 m-thick Anisian to Ladinian shale-dominated Wianamatta Group, principally within the Camden Trough, and underlain by the 800 m-thick lithic and quartzose, Scythian to early Anisian Narrabeen Group. These

Triassic sediments are underlain by up to 2,000 m of Permian sediments comprised of volcanics, clastics and coals. The total sedimentary thickness in the Sydney region is approximately 2,500 m (Kirkham-1, 2,547 m, Woronora-1, 2,278 m), thickening in the offshore region to between 5,000 m and 6,000 m.

The Sydney Basin forms the southern part of an elongate foreland structural trough which extends northwards to the Gunnedah and Bowen Basins along a 1,200 km corridor bounded to the southwest by the Lachlan Fold Belt, and by the New England Fold Belt / Tamworth Arc to the northeast. A passive depositional margin is recognised in the west, with increased depositional thickening along the Hunter Mooki Thrust, bordering the New England Fold Belt.

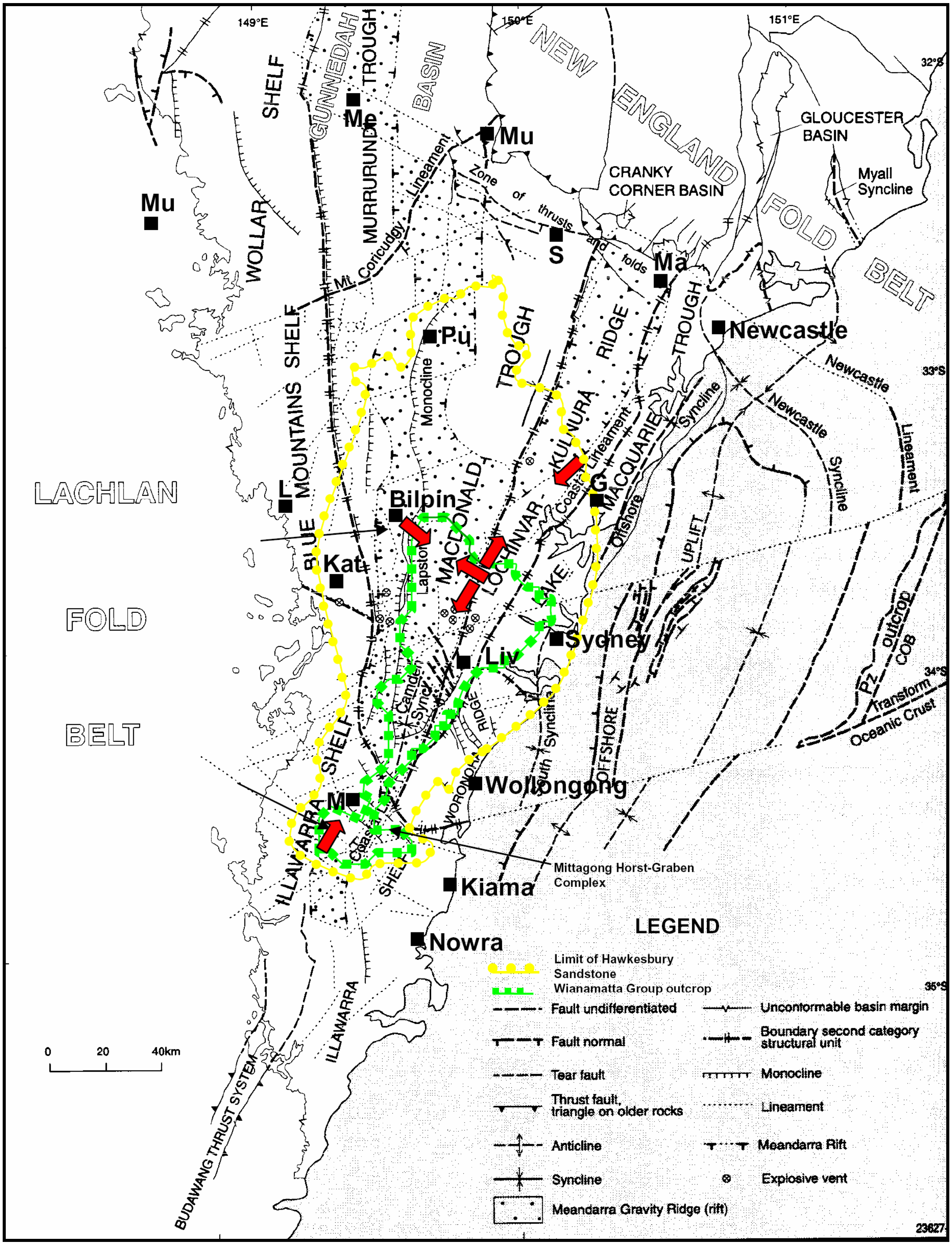

FIGURE 1 Structural map of the Sydney Basin showing the regional distribution of the Hawkesbury Sandstone (modified from Scheiber & Basden (ed) 1996, figure 6.4A)

Quartzose sediments were principally derived from the foreland, and labile sediments from the arc. The eastern margin of the basin has been rifted at the edge of the continental shelf, resulting in the separation of the Lord Howe Rise from the east coast of New South Wales. The traces of transform faults and associated regional structures as recognised mainly in the offshore are shown in Fig. 1. Several thousand metres of probable Jurassic and Cretaceous cover have been removed by erosion, as evidenced from vitrinite reflectance data.

Compared with other basin-margin areas of the Sydney Basin, the subcrop geology of the Southern Highlands district is uniquely characterised by areas of extensive Jurassic and Tertiary basalts, thick preserved sequences of Wianamatta Group shales, and syenitic intrusions of Late Triassic to Early Jurassic age associated with the Mittagong Horst Graben Complex (Lee, 2000).

STRATIGRAPHIC FACIES RELATIONSHIPS OF THE HAWKESBURY SANDSTONE

An informal three-fold stratigraphic subdivision of the Hawkesbury Sandstone (Lee, 2000) has been adopted, based on the recognition of lithofacies differentiation over an extensive region of the Sydney Basin, extending from the Southern Highlands through the central part of the basin to the Central Coast. Units 'A', 'B' and 'C', which range in thickness from 30m to 80m, have both distinctive gamma-ray signatures and lithological characteristics, as depicted in Fig.2. Independent studies of the clay chemistry by Emerson (2000) in Elcom Eveleigh-1 realised a similar stratigraphic variability.

Hawkesbury Sandstone Unit 'A'

The lowermost sequence, Unit 'A' is dominated by medium to coarse quartzose sandstones, generally white in colour, with lesser shales. Massive sandstone bodies attain ten metres in thickness. Sand to shale ratios are typically four to one. Both coarsening upwards and fining upwards clastic cycles are evident, and environments of deposition are considered to be dominantly fluviatile, varying from meandering to braided systems. The distinctive coarsening upward cycles, typical of Unit 'A' are more likely to be associated with distributary bar complexes. The sequence has excellent porosity and permeability, and consequent groundwater potential within the proximal basin margin regions, with deterioration in the more distal basinal regions. A regional aquifer system is associated with the Unit 'A'. Recent discoveries of groundwater supplies exceeding 50 L/sec in the Southern Highlands are all associated with the Unit 'A' sequence, where there is the combined effect of primary and secondary porosity.

Hawkesbury Sandstone Unit 'B'

Unit 'B' is characterised by clayey sandstones, siltstones and shale. The basal contact is usually marked by a sharp transgressive event, which is the most important regional mapable contact identified by geophysical logging. The sequence marks a significant change in depositional environment, associated with a eustatic rise in base level. Eustatic controls on Australian Triassic clastic sequences are well documented (Gorter 1994). The sequence is often characterised by a lower massive upward coarsening cycle, overlain by a fining upwards cycle. The sequence was possibly deposited in a deltaic sedimentary environment. Unit 'B' generally has low porosity and permeability, and has poor groundwater potential. It is considered to be an important regional confining layer that partitions groundwater systems between Unit 'A' and Unit 'C'. In the Kurrajong region, hydraulic head variances of up to 30m have been measured between the two aquifers. Near the basin margins, a higher percentage of coarser clastics is present in the sequence, and its stratigraphic resolution is often less well-defined. In the deeper parts of the basin, Unit 'B' is more shaley (see Liverpool CC bore in Fig.3), and to the west within the Blue Mountains this change in sandstone character has been recognised in outcrop where it has been assigned to the Burralow Formation within the Narrabeen Group. A review of this stratigraphic issue is provided within this paper.

Hawkesbury Sandstone Unit 'C'

Unit 'C' possesses similar characteristics to Unit 'A', dominated by massive clean, medium to coarse sandstones, with minor shale and siltstone. Similar depositional environments are also recognised. Sand bodies attain up to 20 metres thickness. In the Southern Highlands region, the base of the sequence is frequently marked by an upward coarsening cycle, and a blanket sand body which is locally incised into the underlying Unit 'B'. Excellent groundwater potential is recognised within the sequence in the proximal basin margin regions, with a relative decline in more distal regions. Saline groundwaters associated with leakage from the overlying Wianamatta Group (shales) commonly degrade water quality within this aquifer.

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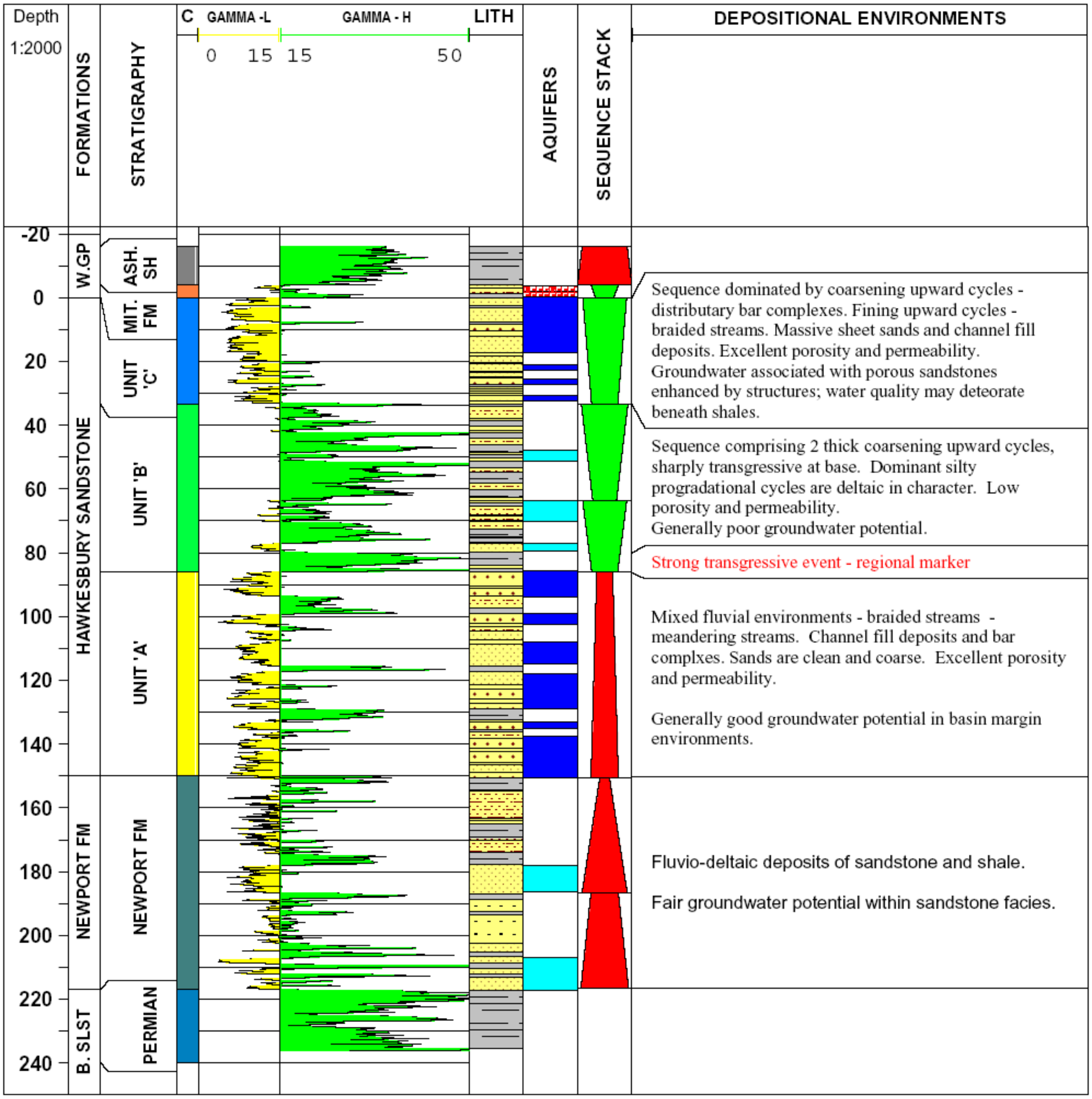

Sequence dominated by coarsening upward cycles - distributary bar complexes. Fining upward cycles - braided streams. Massive sheet sands and channel fill deposits. Excellent porosity and permeability. Groundwater associated with porous sandstones enhanced by structures; water quality may deteorate beneath shales.

Sequence comprising 2 thick coarsening upward cycles, sharply transgressive at base. Dominant silty progradational cycles are deltaic in character. Low porosity and permeability.
Generally poor groundwater potential.

Strong transgressive event - regional marker

Mixed fluvial environments - braided streams - meandering streams. Channel fill deposits and bar complxes. Sands are clean and coarse. Excellent porosity and permeability.

Generally good groundwater potential in basin margin environments.

Fluvio-deltaic deposits of sandstone and shale.

Fair groundwater potential within sandstone facies.

FIGURE 2 Statigraphic and aquifer characteristics of the Hawkesbury Sandstone and Newport Formation
(Note: Relative 'low' and 'high' gamma radiation levels shown in 'yellow' and 'green' shading respectively)

Beneath the Hawkesbury Sandstone, a 20-30m thick sequence of silty shales and interbedded sandstone comprises the Newport Formation. Significant aquifers have been encountered within the sequence to the north of the Mittagong Ranges where higher sand to shale ratios are present. South of the Mittagong Ranges, the Newport Formation is eroded, and the Hawkesbury Sandstone has been deposited directly on Illawarra Coal Measures (ICM) or Berry Siltstone. Fracture-controlled aquifers within the Newport Formation have also been identified in the Sydney region, and in consequence, drilling to test this zone is commonly undertaken when evaluating the Hawkesbury objectives. Groundwater exploration by *Hydroilex* on behalf of Gosford Council within the laterally equivalent Terrigal Formation on the Central Coast has resulted in the development of several new borefields, where combined structural and stratigraphic controls have been exploited, as described by Cook, (2009).

Regional gamma-log correlations of the Hawkesbury Sandstone are illustrated in Figs. 3-4 (refer to section locations in Fig. 1). The correlations, using the base of Unit 'B' as a datum, demonstrate the lateral continuity of the sequences from the Southern Highlands to Bilpin, and Central Coast (Somersby), and variations in thickness afforded by basinal thickening. Significant erosion at the top of the sequence is recognised in some regions, particularly within the main depositional channels, where there is closer well control. Truncation at the top of Unit 'A' by the overlying transgressive shale at the base of Unit 'B' provides the most important regional marker event that is easily recognised in the gamma- log data.

GROUNDWATER OCCURRENCE AND STRATIGRAPHIC CONTROLS

A stratigraphic and structural understanding of the subsurface geology of the southern margin of the Sydney Basin has enabled a better understanding of the hydrogeology of the region. Aquifers having a dominant stratigraphic control are associated with increased porosity and permeability in the upper and lower parts of the Hawkesbury Sandstone. The production potential of these aquifers is enhanced within zones of major fracturing and faulting with resulting yields up to 50 L/sec. Water quality is generally excellent within the sandstone aquifers that are in proximity to the basin margins and recharge areas.

Elevated salinity exists within the Wianamatta Group, and reduced water quality in the underlying Hawkesbury Sandstone is well recognised where natural leakage or mixing occurs within the porous Unit 'C'. The preservation of water quality by the isolation and pressure cementing of the overlying Wianamatta Group is an important bore construction issue throughout the region. Aquifer contamination during bore construction is commonly recognised, with improvement in water quality being experienced after pressure cementing and sufficient time for the aquifer to flush.

Regionally, enhanced water quality and yield, is within Unit 'A', in the lower part of the Hawkesbury Sandstone. However, poor aquifer yields and water quality is evident in most of the central parts of the basin related to either the deterioration in sandstone petrophysical properties or by natural aquifer degradation by salts leaching from the overlying Wianamatta Group. Poor aquifer flushing and discharge induced by a low hydraulic head, together with low porosities in the depocentral regions of the basin, have the effect of 'locking' saline waters within the system.

Elevated levels of iron are common within the Hawkesbury Sandstone, and although the geological relationship remains unclear, the primary associations are clearly of stratigraphic origin, with secondary controls related to both intrusives and structure.

The lower part of the Hawkesbury Sandstone (Unit 'A'), which subcrops as a rim around the margin of the basin, is considered the primary recharge belt (Fig.3). However, at sub-regional scales groundwater flow into the basin is restricted by barriers (eg

Mittagong Horst–Graben Complex), and incised gorges where aquifers provide natural river baseflow. Fracturing, jointing and faulting are accentuated within valley systems and are considered to provide significant zones of enhanced recharge. Within the central parts of the basin, the blanket of Wianamatta Group (see Fig.1) covers an extensive region where there is no recharge.

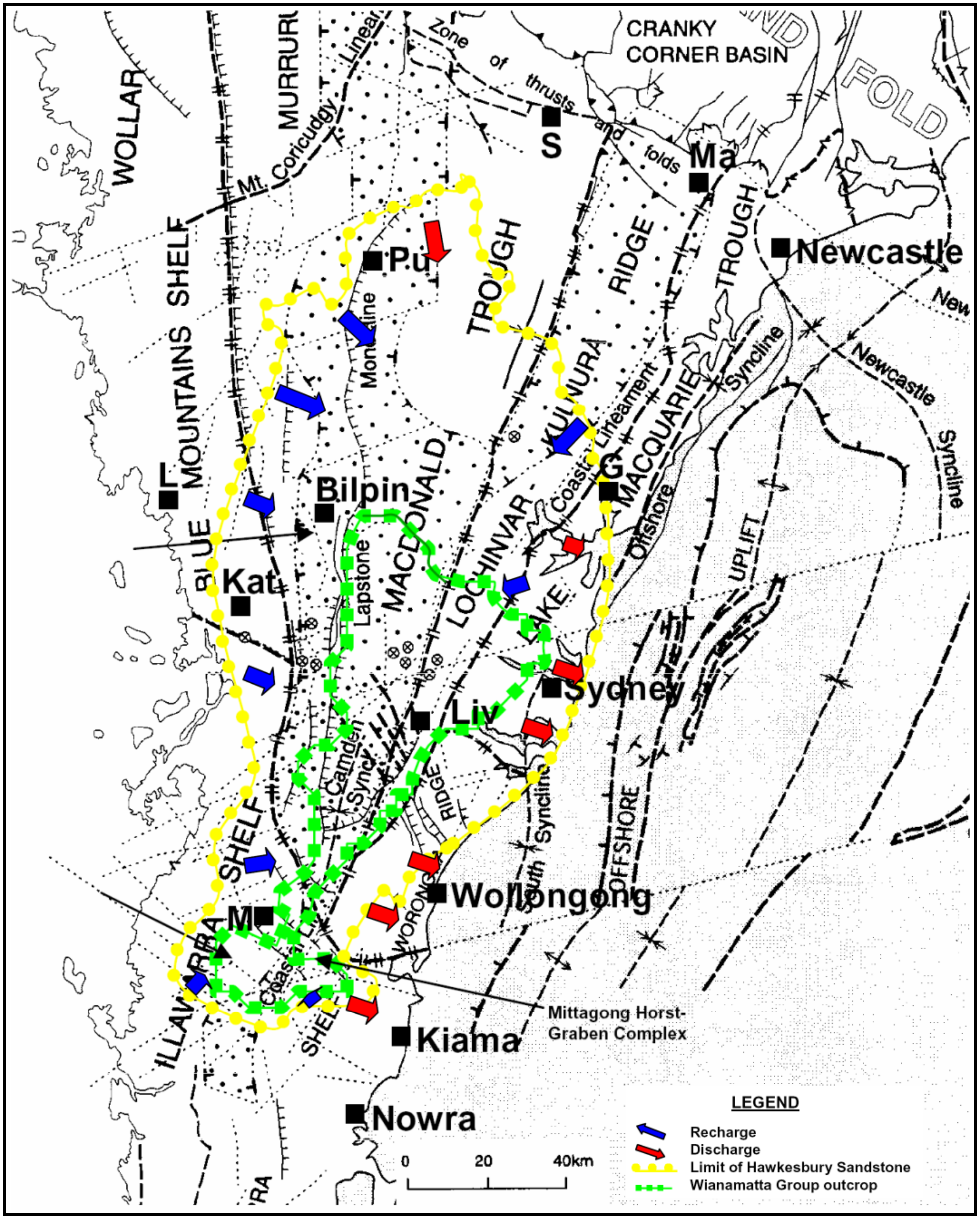

FIGURE 3 Predicted groundwater recharge and discharge trends in the Hawkesbury Sandstone

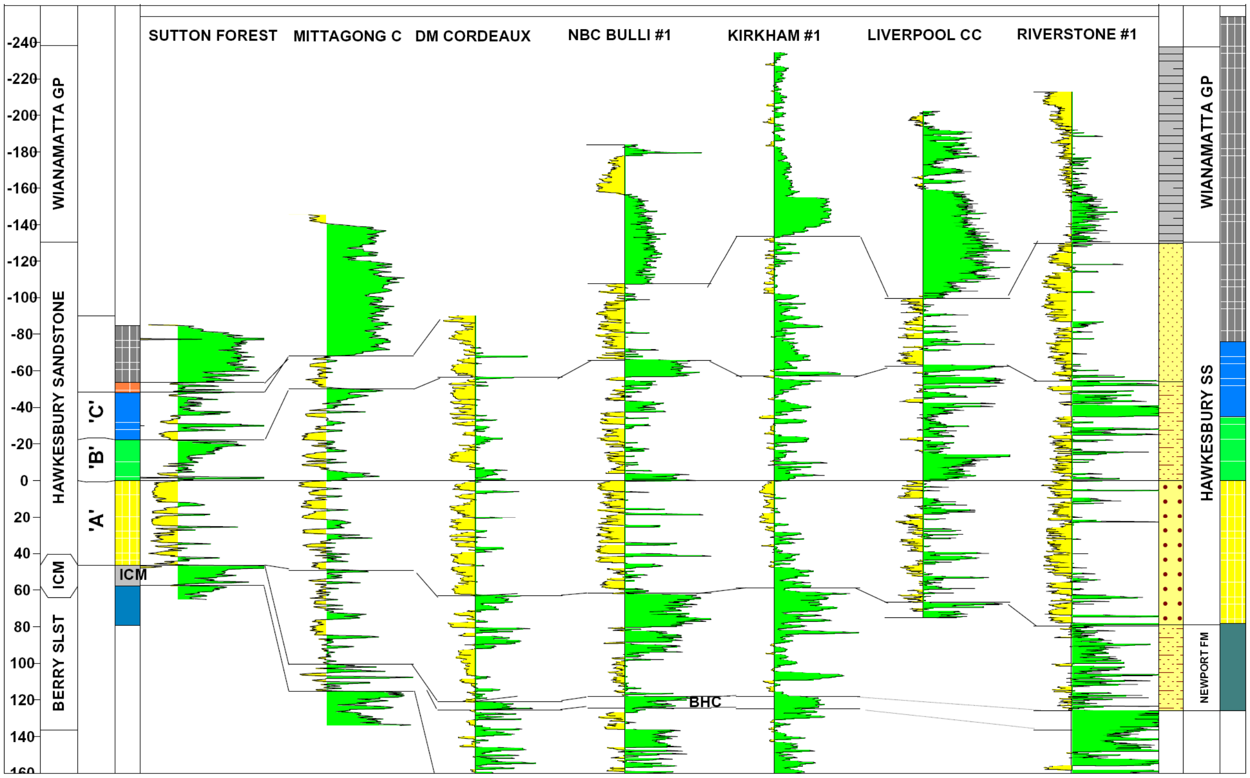

FIGURE 4 Regional correlation Sutton Forest to Riverstone

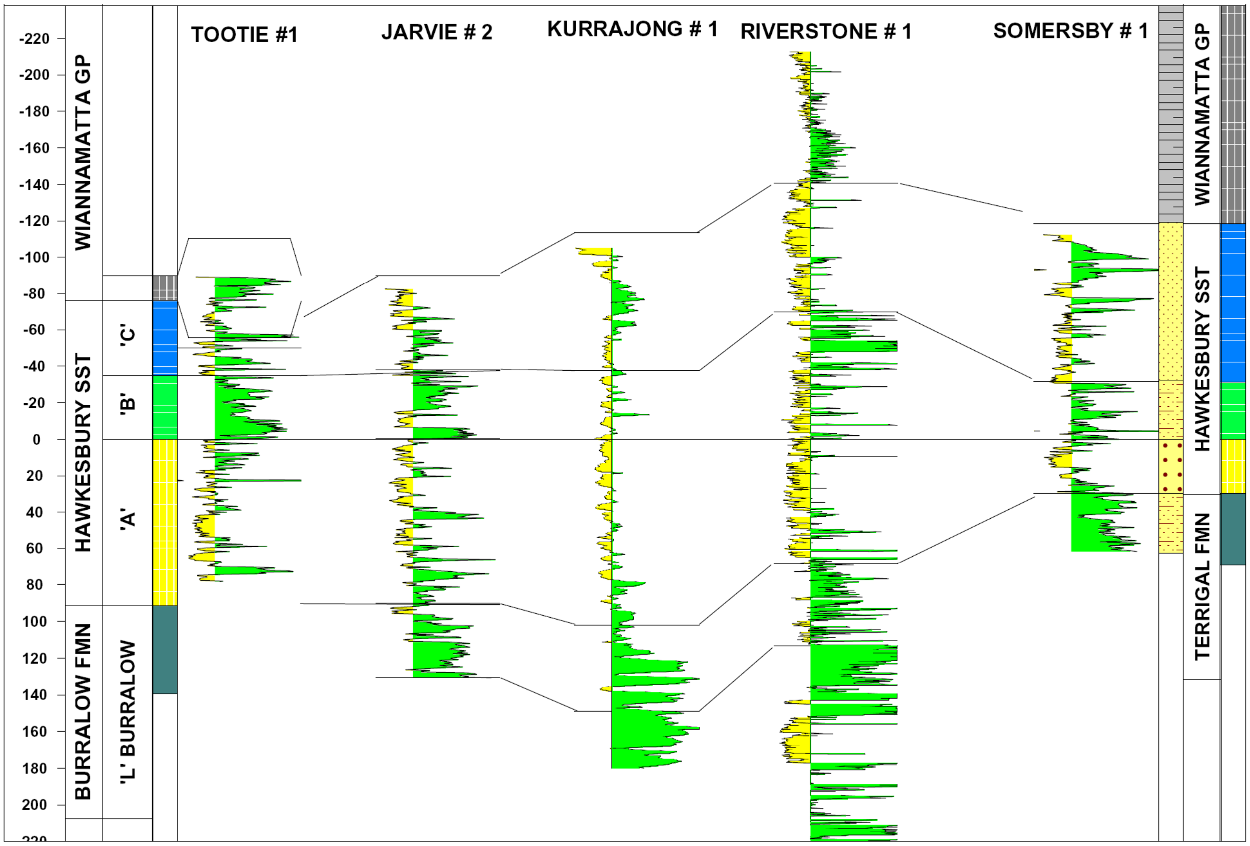

FIGURE 5 Regional correlation Bilpin to Somersby

HAWKESBURY SANDSTONE DISTRIBUTION IN THE BLUE MOUNTAINS

The published geology of the Western Blue Mountains (Goldbery, 1969) follows the work of Standard (1969), who determined that the then-recognised Hawkesbury Sandstone distribution in the region was wrongly assigned, based on outcrop mapping, detailed palaeo-current measurements and lithological studies. In consequence, sandstones having gross characteristics of the Hawkesbury Sandstone were equated to the ‘older’ Narrabeen Group. Significant importance was placed on the occurrence of red-brown shales, which are more common in the Narrabeen Group.

Several important stratigraphic issues have arisen in consequence of the *Hydroilex* revised stratigraphic model of the Hawkesbury Sandstone, leading to a critical review of the established stratigraphic understanding in the Blue Mountains. The following points are noted: (Table 1 provides a summary of the existing and proposed stratigraphic correlatives).

1. In the Sydney region, the three sub-units of the sequence are unclear in outcrop, due to a combination of discontinuous outcrop expression, surficial cover, urbanisation, and limited complete vertical exposures. The lithological similarity between Units ‘A’ and ‘C’ add to mapping difficulty. However, in the sub-surface (Sydney region), detailed geophysical logging has provided an excellent stratigraphic repartition. By contrast, excellent outcrop in the Blue Mountains has led to the field recognition of distinctive lithofacies, which have partly been assigned to the Narrabeen Group (Standard, 1969). Stratigraphic analysis, supported by recent work, questions the formal stratigraphic assignment of several sequences to the Narrabeen Group, supported by other data.
2. The Hawkesbury Sandstone is a transgressive sandstone sequence, which has on-lapped the basin margins. In the Southern Highlands, the sequence transgresses the entire Narrabeen Group and in part rests on basement. In the Blue Mountains the differentiation between the basal Hawkesbury Sandstone and underlying sandstones has been problematic in past mapping.
3. The Unit ‘B’ has a disconformable relationship to the underlying Unit ‘A’, and marks a significant basin-wide event in consequence of a eustatic rise in sea level. It is understandable that the sequence has been assigned as a distinctive formation in the Blue Mountains region.
4. In the Kurrajong Heights region, the Hawkesbury Sandstone attains approximately 200m in thickness. The three sub-units of the sequence are recognisable in geophysical records as shown in Fig.4. In the Mt Tootie region, near Bilpin, approximately 20km further west, the sequence has a similar thickness, based on the reinterpretation. Unit ‘B’ of the sequence has been assigned in published regional mapping to the Burralow Formation, but lithological characteristic and log signatures are typical of the Hawkesbury Sandstone.

5. The Banks Wall Sandstone, as mapped and defined in published data is most likely comprised of 'part' Narrabeen Group and 'part' Hawkesbury Sandstone.
6. In the Katoomba region, a disconformity associated with a very significant change in palaeocurrent directions has been recognised near the Wentworth Falls Claystone which is recognised as a 3-5m thick horizon approximately 80-90m above the base of the Banks Wall Sandstone (and approximately 30m below the top). Below the horizon depositional dips are to the southeast, consistent with trends in the Narrabeen Group, and above the horizon dips are to the northeast, consistent with Hawkesbury Sandstone palaeocurrent directions, as recognised by Goldbery and Holland (1973). The Banks Wall Sandstone was not however subdivided (by Goldbery), except for the isolation of a 'West Burralow Facies'. It is suspected that the sandstones above the disconformity in the Banks Wall Sandstone are equivalent to the basal Hawkesbury (Unit 'A'), and that the Burralow Formation (as defined as a 6-10m thick claystone) is correlable with the basal horizon of Unit 'B' of the Hawkesbury Sandstone. The Wentworth Falls Claystone is likely to represent the top of the Narrabeen Group. The consequence is that most of the sandstones which are mapped as Banks Wall Sandstone in the lower Blue Mountains are likely Hawkesbury Sandstone, dominantly Unit 'A'.
7. It is predicted that the Newport Formation has been transgressed in the area by the Hawkesbury Sandstone, as is the case in the southern part of the basin. Both the Katoomba and Mittagong regions of the basin are located in similar shelfal environments as depicted in Fig.1.
8. It is noted in various maps (Katoomba 1:50k, Penrith 1:100k, Sydney 1:250k) that there is confusion between the silty facies of the Newport Formation, Hawkesbury Unit 'B', and the 'Western Burralow Facies'. The Burralow Formation, which is defined as a prominent claystone marker (in the Lower Blue Mountains region), is more likely the basal marker of the Unit 'B', which is quite distinctive, and mapable throughout the basin. In the Bilpin region, the Burralow Formation has been mapped as a thick sandstone sequence, and more likely represents the entire Unit 'B'. In Kurrajong -1, the stratigraphic assignment is unclear, but it is more likely that that what has been assigned to the Burralow Formation is in fact predominantly Newport Formation, as shown in Fig.5.

The consequences of the above interpretation are:

1. Realisation of approximately 1000 km^2 of additional Hawkesbury Sandstone outcrop in the western part of the basin.
2. Recognition of the existence and distribution of sandstones assigned to the lower part of the sequence which has good porosity and permeability, with excellent recharge potential.
3. An improved stratigraphic understanding of the groundwater controls that will assist in resource management in the Blue Mountains, and a greater understanding of the recharge boundaries west of the Lapstone Monocline.

TABLE 1 Summary of proposed stratigraphic nomenclature of Hawkesbury Sandstone equivalents in the Blue Mountains region

WESTERN BLUE MOUNTAINS	CENTRAL BASIN	SOUTHERN HIGHLANDS WOLLONGONG	STRATIGRAPHIC NOMENCLATURE	COMMENTS
Proposed by Hydroilex	*Published by DPI et al*	*Hydroilex(2000)*		
WIANAMATTA GROUP				Widespread distribution
Unit ‘C’	Hawkesbury Ss	Unit ‘C’	Unit ‘C’	HAWKESBURY SANDSTONE
Unit ‘B’	Burralow Fm	Unit ‘B’	Unit ‘B’	
Unit ‘A’	Upper Banks Wall Ss	Unit ‘A’	Unit ‘A’	
Wentworth Falls Claystone		Newport Formation and Bald Hill Claystone	Basal disconformity	Wentworth Falls Claystone
Lower Banks Wall Sandstone Mt York Claystone Burra-Moko Head Sandstone		Bulgo Sandstone Stanwell Park Claystone Scarborough Sandstone		Lower Banks Wall Sandstone Mt York Claystone Burra-Moko Head Sandstone

CONCLUSIONS

Systematic geophysical studies of groundwater investigation and production bores over a wide area of the Sydney Basin have been successful in developing a stratigraphic framework for the three-fold subdivision of the Hawkesbury Sandstone. Geophysical data from groundwater, stratigraphic and petroleum wells have been utilised to define lithostratigraphic Units ‘A’, ‘B’ and ‘C’. The identification of these regionally mapable sequences by gamma-ray methodology have facilitated:

- The recognition of the association of groundwater resources principally within Units ‘A’ and ‘C’.
- Regional and local correlation control for prognostic targeting of groundwater investigation bores.
- Improved management of aquifer systems, including the testing, certification and mapping of the resource.
- Stratigraphic mapping for the improved understanding of hydrostratigraphic controls as exemplified in the Blue Mountains.
- A framework for petrophysical, water chemistry and structural databases.
- The need to formalise stratigraphic nomenclature for the informally-defined ‘units’described in this paper.

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Surface and ground water connectivity and the impact on water quality in the Goulburn River, New South Wales

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Abstract

Stream and rainfall data the period after 1950 was characterized by above average rainfall and run-off and since 2000 there has been a decline in the Goulburn catchment yield. It is possible that increased surface and ground abstraction and increased actual evaporation have caused a decline in catchment yield, coupled with El Nino droughts. The decline in yield and hence stream height may have also increased the movement of saline ground waters into the surface waters in the lower Goulburn catchment. Groundwater discharges and geology were found to strongly influence surface water chemistry and potentially flow, especially during droughts. Policies that are developed for security and protection of water supplies within catchments, such as the Goulburn River must recognize the temporal and spatial connectivity between the hydrological and elemental cycles.

Keywords: soil moisture, abstraction, water quality, discharge

1. Introduction

World-wide it is recognised, or in some cases becoming apparent, that sustainable use of ground and surface waters must be regarded as a part of the hydrological cycle and managed as an interconnected system. Temporal climatic variations can significantly alter the hydrological cycle and it has become evident in Western and South-Eastern Australia that catchment yields have unexpectedly declined since the late 1970's (Timbal and Jones 2008). The interactions of the ground and surface waters would have also changed since the 1970's but the lack of long term surface and ground water quality and water height records prevents any serious assessment in the Hunter Valley. Recent work in the Murray-Darling Basin has shown that there is a strong climatic influence on the shallow fractured-rock groundwater systems (Rancic *et al.* 2009). Essentially increased rainfall 1940's has caused increased recharge in many groundwater systems and changed catchment salinity dynamics. The aim of this study is to draw together existing datasets that are available within the Goulburn River catchment of the Hunter Valley and investigate surface and ground water interactions and how these interactions may have changed through time.

2. Study Region

The catchment area of the Goulburn River is ~6000 km^2 and stream flow from the Goulburn represents approximately 23% of total flow in the Hunter Valley system

(DWE, 2008). During 2003-2005 there was only one operational mine in the catchment compared with 22 open cut and underground operational mines in the Hunter River catchment. Earlier studies have found that there are a number of ground water provinces, in the Hunter Catchment ranging from fresh surface (<800 uS/cm) to saline aquifers (>10,000 uS/cm) and that these saline groundwaters are hosted in aquifers in the Permian Coal deposits (AGC 1984; Creelman 1994; Creelman *et al.* 1995; Griffin 1960; Harrison and Conaghan 1948; Kellett *et al.* 1989).

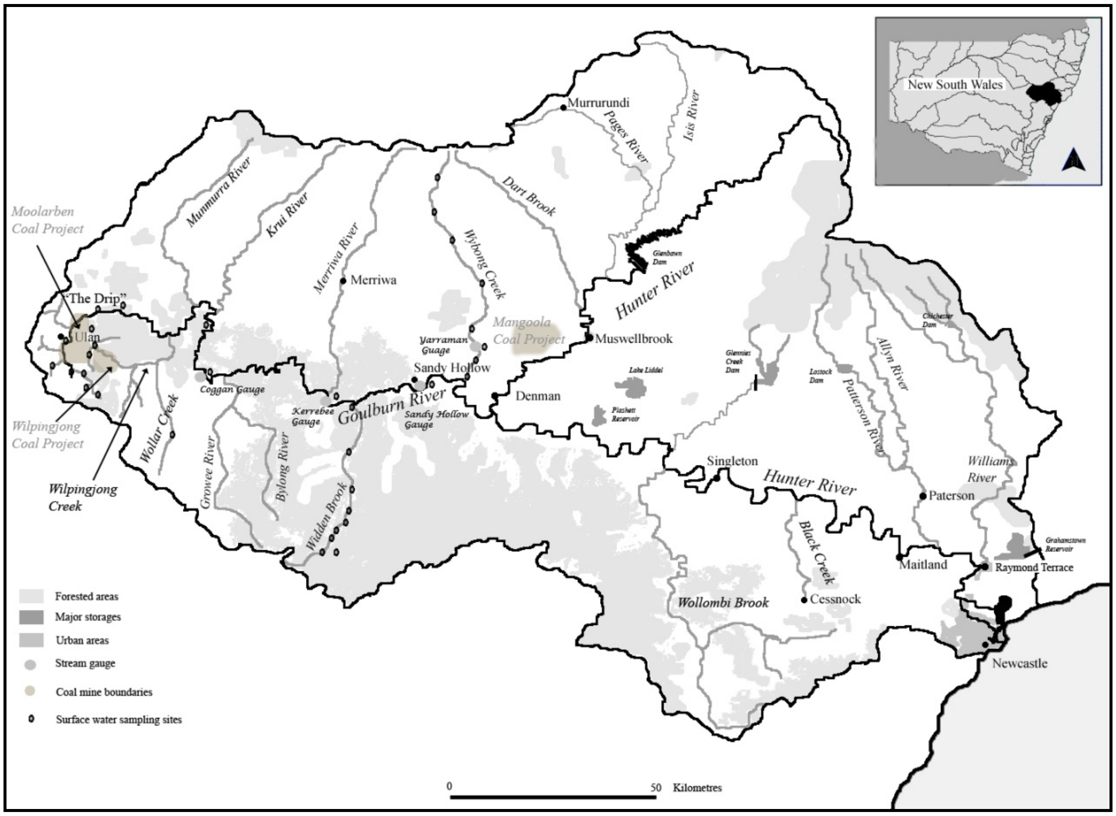

Figure 1. Sampling locations within the Goulburn River Catchment.

3. Methods

3.1 Goulburn Water and Salt Balance

Climate Data

Climatic data was sourced from the Australian Bureau of Meteorology for Stations Scone (66089), Wollar (62032) and Denman (61016). Residual mass curves were used to indicate long-term trends in rainfall and stream flow.

Hydrological Budget

A simple hydrological budget was constructed for the Goulburn catchment and the ground water recharge was calculated using the following equation.

$$G_m = P_m - R_m - ET_m \qquad (1)$$

where G_m = ground water (mm), P_m = precipitation, R_m = runoff (Q_m/catchment area) and ET_m = evapo-transpiration. ET_m was calculated by pan evaporation collected at Scone using a conversion factor 0.69 (Chiew *et al.* 1995)

River flow and Electrical Conductivity

The stream gauge records at Yarraman (210040) in Wybong Creek and at Coggan (210006), Kerrabee (210016) and Sandy Hollow (210031), which are located on the main Goulburn channel have been analysed (Figure 1). The data was extracted from Pineena v9.2 data DVD (Department of Water and Energy 2008) on a daily time step. All calculations and statistical analyses were performed using R statistical software. The Goulburn River catchment is defined in this paper as the area up to the Sandy Hollow and Wybong Gauges.

Goulburn River Surface and Ground Water Chemistry

Surface and ground water chemistry for the Goulburn River was sourced from the technical reports within the environmental impact statements for the Wilpinjong Coal Project (Wilpinjong Coal Project Pty Ltd 2006a & b) the Moolarben Coal Project (Dundon & Associates Pty Ltd 2006; Patterson Britton & Partners Pty Ltd 2006) and the Mangoola Coal Project formerly the Anvil Hill Coal Project (Mackie Environmental Research 2006).Additional surface waters were sampled from the Goulburn River, and two of its tributaries, Widden Brook and Wybong Creek, from the upstream to the downstream sites. The surface and groundwaters were collected at depth of 0.6 of the stream height and at the centre of the channel. Samples were filtered using 0.45µm Micro-pore filter, decanted into sterile vials, sealed tightly and placed in a cold box. Samples with charge balance error greater than 5% were rejected from the analysis.

4. Results and Discussion

4.1 Goulburn Water and Salt Balance

The long term flow records (Figure 2) suggest that prior to 1950 river flow was less than the period after 1950. This long term trend is evident in the rainfall records for Denman and Wollar and these periods that have larger flows and rainfalls (Figure 2), have been labelled as flood-dominated regimes by Erskine (1988) and result in increased erosion, channel change (Erskine and Bell 1982) and ground water recharge. The alternations between flood- and drought-dominated regimes are probably associated with El Nino Southern Oscillation and Inter-decadal Pacific Oscillation events. These trends have also been observed in the Murray-Darling Basin (Rancic *et al.* 2009) and increased groundwater recharge and saline ground water discharge has also probably increased after the 1940's in the Goulburn River catchment.

The unique period in the flow record occurs during the period 2003-2007 where the flow is below 10 ML/day for an extended period (Figure 2). This result is surprising because the rainfall characteristics are not unusual in regards to the long term average (Figure 3). In fact, the residual mass plots show that rainfall was below average during 2003-2006 but stream flow in the Goulburn catchment declined more sharply than previously in the record. This trend is evident in other Australian catchments (Timbal and

Jones 2008). The flow trend between 2000 and 2007 suggests that water abstraction from the alluvial aquifer, significant declines in soil moisture or greater than estimated evapotranspiration may be affecting flow in the Goulburn catchment.

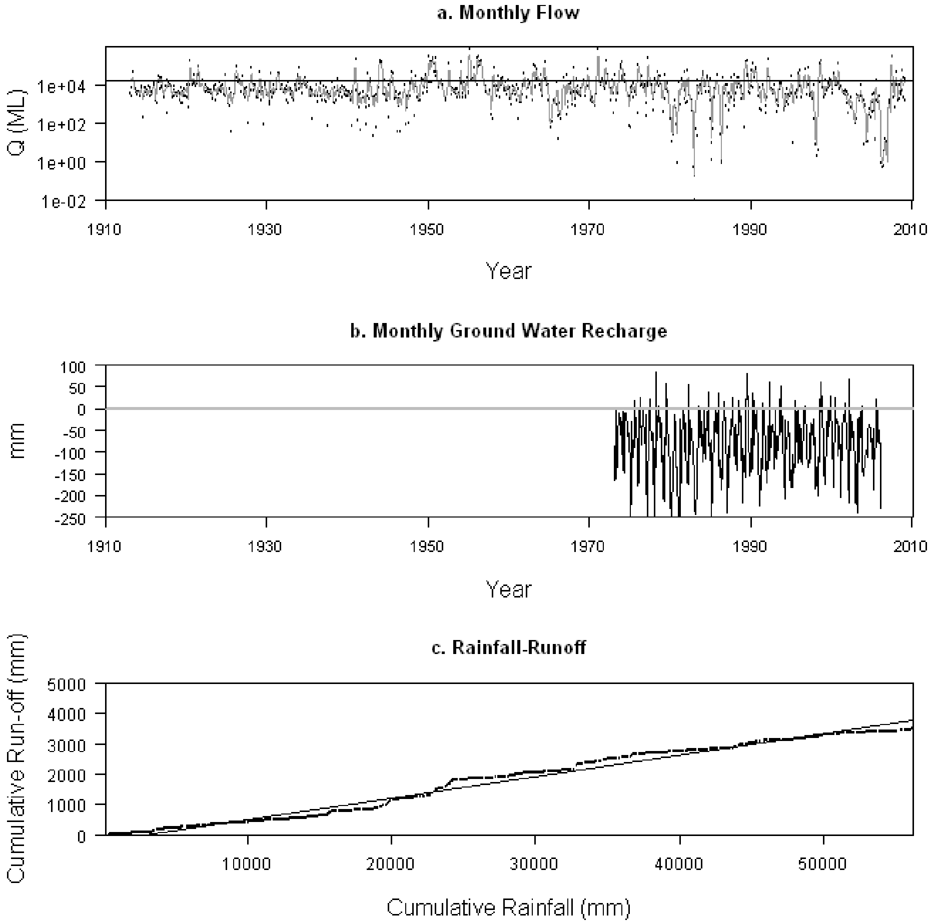

Figure 2. a. Monthly flow in ML (black points), 3 point average (grey line) and record average (solid black line) for the Goulburn River. b. Monthly ground water component of the water balance for the Goulburn Catchment. c. Cumulative run-off vs cumulative rain fall. Gradient of regression line is 7%.

The ground water component of the hydrological cycle follows an inter-annual cycle where recharge occurs in the winter months and deficits occur in the summer months (Figure 2b). It is evident that after December 2004 there was there was reduced ground water recharge in the Goulburn Catchment until the flood in June 2007. However during December 1994-1996 similar deficits occurred and whilst surface flow declined during this period it did not cease. It is likely that soil moisture deficits coupled with surface and ground water abstractions have caused reductions in catchment yields and potentially contributed to increased saline ground water discharges in the lower Goulburn catchment since 2000.

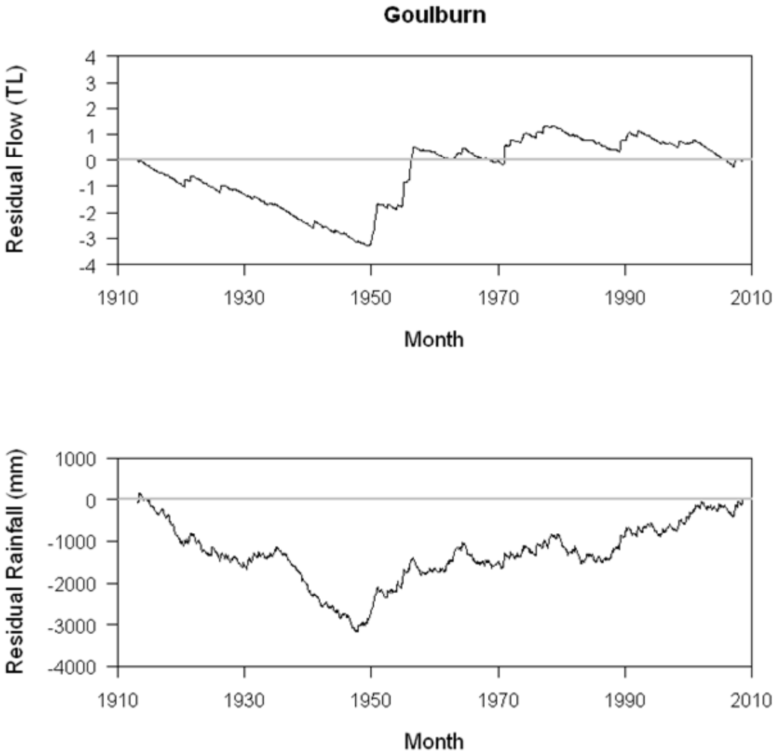

Figure 3 Residual mass plots for month flow (Goulburn River) and monthly rainfall (Denman).

The long-term average flux (1913-2009) of salt from the Wybong Catchment is 3.5 Mg/km^2/yr and the Goulburn River Catchment 1.6 Mg/km^2/yr. But during the higher rainfall period between 1990-2000 the flux of salt from the from the Wybong Catchment was 4.1 Mg/km^2/yr and the Goulburn River Catchment 1.7 Mg/km^2/yr. These fluxes decline during the drought period of 2000-2009; 2.5 Mg/km^2/yr from the Wybong and 0.9 Mg/km^2/yr from the Goulburn River Catchment. The salt load in the Goulburn River declines between Kerrabee and Sandy Hollow gauging stations. These stations are only 23 km apart and the main inputs of fresh water are from the Triassic Sandstone Aquifers that flank the southern side of the catchment.

4.2 Surface and Groundwater Chemistry

The Goulburn River appears to be strongly influenced by the regional geology and the ground waters which are hosted in the coal and inter-burden aquifers (Figure 4). In the upper catchment and the lower catchment the chloride dominates the surface and the ground waters suggests a close interaction between the two systems (Figure 4). In the middle catchment downstream of “The Drip” (a natural spring that feeds into the Goulburn) it is possible that water hosted in the Narrabeen Group Sandstones geological unit discharges to the Goulburn River, thus reducing the salt load and changing the stream geochemistry. This recharge is also reflected in the sustained flows in this part of the catchment (Coggan Gauge) over the period of record. Basaltic and granitic weathering in the Liverpool Ranges (upper Wybong catchment and Goulburn headwaters) supplies Ca and Mg ions to the surface waters. Conversely the stream chemistry in the lower portion (<200m) of the Goulburn and Wybong Catchments is characterised by chloride which is probably sourced from the Permian geological units (Figures 4). This inference is supported by the strontium isotopic ratio of the ground and surface waters in the lower Goulburn catchment (Figure 5). The input of freshwater from streams such as the Widden Brook coupled with potential transmission losses of the more saline Goulburn River water into the alluvial sand aquifers beneath the river bed may explain the change in saltload between the Kerrebee and Sandy Hollow stream gauges.

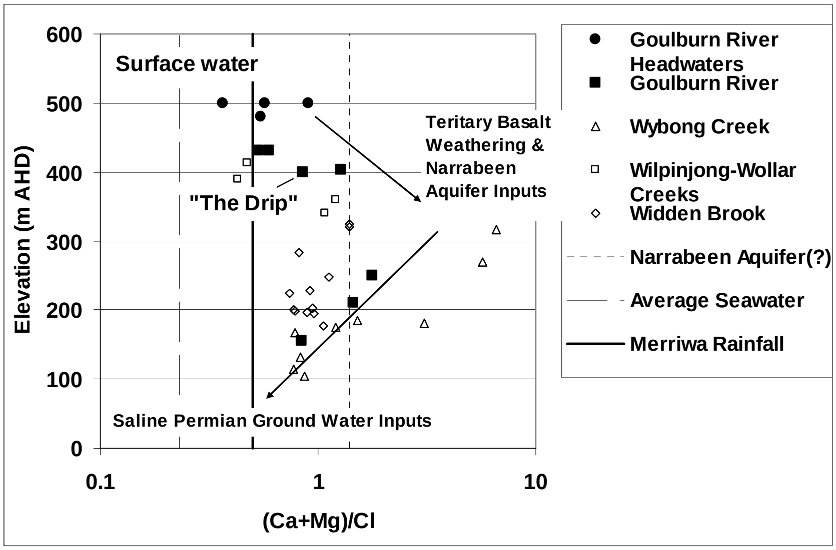

Figure 4. The relationship between divalent cation:chloride ratio and elevation for the surface waters in the Goulburn River catchment..

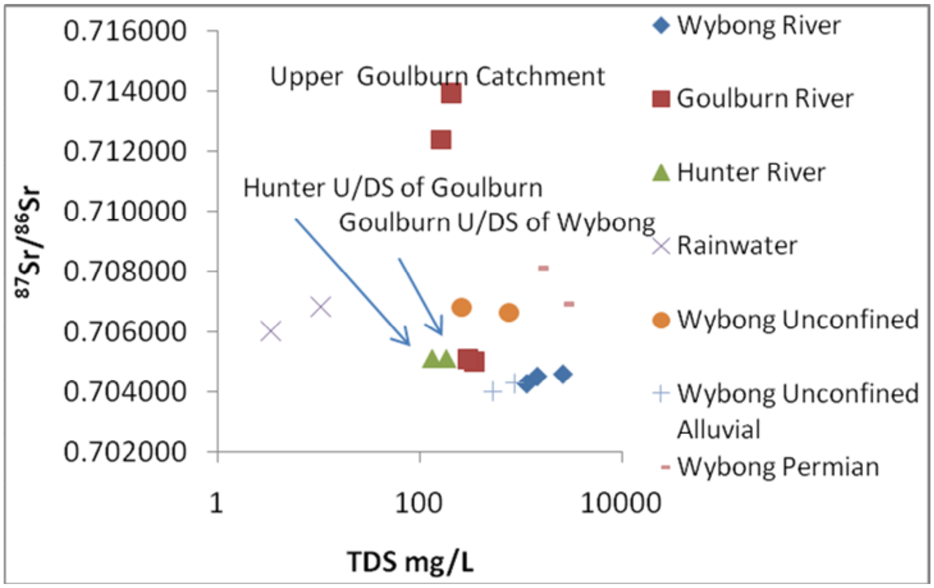

Figure 5. Strontium isotope relationship between the surface waters and ground waters in the Goulburn and Hunter River catchments.

5. Conclusions

The quantity and quality of the surface waters in the Goulburn River catchment are controlled primarily by antecedent rainfall conditions. But it is evident from this study that the groundwater and geology strongly influence surface water chemistry and flow. Policy and management of the region should protect freshwater aquifer systems that are hosted in the Triassic Sandstones and Tertiary volcanics to maintain water quality during seasonal and decadal droughts. Since 1950 the Goulburn River catchment has experienced increased rainfall and stream flow. These flows have altered the surface and ground water interactions, and possibly increased saline discharges due to an increase in recharge. Climatic dynamic appears to be a key driver of salinity and increasing water tables in the Murray-Darling Basin. Increased river and dryland salinity in the Goulburn Catchment could be caused by increased rainfall since the 1950's. Since 2000 catchment yield of the Goulburn River has declined, below the long-term average, which is a similar scenario in many other catchments of South-Eastern Australia. This is a confronting issue for water policy, licensing and management, because previous decisions and research directions have been based on hydrological conditions that prevailed during the wet conditions of the 1950s.

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Surface and groundwater interactions and salinity dynamics in the Wollombi Brook, Hunter River Catchment

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Abstract

Salinity in the Hunter catchment is a major concern. It appears to be sourced from salts associated with Permian strata as well as weathering of regolith derived from Permian rocks. In this work hydro-geochemical analysis of stream and groundwater components in the Wollombi Brook subcatchment are used to investigate surface-groundwater interactions. Relationships between stream salinity and discharge were investigated and a hydro-geochemical survey of the Wollombi Brook was undertaken between 2005-2008. Major ion, strontium, oxygen and hydrogen isotope data collected during this survey were analysed to build a conceptual model for groundwater interactions in the catchment. This study aimed specifically to examine the interactions between the floodplain aquifer and other surface and groundwater components. The floodplain aquifer may act as a buffer between the deeper saline waters associated with the Permian strata and the surface waters of the Wollombi Brook.

Keywords: Sr isotopes, salinity pool riffle, floodplain dynamics

Introduction

Salinisation of groundwater, surface water and soil resources is a pressing issue in many Australian catchments. Location of the initial sources and sinks of solutes, solute transport mechanisms and different landscape responses to hydrologic perturbations influence the level of salinisation in a particular location (Peck and Hatton, 2003). Factors affecting landscape salinity distribution and dynamics include: underlying geology; climate variations; partitioning of rainfall and runoff within catchments; groundwater-surface water interactions; groundwater aquifer interactions; and human impacts. The Hunter River, a New South Wales coastal catchment has significant salinity problems arising from surface groundwater interactions (Kellett *et al.,* 1989). In this paper we explore surface groundwater interactions and salinity dynamics using strontium isotopes and geochemistry in the Wollombi Brook subcatchment of the Hunter River.

Site Description

The Wollombi Brook is the major southern tributary of the Hunter River catchment, covering an area of ~1700 km^2 (Fig 1) and can be considered an analogue to other sand bed streams within the catchment (Erskine, 1996). Fresh water is contained in an unconfined alluvial aquifer and the stream. In the mid-lower catchment below the Broke town-ship, the Wollombi Brook traverses Permian geologies associated with saline soils and groundwaters throughout the Upper Hunter catchment. This part of the Wollombi Brook catchment has open cut and long wall mining operations. The catchment of the north arm, upstream of Millfield, also drains the Permian Maitland Group and the Greta Coal Measures.

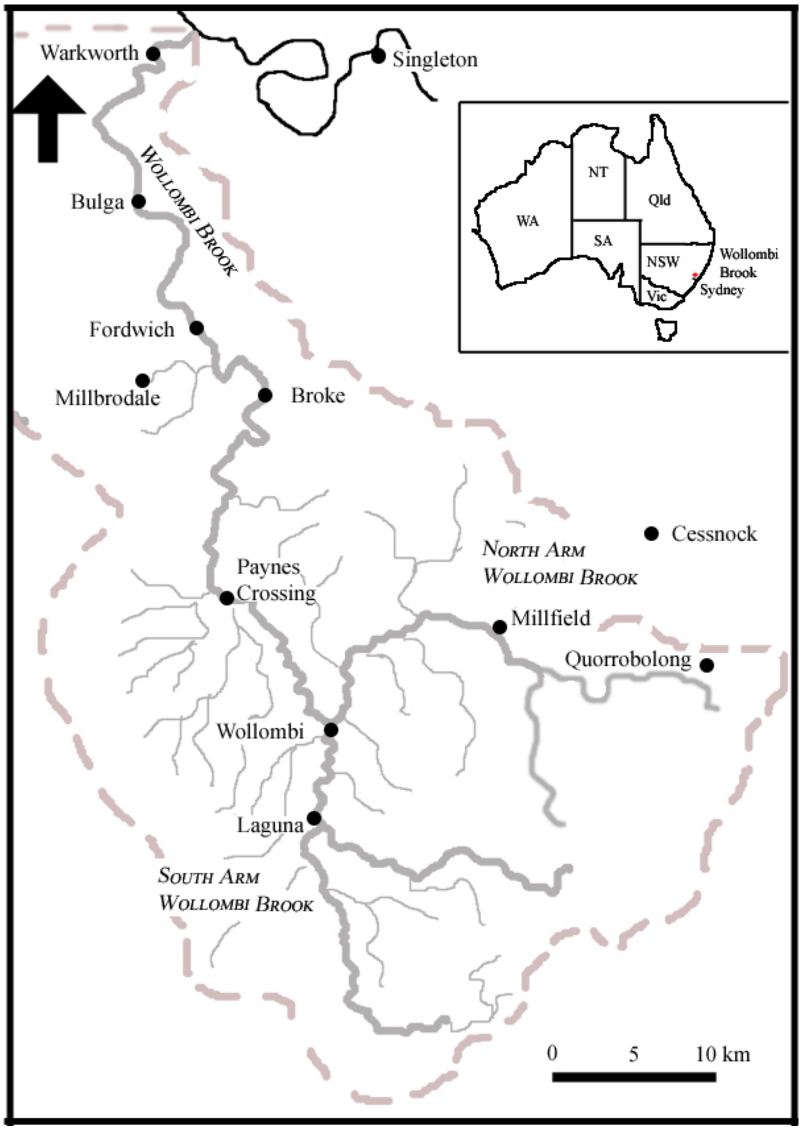


Figure 1 The Wollombi Brook.

This region has been previously extensively mined and a new underground long wall operation at Cessnock-Quorrobolong began in 2006. The south and the head waters of the northern arm of the Wollombi Brook drain Triassic Narrabeen Group sandstones. The impacts that coal mining together with the traditional mixed agriculture in the catchment may have on stream salinity is a major concern. Current salinity dynamics in the Wollombi Brook are therefore of considerable importance in managing the catchment.

Geological Setting

In the Wollombi Brook catchment, high elevation areas are the result stripping of the overlying Triassic age sandstones by the Wollombi Brook which has produced the classic Sydney Basin sandstone escarpments and cliffs in the southern parts of the catchment.. Lower relief landforms occur north and east of this escarpment, dominated by Permian sediments intruded by Tertiary age alkali basalt/ dolerite. Quaternary floodplain deposits infill valleys and the floodplain is broadest between Broke and Bulga. Extensive sand deposits occur in the Wollombi Brook channel, creating a pool and riffle system which shapes the hydrologic and hydro-geochemical regime in the mid-lower reaches of the Brook. The Permian sediments consist of inter-bedded shales, sandstone, coals and tuffs, reflecting continental and marine deposition phases. Two coal bearing units of the Permian rocks are important for contributing salinity to the landscape, the Whittingham measures and the Wollombi Measures. The Wollombi measures occur close to the ground surface throughout the mid catchment. The Whittingham measures, in particular the Jerry's plain sub group lies close to the ground surface throughout the lower catchment. The Whittingham Coal measures were deposited over marine sediments of the Maitland group in a fluvio-deltaic environment. Marine transgression interrupted sedimentary coal formation which later recommenced to form the Jerry's Plain subgroup. This subgroup was terminated by a second transgression which produced the Denman formation (Golab *et al*., 2006). The Wollombi Coal measures were deposited after the Whittingham Coal measures, towards the very end of the Permian. They are considered to have been deposited in a fluvial and upper deltaic system (Kramer *et al*., 2001) and to have not subsequently, been inundated with sea water (Kellett *et al*., 1989).

Stream morphology

The Wollombi Brook is a sand bed stream with high transmission losses of water. The Brook can be thought of as intermittent in that dislocation of the main channel occurs in most years. Pools become isolated from the main channel and stream discharge is highly responsive to rainfall events. It is likely that these pools and the water in the channel itself remain connected via groundwater in a shallow alluvial aquifer during these periods. At the top of the catchment, the stream is more tortuous, incising steep slopes of the Triassic sandstone. In the Mid-lower catchment, topographic gradients are less and the stream is bounded by a horizontally extensive floodplain, surrounded by the Wollombi Coal Measures. In the lower catchment, this floodplain shrinks in again as the Brook meanders through undulating rises in the Whittingham Coal Measures to its confluence with the Hunter River. The floodplain depth is up to ~15m at Warkworth and Fordwich (DNR bore log, 2000).

METHODOLOGY

Stream gauging

Time series records of discharge, Q, (ML/day) and EC (uS/cm) were obtained for the period 1990 to 2005 and analysed for Bulga and Warkworth stream gauges (Fig 1). The Bulga gauge is located in the mid-catchment, within the Wollombi Coal Measures; the Warkworth gauge is located within the Whittingham Coal Measures ~ 2km upstream from the confluence with the Hunter River. These gauges are both positioned along sections of the stream where groundwater and through-flow solute composition is affected by Permian sediments or regolith derived from Permian sediments. The data sets had significant gaps with 28% of EC data was missing for Warkworth 41% of EC data was missing for Bulga gauge. No data recorded for Bulga during the period October 1987 to March 2000. There were large periods in both data sets where zero flow or flows of 0.01 were recorded. These typically coincided with years of below average rainfall and were therefore retained in the data sets. At Bulga, there were no gaps in the EC data set between 2000 and 2005. The bulk of missing data occurring during the period 1995-2000, coinciding with missing stream discharge values, so analysis was restricted to the period 2000-2005. Gauged stream flow measurements were supplemented by instantaneous flow measurements between 1977-1989 by Department of Water and Energy staff and during field missions in 2008 using an Ott C2 Flow meter.

Data Analysis

Stream salinity was analysed using Q and EC data sets gauged at Warkworth and Bulga. The relation between stream salinity and discharge was investigated using EC and the discharge hydrograph for the Warkworth and Bulga gauging sites for years which had close to complete salinity and discharge records. In addition, rainfall was compared with EC at the upstream gauge, Bulga, was compared with EC at the downstream gauge, Warkworth.

Geochemical Analysis

Samples for cations and anions analysis were collected and filtered in the field. These samples and the historic samples were later analysed at the DWE Sydney laboratories. Ground water samples were collected after the bores were purged and the EC, pH and temperature of the water had stabilised. Alkalinity of the samples was measured by titration in the field. To investigate ground and surface water interactions water samples collected in 2008 were analysed for $^{87}Sr/^{86}Sr$.

Results and Discussion

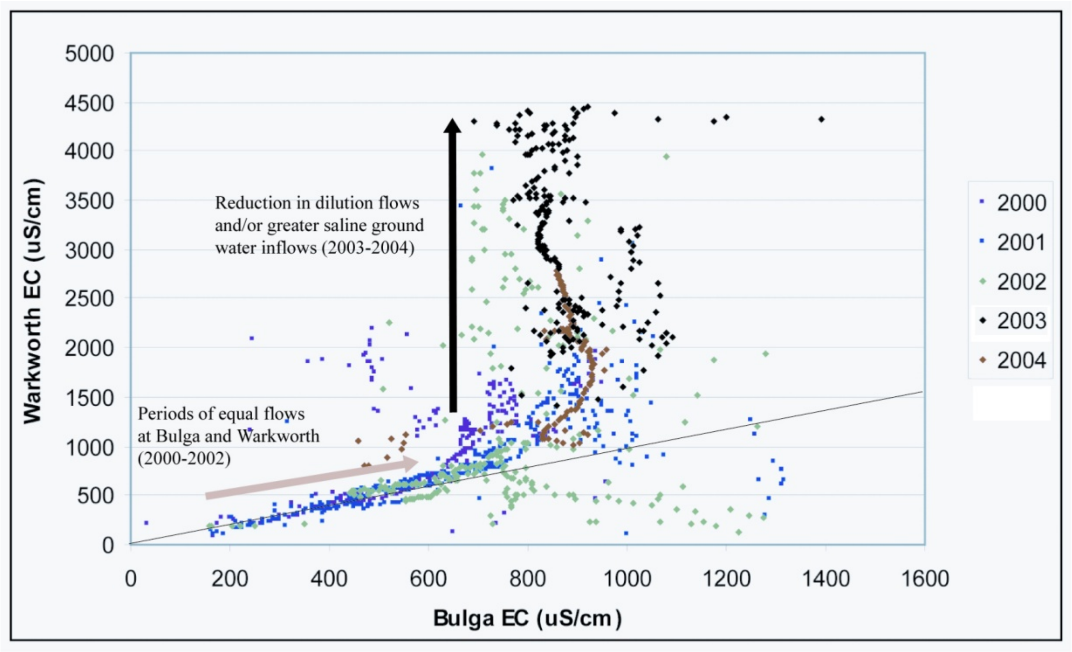
4.1 Stream discharge and salt loads

In comparisons of both stream EC and discharge between Bulga and Warkworth, dual trends were identified which corresponded to high and low stream flows (Fig. 2). During periods of low discharge, EC at Warkworth varied significantly relative to EC at Bulga and was generally higher than the 1:1 line. In addition, during these low discharge periods, flow at Warkworth varied widely and was greater relative to flow at Bulga. These trends indicate an increased input of both solutes and water to the system during low stream flows between Bulga and Warkworth that is different from that above Bulga.

This is reflected in the TDS and flow relationship at the Bulga and Warkworth Gauges and stream bicarbonate load (Fig. 3). Figure 3 shows that between the December run-of-river gauging there was a transmission loss from the stream between Broke and Fordwich. This indicates that the alluvial unconfined aquifer was gaining water between the two gauging stations

4.2 Saline water sources

There are two thrust faults above the Warkworth stream gauge (Majchrzak-Hamilton and McLaren, 1993) which may cause hydraulic conductivity discontinuity and conduits via fault and fracture flow which allow groundwater discharge from the Permian sediments to the stream. During 2006-2008 ground water height in the monitoring bores was greater than the stream height, except flood that occurred on June 6-10 2007. No major fault structures proximal to the stream have yet been identified upstream of Bulga. In addition, between Bulga and Warkworth, the stream enters the Whittingham coal measures. The floodplain contracts and thus there is potential for more direct exchange of groundwater hosted in and the Permian strata and the stream between Bulga and Warkworth. The Whittingham Coal Measures are also reported to, on average, have a higher hydraulic conductivity than the Wollombi Coal Measures, potentially facilitating greater groundwater discharge to the stream along this reach. This is reflected in addition salt inputs to the lower reach of the Wollombi Brook (Fig. 2 and 3).



Reduction in dilution flows and/or greater saline ground water inflows (2003-2004)

Periods of equal flows at Bulga and Warkworth (2000-2002)

Figure 2 EC (uS/cm) Warkworth vs EC (uS/cm) Bulga for 2000-2004. Lines indicate 1:1 relationship between EC at Bulga and Warkworth.

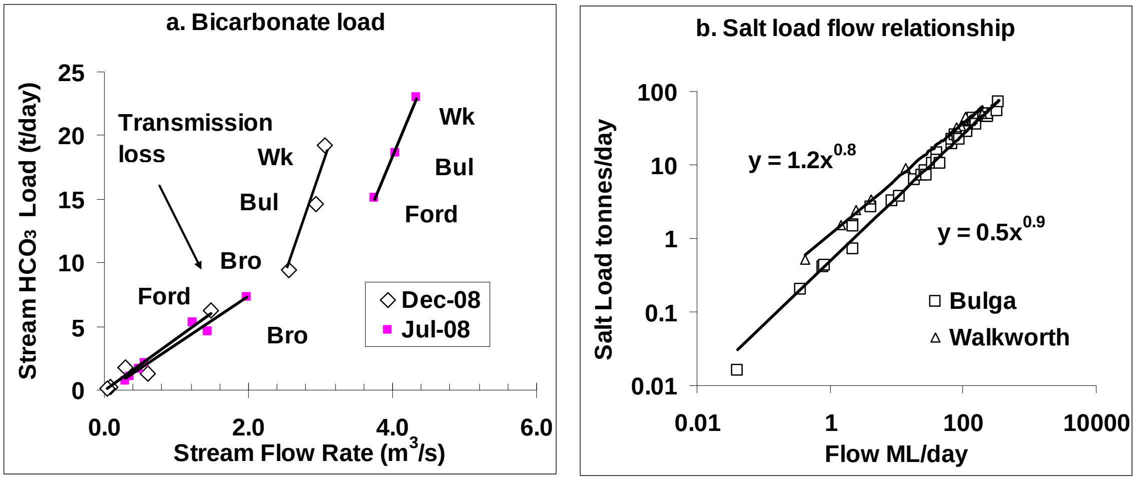


Figure 3. a. Wollombi Brook Bicarbonate load (2008). Wk=Warkworth, Bul=Bulga, Bro=Broke Ford=Fordwich. Italics are samples from December 2008. b. Instantaneous flow and TDS data at the Bulga Gauge (1977-1989) and Warkworth Gauge (1979-1980).

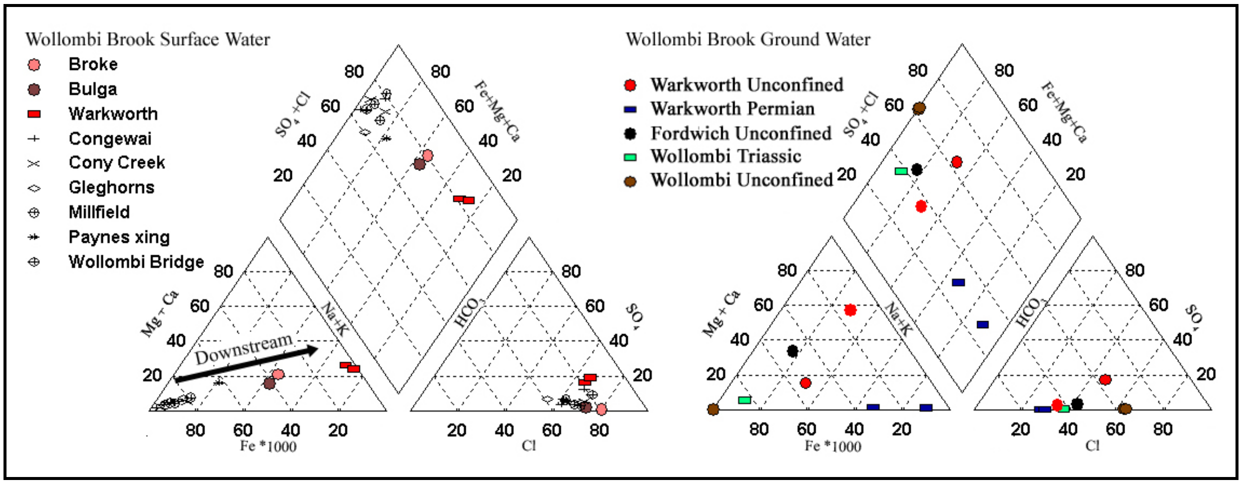


Figure 4. Surface and ground water chemistry Wollombi Brook catchment (2006).

This groundwater discharge model is supported by the geochemistry and strontium isotopic data which indicate ground water interactions between the Permian aquifers at Broke, Bulga and Warkworth with the unconfined alluvial aquifers at Warkworth (Fig 4). The stream water chemistry becomes sodium dominated in its lower reaches, whereas the upper reaches have characteristic iron signature. This is also reflected in the ground waters hosted in the Triassic sandstones and unconfined aquifers near the Wollombi Brook town-ship. The river water Sr isotopic ratio is characterised by the ground water from the headwaters of the catchment (Fig 5). This suggests that the Triassic aquifers are important for the supply of fresh water to the Wollombi Brook and possibly other catchments in the southern Hunter Valley. During 2005-2006 south-eastern Australia was significantly effect by drought and the Wollombi Brook in the lower reaches had ceased to flow. In the upper catchment flow was reduced but persisted and this would represent base flow conditions. It is possible that this base flow was probably maintained by groundwater discharge from the Triassic sandstone aquifers.

The Permian aquifer in the lower catchment are saline and Na-HCO_3 in nature. During an earlier study the chemistry of waters of the stream bed sediments appear to be more controlled by stream water chemistry than the surrounding ground waters at the Fordwich and Warkworth (Pritchard, 2005). Although the stream bed water appears to be predominantly controlled by the stream, some samples collected in 2006 indicate that discharge of Permian ground does influence stream bed waters at some reaches of the stream. The strontium isotopic data also indicates that during high flow periods there is also a possible interaction is confined between the saline Permian ground waters and the unconfined alluvial aquifer at Warkworth (Fig 5).

A limitation to the assessment of the interactions of surface and ground water interactions in the Hunter Valley is the availability of geochemical and ground water level data. The Department of Water and Energy in recent years have installed groundwater level recorders at the sampled ground water sites within the Wollombi Brook. However, these measurements need to be complimented by data collect by all water users. There is also an ad hoc collection of surface and ground water geochemical samples. It is apparent from the surface and unconfined alluvial water analysis that monthly water samples collected at the stream gauges and at other locations within the Brook would greatly strengthen our understanding of the interactions within the catchment. The evaluation of the monthly monitoring data is essential for the development of sound water management practice.

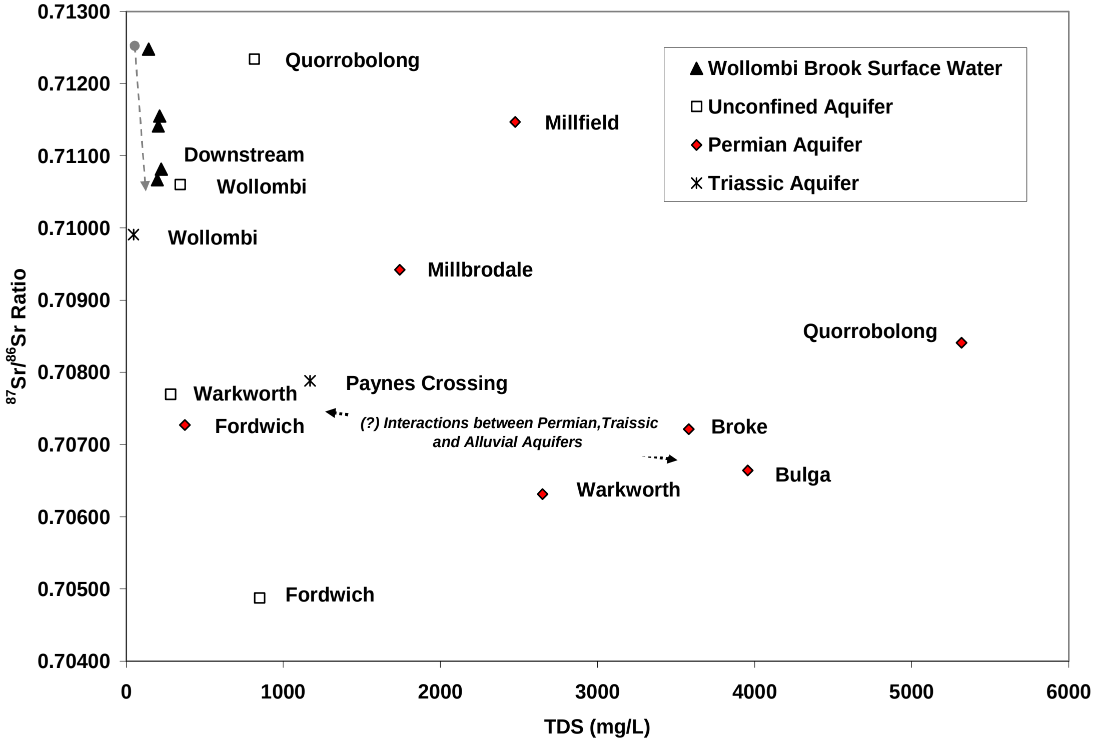


Figure 5 The relationship between the strontium isotopic ratio and TDS (mg/L) within the Wollombi Brook surface and ground waters. Location names of the ground waters are shown

Conclusions

Wollombi Brook is a highly connected stream and groundwater system and water quality and quantity are influenced by ground water discharges along its length. Saline ground waters from the Permian strata can discharge into the stream and the unconfined alluvial aquifer below Broke, especially during low flow periods. It is possible that the extraction of water from the stream and the unconfined alluvial and Triassic aquifers could result in saline ground discharge from the Permian geology.

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Extent of longwall mining influence on deep groundwater overlying a Southern Coalfield mine

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Abstract

Surface subsidence and strata movement result from longwall mining. As a consequence, groundwater systems are altered, there are groundwater inflows to the mine, and there may be drainage of surface water to the mine; therefore, the effects of longwall mining are particularly important near water supply reservoirs. Yet there has been limited work undertaken on the effects of longwall mining on deep groundwater and the aquifers and aquitards overlying mined longwalls.

A deep groundwater investigation was undertaken at Dendrobium Colliery Area 2, which is located in the Southern Coalfield of New South Wales, Australia. It is adjacent to Cordeaux Reservoir, which provides Sydney with some of its drinking water.

The investigation involved the analysis of piezometric data from 20 boreholes, comprising over 100 vibrating wire piezometers, monitoring ten stratigraphic units. The investigation demonstrated that there were no impacts to: the Cordeaux Crinanite, an igneous intrusion that has the potential to provide a drainage pathway between the reservoir and the longwall goaf; or the Bald Hill Claystone, the uppermost aquitard that under natural conditions can restrict vertical leakage. However mining effects have extended to many of the stratigraphic units overlying the longwalls, including: the Wombarra Claystone, the aquitard closest to the depth of mining, which controls the vertical flow of groundwater into the mine workings; and the Scarborough Sandstone, an aquifer which is in hydraulic connection with the reservoir at locations close to the reservoir. The mining impacts to the Wombarra Claystone bring into doubt the adequacy of the aquitard to restrict vertical leakage to the mine. This doubt is supported by an inflow event in 2007 that was found to be characteristic of Scarborough Sandstone groundwater, which overlies the Wombarra Claystone.

The investigation has provided a greater understanding of the impact of longwall mining on the deep sandstone aquifers and claystone aquitards overlying the longwalls. The findings from this investigation can broadly be applied to other longwall coal mines, including the continued mining at Dendrobium.

Keywords: longwall mining, groundwater, Dendrobium

Introduction

An investigation into the influence of longwall mining on deep groundwater at Area 2 of Dendrobium Colliery (NSW) was undertaken due to the limited research undertaken on the effects of longwall mining on deep groundwater and the aquifers and aquitards overlying mined longwalls in the Southern Coalfield. This was exemplified by the strategic review of the impacts of underground coal mining on natural features in the Southern Coalfield (NSW Department of Planning, 2008), which acknowledged that further investigation and research is warranted into impacts to deep aquifers. Dendrobium

Colliery was chosen due to the extensive groundwater monitoring network, occasional large inflows into the mine (June 2007 and February 2008) and the presence of the Cordeaux Crinanite (a potential drainage pathway).

The paper provides a summary of the current understanding of longwall mining effects on groundwater and the main findings from the deep groundwater investigation at the Dendrobium Colliery Area 2, in the Southern Coalfield of NSW (Madden, 2009).

Current understanding of longwall mining effects on groundwater

The impact on groundwater systems from longwall mining is attributed to subsidence, strata movements and drainage. If the strata overlying the longwalls are of adequate primary or secondary permeability, or secondary permeability fractures develop, there is potential for groundwater to drain to the mine and overlying aquifers can become dewatered. Aquifers that are separated from the mine by aquicludes/aquitards may not drain to the mine (Booth, 2002), however fracturing and deformation of low permeability units may provide hydraulic connectivity between aquifers.

Subsidence and strata movements affect groundwater by: deforming existing fractures; creating new fractures; separating bedding planes; enlarging existing joint apertures; and changing the hydraulic properties of the strata, such as porosity and permeability. As a result, changes to hydraulic gradients, piezometric levels, and groundwater flow paths occur. These changes are separate to drainage to the mine (Booth, 2002, 2006; Booth et al., 1998). Additionally, confined aquifers can become unconfined, causing water quality changes (Booth, 2007).

The area above longwalls can be divided into three zones based on deformation and hydrologic response as follows (in ascending order) (Booth, 2002, 2006; Forster, 1995):

- Caved/fractured zone – highly fractured with large increases in vertical and horizontal permeability which drains directly to the mine.
- Constrained zone – subsides with little fracturing or alteration to the original physical properties (such as low permeability); horizontal permeability may increase if bedding plane separation occurs; this zone typically forms a barrier to vertical drainage from the surface and shallow aquifers to the mine.
- Surface zone – upper aquifers have an increased permeability where fracturing at the surface and within the shallow strata occurs; shallow groundwater typically does not drain to the mine, assuming the aquiclude zone retains its original physical properties; sometimes there are significant groundwater level declines which typically recover.

The usual response of bedrock aquifers to longwall mining is a decline in piezometric level due to (Booth, 2002, 2003):

- Direct drainage to the mine.
- Increase in fracture porosity, which causes large declines in piezometric level in confined bedrock aquifers because of their inherently low storativity.
- The transmitted drawdown effect (cone of depression), which spreads outwards through the aquifer as water drains towards the groundwater sink in the subsiding area. This secondary effect occurs ahead of undermining. The decline in piezometric level is gradual in transmissive units, whereas in poorly transmissive

units, the decline in piezometric level is more rapid and occurs closer to the site and time of undermining.

- Leakage to lower aquifers via fractured aquitards.
- Increased permeability which causes decreased hydraulic gradients.

The ground surface generally subsides in the shape of a trough-shaped depression and can be divided into an inner subsidence trough (above the extracted longwall) and an outer subsidence trough (beyond the extracted longwall) based on differences in stress, deformation and hydraulic effects. Groundwater levels within the inner subsidence trough in the surface zone and above the aquiclude typically partially recover soon after undermining due to post-subsidence compression and settlement, whereby fractures and bedding plane separations may close and there is a decrease in porosity and permeability. Beyond the inner trough, within the rib zone, the strata typically continue to have a higher permeability. Long-term groundwater level/piezometric level recovery is dependent on connection to recharge and the ability of water to flow to the impacted area. Generally, groundwater levels in the surface zone typically fully recover and piezometric levels in the lower fractured/caved zone usually do not recover (Booth, 2002, 2003, 2006). Factors that can delay or prevent groundwater level/piezometric level recovery include (Booth, 2002, 2003):

- aquifers with low transmissivities, restricting lateral recharge;
- natural barriers to recharge (and reduced recharge e.g. drought conditions);
- leakage through fractured aquitards;
- decreased gradients;
- changed groundwater flow paths;
- continued mining.

Study area

Dendrobium Colliery Area 2

Dendrobium Colliery is located northwest of Wollongong (Fig. 1), in the Southern Coalfield of NSW. Area 2 is located adjacent to the stored water within Cordeaux Reservoir, within the Metropolitan Special Area of the Sydney Catchment Authority and partly within the Cordeaux Dam Notification Area of the Dams Safety Committee of NSW.

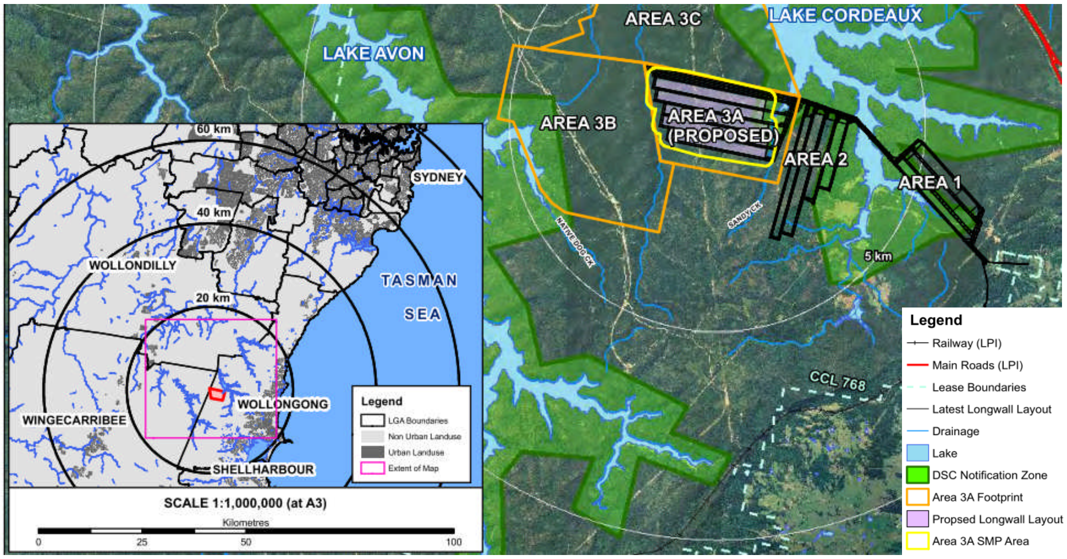

Figure 1 Location of Dendrobium Colliery (modified from Cardno Forbes Rigby, 2007a)

BHP Billiton Illawarra Coal extract coal at Dendrobium Colliery by underground longwall mining methods. Two longwalls were extracted at Area 1, from early 2005 to early 2007. Area 2 contains Longwall 3 (LW3), Longwall 4 (LW4), Longwall 5 (LW5) and Longwall 5A (LW5A), with LW3 extraction completed in late 2007, LW4 extraction completed in late 2008, and LW5 currently being extracted. The coal extraction at Area 2 commences from the southern ends of the longwall panels. Approval has been granted for mining at Areas 3A, 3B and 3C (final longwall layouts are yet to be approved (Brassington, G.M. 2009, pers. comm., 2 June)).

The lengths and widths (pillar rib to pillar rib) of the longwalls were proposed at 1,615 m by 245 m (LW3), 1,965 m by 245 m (LW4), 2,965 by 245 m (LW5), and 3,010 m by 165 m (LW5A). The planned thickness of the Wongawilli Coal Seam extraction was about 3.75 m. The depth of cover to the Wongawilli Coal at Area 2 ranges from 145 m near the southern end of LW3 to 315 m above LW5 (Comur Consulting, 2007).

Geology

The geology of Dendrobium Colliery Area 2 comprises the Triassic Hawkesbury Sandstone, the Permian to Triassic Narrabeen Group, the Permian Illawarra Coal Measures and an igneous intrusive sill.

The Hawkesbury Sandstone outcrops on the ridgelines and is underlain by the Narrabeen Group, which consists of the following (in descending order) the Newport Formation, Bald Hill Claystone, Bulgo Sandstone, Stanwell Park Claystone, Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone (Moffitt, 2000). To the east of the ridgelines, in the vicinity of the reservoir, the most common outcropping lithology is the Bulgo Sandstone.

The Narrabeen Group is underlain by the Illawarra Coal Measures; a sequence of interbedded sandstone, siltstone, claystone, and coal with minor tuff, conglomerate and intrusions (Moffitt, 2000). In the Dendrobium area, the Illawarra Coal Measures generally consist of (in descending order) the Bulli Coal, Loddon Sandstone, Balgownie Coal, Lawrence Sandstone, Burragorang Claystone, Eckersley Formation, Wongawilli Coal and others.

The longwalls at Area 2 are located near previous workings (Nebo Colliery) in the Wongawilli Coal Seam (to the south of the longwalls). The Wongawilli Coal Seam is the thickest and most widespread coal interval in the Southern Coalfield. Besides coal, the seam contains siltstone, claystone and sandstone (Moffitt, 2000).

A large igneous intrusive sill, the Cordeaux Crinanite, occurs to the south of Area 2, above LW5 and LW5A. The approximate base of the Crinanite is within the Balgownie Seam and the roof of the Crinanite may extend up to the Stanwell Park Claystone. The main body of the Crinanite is almost 100 m thick (GHD-Geotechnics, 2006).

Hydrogeology

The hydrogeology of the Southern Coalfield is controlled by a sub-horizontal sedimentary sequence of aquifers and aquitards. Typically the claystone units act as aquitards (Bald Hill Claystone, Stanwell Park Claystone and Wombarra Claystone) and the sandstone units act as aquifers (Hawkesbury Sandstone, Bulgo Sandstone, Scarborough Sandstone and Coal Cliff Sandstone). The coal seams usually have a high permeability (GHD-LongMac, 2004) and the Cordeaux Crinanite generally has low bulk permeability (GHD-Geotechnics, 2006).

The aquifers of the Narrabeen Group are generally of poorer quality and permeability than the Hawkesbury Sandstone aquifer, which is considered the only economic aquifer in the general area (Merrick, 2007). The main role of groundwater in the sandstone aquifers of the Southern Coalfield is to provide baseflow to streams and to support groundwater dependent ecosystems. The Hawkesbury Sandstone and Bulgo Sandstone are likely to provide most of the baseflow.

Recharge from the Cordeaux Reservoir to the Scarborough Sandstone is likely to be enhanced by valley closure effects. It is expected that the Stanwell Park Claystone underlies much of the Cordeaux River Arm, and that the Stanwell Park Claystone is damaged (fractured) due to valley closure effects (GHD-LongMac, 2006). As the Scarborough Sandstone underlies the Stanwell Park Claystone, a hydraulic connection and recharge from the reservoir to the Scarborough Sandstone is likely.

Underlying the Hawkesbury Sandstone is the Bald Hill Claystone, a major aquitard. However the Bald Hill Claystone is only present in part of Area 2 and is not located beneath the Cordeaux Reservoir (Comur Consulting, 2007), limiting its ability to restrict downward groundwater flow. The Stanwell Park Claystone and Wombarra Claystone are the other aquitards at Area 2, that under natural conditions, are expected to limit downward groundwater flow.

Method

The investigation involved assessing the groundwater from 20 boreholes (DDH23, DDH24, DDH37, DDH38, DDH39, DDH47, DDH48, DDH49, DDH50, DDH52, DDH60, DDH71, DDH72, DDH73, DDH74, DDH75, DDH78, DDH79, DDH80 and DDH94) (Fig. 2). Piezometers monitor the pore pressures at over 100 different points and intersect the Cordeaux Crinanite, Bald Hill Claystone, Bulgo Sandstone, Stanwell Park Claystone, Scarborough Sandstone, Wombarra Claystone, Coal Cliff Sandstone, Bulli Coal, Balgownie Coal and Wongawilli Coal.

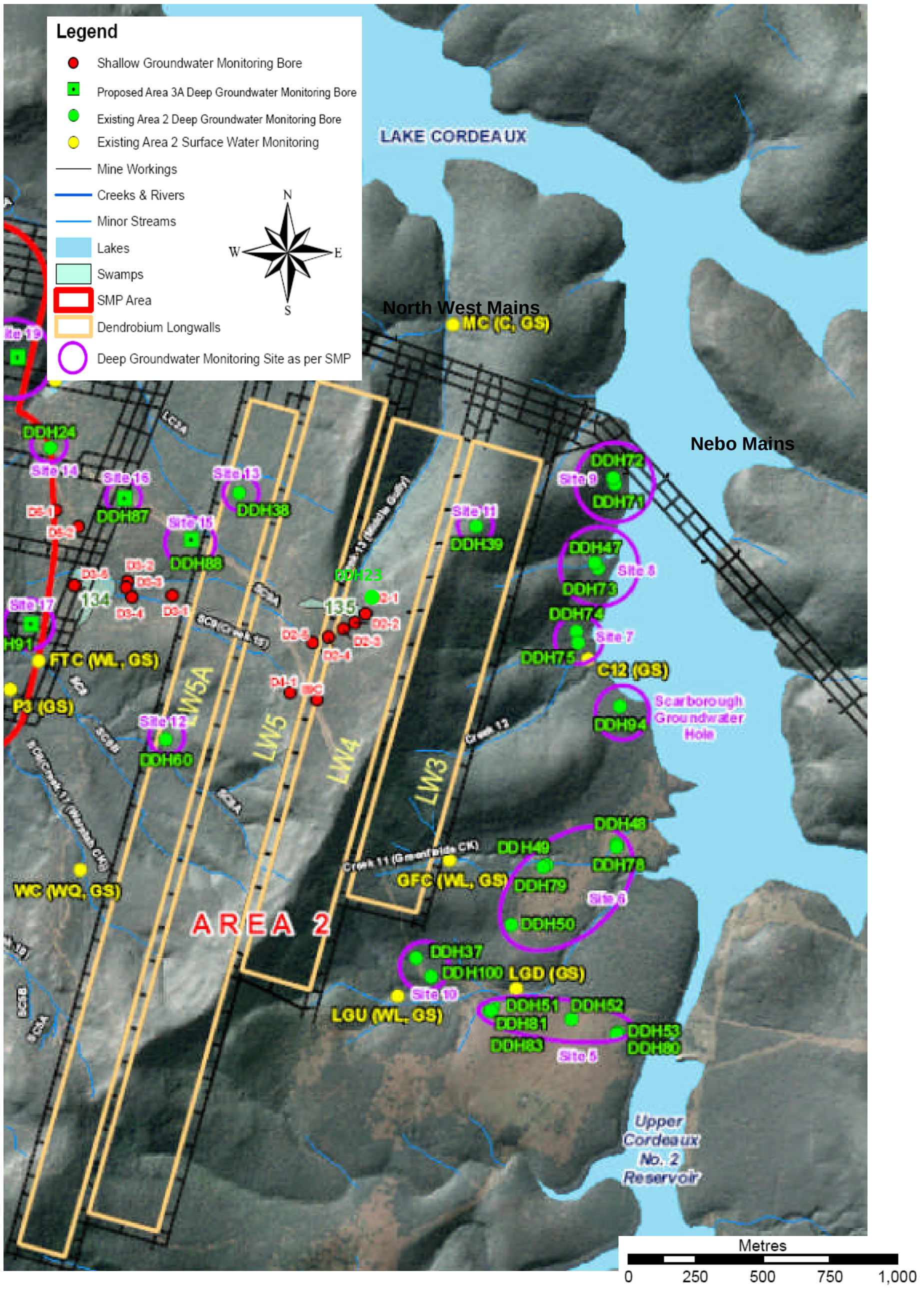

Figure 2 Monitoring network (modified from Cardno Forbes Rigby, 2007b)

The boreholes were typically drilled vertically, however four boreholes were drilled at 11° or 40° from the vertical. Most of the boreholes were not drilled directly over the longwalls. All boreholes were installed with strings of vibrating wire piezometers, which were grouted in the boreholes. Pore pressures are converted to piezometric levels and are monitored continuously.

For each borehole, a graph was prepared of the vertical hydraulic gradient down through the stratigraphic section, based on the average piezometric level for the entire monitoring period, in order to recognise where mining has had an effect on the groundwater system. Hydrographs for each borehole, which included the depths of the stratigraphic units and longwall face advance, and hydrographs for each stratigraphic unit were also produced. An example of the vertical hydraulic gradient and hydrographs for DDH72 is shown in Fig. 3.

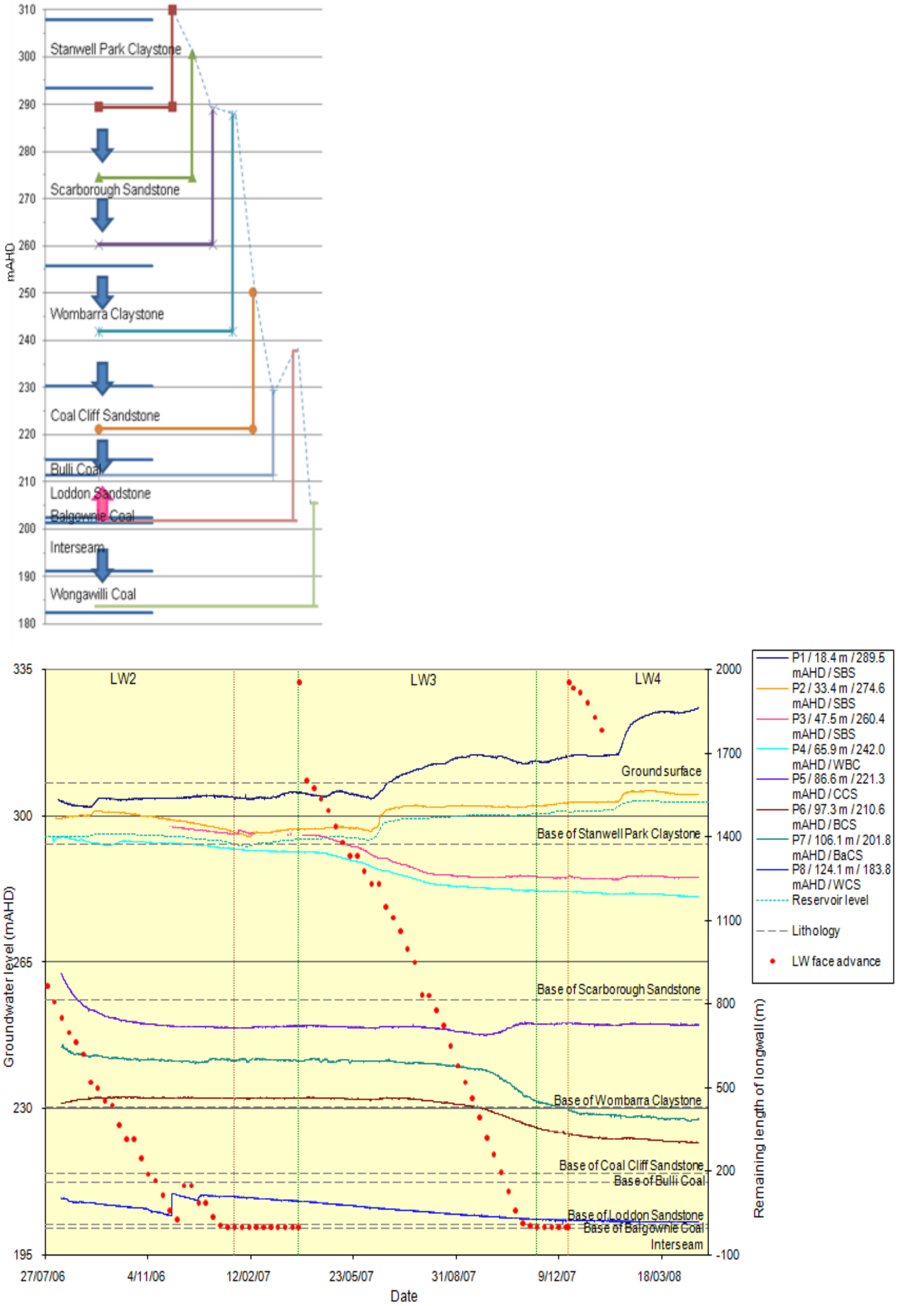

Figure 3 An example of the vertical hydraulic gradient and piezometric responses at Dendrobium (DDH72) (Madden, 2009)

Main Findings

The main findings from the investigation by Madden (2009) are summarised below. For details, including graphics, please refer to the original investigation.

The impacts from longwall mining at Area 2 have not extended to the Cordeaux Crinanite or the Bald Hill Claystone. This indicates the crinanite, which extends beneath

Upper Cordeaux No. 2 dam (Fig. 2), has not become a drainage pathway between the reservoir and the longwall goaf. Although there is only one piezometer intersecting the Bald Hill Claystone, the lack of mining effect indicates the aquitard has not been compromised at this location.

Mining effects have extended to the Stanwell Park Claystone at DDH39 (Fig. 2), causing a decline in piezometric level and a change from confined to unconfined conditions. DDH39 is located over LW3, with no other deep boreholes located over longwalls extracted during this project. There is also potentially a mining impact within the Bulgo Sandstone (one piezometer) and at another location within the Stanwell Park Claystone, with a possible increase in permeability the cause for the greater responsiveness of the groundwater levels/piezometric levels to rainfall at these locations. It is expected that the impact on the groundwater system due to longwall mining extended into the Bulgo Sandstone at the DDH39 location.

A third of the Scarborough Sandstone piezometers indicate an impact from mining; typically a rapid decline in piezometric level shortly after the commencement of LW3 and a change from confined to unconfined conditions. Mining has impacted the upper, mid and lower Scarborough Sandstone.

Most of the piezometers intersecting the Wombarra Claystone and all the piezometers intersecting the Coal Cliff Sandstone, Bulli Coal, Balgownie Coal and Wongawilli Coal have piezometric levels which responded to mining at Area 1 and/or Area 2. As a result of the mining impact to the Wombarra Claystone, there is doubt over the adequacy of the Wombarra Claystone as an aquitard to restrict vertical leakage to the mine. This is supported by:

- downwards vertical groundwater flow directions, which indicate the strata below the Wombarra Claystone, and at certain locations the Wombarra Claystone and the stratigraphic units above, are impacted by mining;
- exploratory numerical modelling of candidate inflow mechanisms (Merrick, 2009);
- the June 2007 inflow event, which was found to be characteristic of the Scarborough Sandstone water (Ecoengineers, 2008).

The Coal Cliff Sandstone piezometric levels at Area 2 typically declined more rapidly during the mining of LW2 in Area 1 than during the mining of LW3 in Area 2. It is likely the decline during the mining of LW2 was associated with the Nebo Mains (Fig. 2), as the piezometers intersecting the Coal Cliff Sandstone were installed when the Nebo Mains was close to the monitoring sites, such as DDH72 (Fig. 3). The piezometric response during the mining of LW3 was typically less rapid, as the system had already become partly depressurised.

The Bulli Coal, Balgownie Coal and Wongawilli Coal piezometric levels typically declined during the mining of LW3 in response to the fractured/caved zone and the associated fracturing and increases in vertical and horizontal permeability. The smallest declines in piezometric level tended to occur at the locations that had already been impacted by mining, such as from earlier mining of the Wongawilli Coal Seam at the adjacent Nebo Colliery to the south, and at the Mt Kembla Bulli Coal Seam workings to the east. The largest declines in piezometric level appear to have occurred at locations that had not been previously impacted by mining, and at locations further from the Cordeaux Reservoir.

Fig. 3 illustrates the clear loss of pressure in the lower Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone as LW3 approached DDH72. The response of the upper and mid Scarborough Sandstone to lake dynamics and a lack of response to mining is also evident. All pressures, except the lower Scarborough Sandstone, remained greater than atmospheric (remained confined) despite mining.

Longwall mining has extensive effects on the Bulli Coal and Wongawilli Coal piezometric levels. The Area 2 Bulli Coal piezometric levels are likely to have been drawn down by previous mining of the Bulli Coal in the general area, especially by the Mt Kembla workings, and the Wongawilli Coal piezometric levels at Area 2 notably declined during the earlier Area 1 mining.

There was no obvious piezometric response to the June 2007 or February 2008 inflow events. This is in part due to the location of the piezometers at some distance from the mining face.

Conclusions

The investigation at Dendrobium Colliery Area 2 has provided a greater understanding of the impact of longwall mining on the deep sandstone aquifers and claystone aquitards overlying the longwalls. The investigation has illustrated the extent of mining influence (i.e. declines in piezometric levels, confined to unconfined changes); the widespread influence of longwall mining on the deeper stratigraphic units; and the influence from the development of the headings on the nearby groundwater. However, it has not been possible (without modelling) to infer the height of the free-draining fractured zone, taken to be the zone of negative or zero water pressure above a mined longwall, as no piezometers are close enough to the mined longwalls to show the expected unsaturated conditions in this zone. (DDH39, which is located over LW3, was destroyed as the longwall face approached.) All deep measurements made adjacent to the longwall panels, excluding parts of the Scarborough Sandstone, are above atmospheric pressure and depressurisation eases gradually with height above the coal seam. The broader study by Madden (2009) did not identify the observed inflow events to be associated with a direct loss of water from the reservoir. The findings from this investigation can broadly be applied to other longwall coal mines, including the continued mining at Dendrobium.

Acknowledgements

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Deep Groundwater Response to Longwall Mining, Southern Coalfield, New South Wales, Australia

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Abstract

Longwall coal mining causes surface subsidence and strata movement, which alters groundwater systems and can result in surface water and groundwater being redirected along new fracture and drainage pathways, including vertical drainage to the mine. The Metropolitan Special Area, part of Sydney's drinking water catchment, is located in the Southern Coalfield. It is important to understand the potential for loss of baseflow from mining activity for management of the drinking water supply storages.

A groundwater assessment was undertaken at Dendrobium Colliery Area 1, to determine the impacts to the deep groundwater systems, particularly the Narrabeen Group strata, from longwall mining. The investigation involved the analysis of piezometric data from 10 boreholes, comprising over 60 vibrating wire piezometers, monitoring six stratigraphic units. Dendrobium Colliery is located on the Woronora Plateau adjacent to Cordeaux Reservoir, which is used to supply drinking water to Sydney.

The piezometric response in the main aquifers and aquitards above the mined coal seam and the likely causes for the observed responses were determined. Levels in the deeper stratigraphic units closest to the mine (Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone) initially declined in three apparent stages: rapidly, close to the longwall face; gradually, as mining progress slowed; and then rapidly again, as the longwall face passed by. The initial sharp decline is likely to be attributed to *in situ* dilation of fractures and bedding planes in advance of the subsidence wave and/or the transmitted drawdown effect. The gradual decline is expected to be in response to some settlement during the slower mining period. The second rapid decline is primarily a response to the dilation of fractures and bedding planes coinciding with maximum subsidence. The rapid declines in piezometric level are associated with the creation of new voids in low permeability strata.

Keywords: longwall mining, groundwater, drinking water, Southern Coalfield

Introduction

An evaluation of the impact of longwall coal mining on deep groundwater, particularly in the Narrabeen Group strata, at Dendrobium Colliery Area 1, was undertaken due to the occurrence and future plans for longwall mining within drinking water catchments and the concerns for the potential loss of yield to these catchments. The investigation provided a greater understanding of the effects of longwall mining on the groundwater systems, with this paper focussed on one aspect of the investigation only; the piezometric response of the main sandstone aquifers and claystone aquitards above the mined coal seam to mining progress and the likely causes.

Known groundwater response to longwall mining

The impact to groundwater from longwall mining is mainly through subsidence, strata movements and drainage. Subsidence and strata movements affect groundwater by: deforming existing fractures, enlarging existing fracture apertures, creating new fractures, separating bedding planes, and changing the hydraulic properties of the strata. As a result, the piezometric levels can decline; baseflow discharge to streams can reduce; groundwater flow patterns can alter; aquifers can change from confined to unconfined, causing water quality changes; and upper aquifers can leak to lower aquifers (Booth, 2002, 2006, 2007; Booth et al., 1998).

The usual response of bedrock aquifers to longwall mining is a decline in piezometric level due to (Booth, 2002, 2003):

- Direct drainage to the mine.
- Increased fracture porosity, which causes large declines in piezometric level in confined bedrock aquifers because of their low storativity.
- The transmitted drawdown effect, which spreads outwards through the aquifer as water drains towards the lower piezometric levels in the subsiding area. This secondary effect occurs prior to undermining. The decline in piezometric level is gradual in transmissive units, and more rapid, and occurs closer to the monitoring site and time of undermining, in poorly transmissive units.
- Leakage to lower aquifers via fractured aquitards.
- Decreased hydraulic gradients as a result of increased permeability.

Shallow strata typically undergo subsidence and shear deformation, with the opening of fractures and bedding planes which increases fracture porosity and permeability. Compression and settlement follow within the subsidence trough, with the partial closure of fractures and bedding planes and a decrease in porosity and permeability. Beyond the inner trough, within the rib zone, the strata typically continue to have a higher permeability (Booth, 2002, 2006). Deeper strata also generally undergo the above sequence, with some differences expected due to variances based on the deformation zones above the mine and associated stress distribution.

According to Booth (2002), the piezometric levels in a shallow confined aquifer respond to the above sequence as follows:

- gradual decline in piezometric level as mining advances due to the transmitted drawdown effect
- rapid decline in piezometric level due to undermining, subsidence and increased fracture porosity
- minimum piezometric level due to maximum dilation (fracture opening)
- rapid, partial recovery of piezometric level due to the partial re-closure of fractures
- gradual, long-term recovery of piezometric level due to settlement and recharge.

Study area

Dendrobium Colliery Area 1

Dendrobium Colliery is located northwest of Wollongong (Fig. 1), in the Southern Coalfield. Area 1 is situated between the two arms of Lake Cordeaux, Kembla Creek and

Goondarrin Creek, and is located within the Sydney Catchment Authority's Metropolitan Special Area and within the NSW Dam Safety Committee's Notification Area.

BHP Billiton Illawarra Coal extract coal at Dendrobium Colliery by underground longwall mining methods. Two longwalls were extracted at Area 1; extraction of Longwall 1 (LW1) (western longwall) commenced in March/April 2005 and was completed in December 2005 and the extraction of Longwall 2 (LW2) (eastern longwall) commenced in February 2006 and was completed in January 2007. Both longwalls were extracted from the northwest to the southeast. Mining is currently being undertaken at Area 2 (Longwalls 3, 4, 5 and 5A) and approval has been granted for mining at Areas 3A, 3B and 3C (final longwall layouts are yet to be approved (Brassington, G. 2009, pers. comm., 2 June)).

At Area 1, LW1 and LW2 have a length of approximately 1,800 m and a width of 245 m (pillar rib to pillar rib). The thickness of the extracted Wongawilli Coal Seam varies from 3.3 to 3.4 m. The depth of cover to the seam ranges from 137 to 322 m, depending on the surface topography and due to the ridgeline over some of the workings (Comur Consulting, 2007).

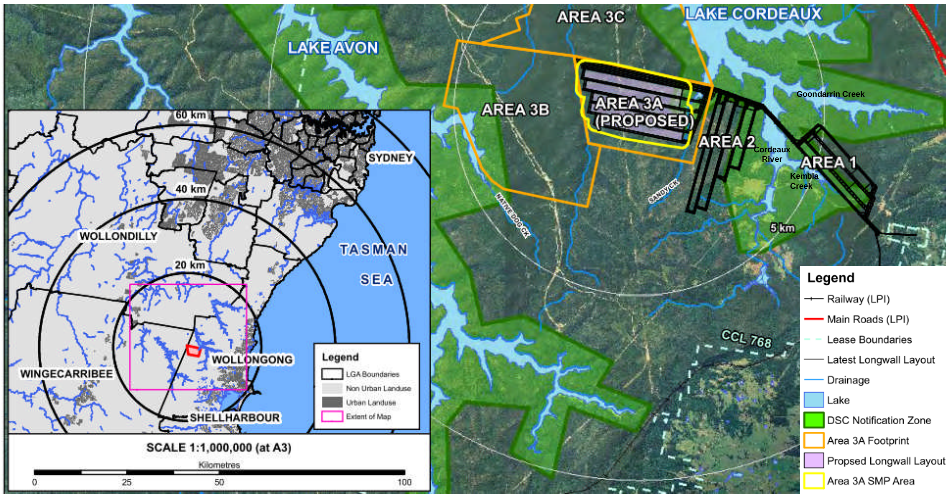

Figure 1 Location of Dendrobium Colliery (modified from Cardno Forbes Rigby, 2007)

Geology

The geology of Dendrobium Colliery Area 1 comprises the Triassic Hawkesbury Sandstone, the Permian to Triassic Narrabeen Group, and the Permian Illawarra Coal Measures. A conceptual model illustrating the vertical profile of the stratigraphic units is shown in Fig. 2.

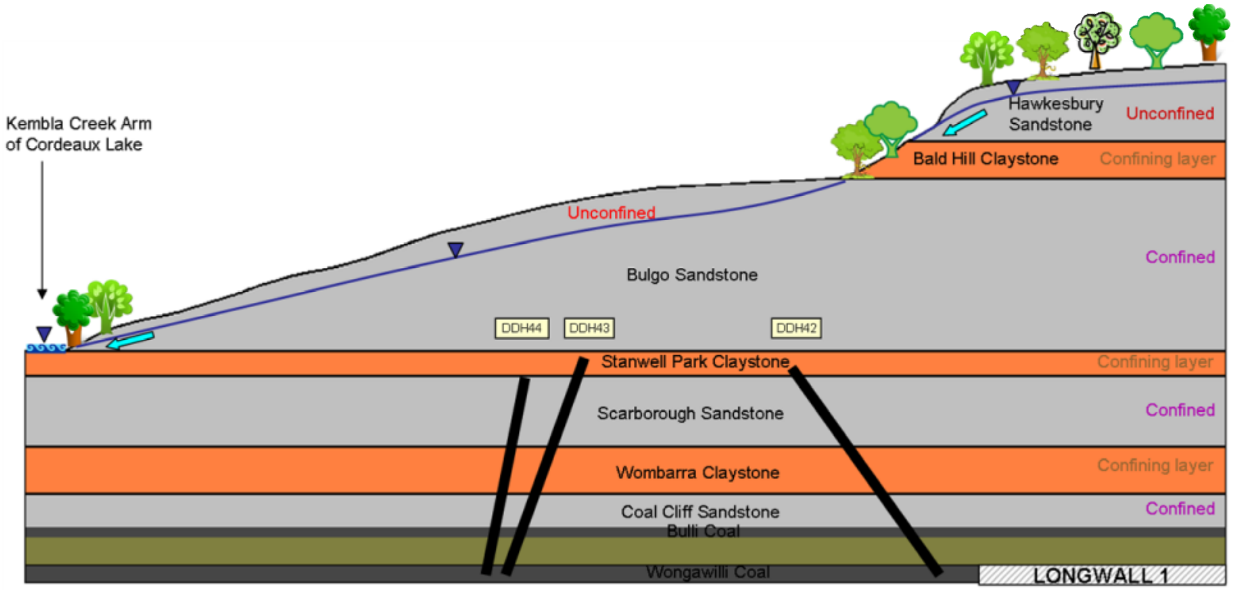

Figure 2 Conceptual model of the vertical stratigraphic profile and pre-mining groundwater conditions, with location of DDH40 series of boreholes drilled upwards from the Wongawilli workings (modified from Madden, 2008)

The Hawkesbury Sandstone outcrops on the ridgelines and is underlain by the Narrabeen Group, which consists of the following (in descending order) the Newport Formation, Bald Hill Claystone, Bulgo Sandstone, Stanwell Park Claystone, Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone (Moffitt, 2000).

The Narrabeen Group is underlain by the Illawarra Coal Measures; a sequence of interbedded sandstone, siltstone, claystone, and coal with minor tuff, conglomerate and intrusions (Moffitt, 2000). In the Dendrobium area, the Illawarra Coal Measures generally consist of (in descending order) the Bulli Coal, Loddon Sandstone, Balgownie Coal, Lawrence Sandstone, Burragorang Claystone, Eckersley Formation, Wongawilli Coal and others.

Extensive coal mining was conducted in proximity to Dendrobium Colliery Area 1, within the Wongawilli and Bulli Coal Seams (the southern ends of the longwalls are beneath previous workings in the Bulli Coal Seam). The Wongawilli Coal Seam is the thickest and most widespread coal interval in the Southern Coalfield. Besides coal, the seam contains siltstone, claystone and sandstone (Moffitt, 2000).

Hydrogeology

The hydrogeology of the Southern Coalfield is controlled by a sub-horizontal sedimentary sequence of aquifers and aquitards. Typically the claystone units act as aquitards (Bald Hill Claystone, Stanwell Park Claystone and Wombarra Claystone) and the sandstone units act as aquifers (Hawkesbury Sandstone, Bulgo Sandstone, Scarborough Sandstone and Coal Cliff Sandstone) (Fig. 2). The coal seams usually have a high permeability and also act as aquifers (GHD-LongMac, 2004).

The Hawkesbury Sandstone is the most important regional aquifer, which is capable of producing low to moderate groundwater yields and has quite good water quality, with salinities typically less than 1,000 mg/L. Underlying the Hawkesbury Sandstone is the Bald Hill Claystone, a major aquitard that will retard downward flow unless severely fractured (Merrick, 2007). The Stanwell Park Claystone and Wombarra Claystone were also confirmed as significant aquitards (GHD-LongMac, 2006). The Wombarra Claystone aquitard controls the vertical flow of groundwater into the mine workings (Merrick, 2007).

The aquifers of the Narrabeen Group are generally of poorer quality and permeability than the Hawkesbury Sandstone aquifer (Merrick, 2007). The Scarborough Sandstone was identified as the main aquifer overlying the mining at Dendrobium Colliery at Area 1 (GHD-LongMac, 2006), and from the limited groundwater quality information available, is slightly acidic to slightly alkaline and has a low salinity, with better groundwater quality expected near the lake.

At Dendrobium Colliery Area 1, groundwater in the upper sandstone aquifers (Hawkesbury Sandstone and Bulgo Sandstone) is expected to flow laterally due to the sub-horizontal gradient of the aquitards and known discharge as baseflow to streams, including Lake Cordeaux. Following the damming of the Cordeaux River, some of this lateral flow may be impeded, with localised recharge from the lake to the Scarborough Sandstone aquifer possible.

Method

The deep groundwater monitoring network at Area 1 comprises ten boreholes monitoring the piezometric levels at 62 different points (Fig. 3). The piezometric levels obtained from all these boreholes were used in assessing the impact of longwall mining on the overlying aquifers and aquitards at Dendrobium Area 1 (Madden, 2008). However for the purpose of this paper, only the DDH40 series of boreholes (DDH42, DDH43 and DDH44) will be discussed further, as these boreholes are deemed to be more representative of the piezometric response to longwall mining away from an apparent influence from the lake or previous mining. Additionally, data is available near the commencement of mining (and prior to mining for DDH42 and DDH43).

The DDH40 series of boreholes were drilled upwards from the Wongawilli workings, at an angle from the horizontal of 54° (DDH42), 70° (DDH43) and 79° (DDH44) (Fig. 2). Vibrating wire piezometers were installed and grouted in the boreholes, and are manually monitored with portable readout units (GHD-LongMac, 2006). Therefore, the frequency of monitoring is not ideal (every 10 minutes to every two months, typically every few days), and may be masking some effects. The piezometers intersect the Stanwell Park Claystone, Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone.

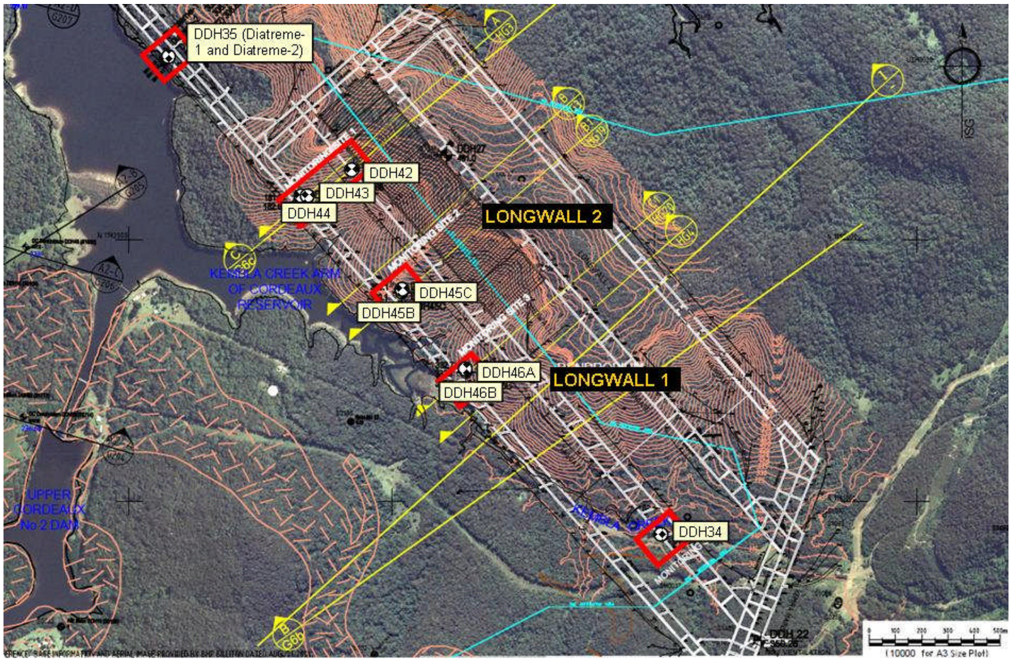

Figure 3 Deep groundwater monitoring network (modified from GHD-LongMac, 2006)

Results and Discussion

Of the DDH40 boreholes, DDH42 is considered to be most representative of the mining influence on groundwater, as it is located closest to the mine. Also, there are some limitations with the important early data for DDH43 and DDH44, including infrequent monitoring/data gaps and a lack of pre-mining data for DDH44. The hydrographs for DDH42 (Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone) are shown at Fig. 4.

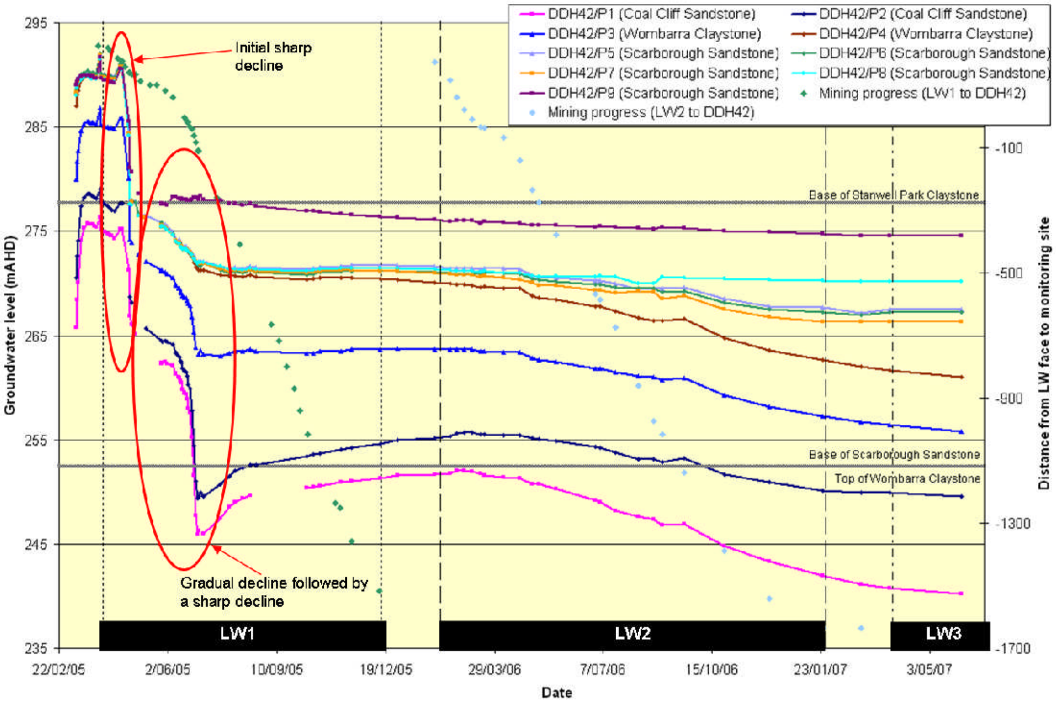

Figure 4 Piezometric levels at DDH42

The DDH42 piezometric levels declined sharply when the advancing longwall face (LW1) was close to DDH42 (about 178 m away). The sharp decline may be due to the transmitted drawdown effect, which occurs suddenly and close to the monitoring site in poorly transmissive units. Alternatively, or in addition, the response may have been due to *in situ* tension/dilation of fractures and bedding planes in advance of the subsidence wave. The new void space created in the low permeability strata, and the low storativity of the confined units, is likely to have been the cause of the large and rapid decline (Booth, C. 2008, pers. comm., 24 June).

After this response, the DDH42 piezometric levels decreased at a much reduced rate and then typically decreased fairly rapidly again. The reduced rate of decline appears correlated with mining progress and may indicate some settlement during the slower mining periods and a reduction in the transmitted drawdown effect. The decline typically accelerated as the longwall face and subsidence wave travelled towards DDH42, with a minimum piezometric level obtained shortly after LW1 had passed DDH42. The rapid decline was likely to be partially due to the transmitted drawdown effect and primarily a response to the dilation of fractures and bedding planes in the low permeability strata, coinciding with maximum subsidence (maximum dilation) and with the closest distance of the longwall face to DDH42. There is also likely to be some drainage of groundwater from the Coal Cliff Sandstone to the mine (Booth, C. 2008, pers. comm., 24 June). The extent of decline in piezometric level reduced with vertical distance from the mine.

There are some differences in the piezometric responses for DDH43 and DDH44 compared to DDH42, which is located closer to the mine, including a more gradual decline in piezometric level coinciding with maximum subsidence. This may be associated with a lesser influence from the caving rockmass over LW1 due to the greater distance of these boreholes from LW1.

Following maximum subsidence, the piezometric levels from the DDH40 boreholes typically gradually declined to the completion of monitoring, with various Scarborough Sandstone piezometers and one Wombarra Claystone piezometer becoming dry. The Coal Cliff Sandstone piezometers of DDH42 rebounded prior to declining during the mining of LW2. The rebound may be associated with the redistribution of stress of the caving rockmass.

Piezometric levels declined fairly rapidly with the advancement of LW1, with a more gradual decline, or a lack of clear response, with the advancement of LW2. This may be attributed to the greater distance of the monitoring sites to LW2, the change from confined to unconfined conditions prior to the mining of LW2 at some locations, and/or the residual net increase in permeability which permanently affects the groundwater system (Booth, 2002).

Conclusions

The investigation at Dendrobium Colliery Area 1 has provided an enhanced understanding of the piezometric response in the groundwater systems of the Southern Coalfield to longwall mining. The investigation has highlighted the importance of site specific factors for predicting the piezometric response, for example: the permeability of the strata governs whether the piezometric level declines gradually and far from the longwall face (high permeability) or rapidly and close to the longwall face (low permeability); and the proximity to the mine and mining progress influences the rate of decline in piezometric level, with a slower rate further from the mine or with a reduction in mining progress.

Acknowledgements

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Tools and logistics of implementing applied tracer tests

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Abstract

Applied tracers are a useful tool to understand the interaction between groundwater and surface water resources. An applied tracer test is to be conducted in the Waratah Rivulet catchment in the southern part of the Sydney Basin. The catchment supplies water to Woronora Lake, one of Sydney's water supply system storages. The catchment is mostly natural, undisturbed land with the exception of coal mining at depth that is progressing beneath the rivulet sub-catchment. The maintenance of base flows is an important consideration for future land and water management.

The purpose of this investigation is to further understand the connectivity of both water resources (surface and groundwater) in a catchment that is impacted by longwall mining. This paper describes the practical tools and logistics involved in conducting an applied tracer test using fluorescent dyes. The paper shows that the devised solution can provide a reliable, reproducible and scientifically sound investigation.

The outcome of the study will be an enhanced understanding of the impact of longwall mining activities on surface water flow and quality and water balance. The results of the study will provide sound scientific data which can be utilised to develop future management options and a framework for the monitoring and assessment of the impacts of longwall mining on flow and water quality in drinking water supply catchments.

Keywords: tracer tests, fluorescent dyes, groundwater-surface water interaction

Introduction

Applied tracers are a useful investigation tool for a broad range of hydrogeological applications. As the tracer application is controlled and well characterised this technique is a powerful and insightful tool that can quantify groundwater-surface water interactions, aquifer properties, groundwater velocities and flow rates. A wide range of materials have been successfully used as tracers and include radio isotopes (environmental tracers), dissolved gases, fluorescent dyes, non-pathogenic microorganisms and non-reactive anions.

Dye tracers have been used successfully in many hydrogeological investigations and many published reports exist on the properties of dyes, techniques and theory of qualitative and quantitative dye tracing (Aley and Fletcher, 1976, Smart and Laidlaw, 1977, USEPA, 1988, Aley, 2002).

Fluorescein and Rhodamine WT are two fluorescent dyes commonly used in groundwater and surface water investigations as they are characterised by the following properties:

- Both dyes are non-toxic and do not pose human health or ecotoxicological risks at typically applied concentrations (less than 100 mg/L).
- They can be easily applied and can be detected at concentrations below the visible threshold (<0.1 mg/L).
- They are generally considered a conservative tracer (do not appreciably sorb or degrade).
- In surface waters both dyes photodegrade quickly. Divine et al (2006) estimated photodegradation rates of approximately 1.49 hr^{-1} and 0.9 hr^{-1} for Fluorescein and Rhodamine WT, respectively. Thus any dyes present in the discharge water will photodegrade quickly when discharged to the surface.
- Both dyes can be easily detected in the field using a portable flurometer at detection limits less than 0.0001 mg/L.

An applied tracer test using fluorescent dyes will be conducted at the Waratah Rivulet catchment, which is a Sydney Catchment Authority (SCA) drinking water supply catchment. Longwall mining is currently active below Waratah Rivulet and this increases surface water and groundwater interconnectivity. The applied tracer test is to be carried out to examine groundwater and surface water interconnectivity.

Fluorescent dye tracers will be added to the shallow Hawkesbury Sandstone aquifer system underlying the Rivulet (via borehole injection) to map the fracture network and to identify locations where groundwater re-emerges. The experiment will be undertaken over a river reach that has a straight line distance of 3 km and is heavily impacted upon by surface rock cracking. Ultimately this study will provide valuable insights into the flow characteristics of an aquifer which has been altered by longwall mining related subsidence.

Background

The Waratah Rivulet sub-catchment is situated approximately 31 km north of Wollongong and is located within the larger Woronora River Catchment Area. The Waratah Rivulet Catchment is part of the Woronora Special Area, which is a protected catchment that supplies water to the Woronora Dam. This dam is the sole source of supply to Helensburgh and the Sutherland Shire (PB 2007).

Environment

The terrain in the catchment is typical of areas underlain by Hawkesbury Sandstone and is characterised by steep and rugged, inaccessible areas, with outcropping sandstone, incised gullies and elevated plateaus. Exposed sandstone outcrops are often interspersed with pockets of residual and colluvial sandy soils of relatively low fertility (PB 2007).

The Waratah Rivulet flows in a northerly direction and its headwaters are in the Darkes Forest. Forest Gully and Un-named Tributaries are two tributaries to the Waratah Rivulet. The Rivulet stream bed is comprised almost entirely of sandstone rock outcrops and rock bars. The channel profile is 20-30 m wide (PB 2007).

The climate is temperate to subtropical and the area receives a relatively uniform distribution of rainfall throughout the year. Rainfall records maintained by the Bureau of

Meteorology from 1894 to 2009 (Darkes Forest Station) indicate that the average annual rainfall within the Catchment Area is 1,427 mm (PB 2007).

The geology of this area comprises a gently deformed sequence of Mid Triassic sandstone that forms the upper sequence of the Sydney Basin sediments. The surface geological unit exposed through much of the Waratah Rivulet catchment area is the Hawkesbury Sandstone. This sandstone unit overlies other sandstones (Newport Formation, and Bulgo and Scarborough Sandstones), claystones (Bald Hill and Stanwell Park Claystones) and shales (Wombarra Shale) of the Triassic Narrabeen Group. Underlying the Narrabeen Group is the Permian Illawarra Coal Measures. The total thickness of the Hawkesbury Sandstone exceeds 100 m with the Narrabeen Group having more than 430 m thickness.

The recognised regional aquifers are within the Hawkesbury Sandstone and the Narrabeen Group sandstones at Waratah Rivulet. Despite having generally low permeability the Hawkesbury Sandstone unit has relatively higher permeability compared to the other geological units and secondary porosity (fractures) dominate over primary porosity (Merrick 2008).

Mining

Longwall mining is currently undertaken in the Waratah Rivulet sub-catchment. The mining lease covers an area of 5,195 hectares (PB 2007). Mining occurs in the upper coal seam unit of the Permian Illawarra Coal Measure, known as the Bulli seam, which has a thickness of 3.2- 3.6 m across the catchment area. The Permian Illawarra Coal measures underlie the Narrabeen Group. The longwall panels lie directly underneath the catchment in a southwest – northeast direction, 450 – 500 m below the ground surface.

Longwall mining has resulted in visible fracturing and subsidence of the rivulet streambed. Mining in the Waratah Rivulet sub-catchment has enhanced aquifer recharge rates as subsidence related fractures, joints and bedding planes have increased permeability and porosity of the Hawkesbury Sandstone aquifer (Jankowski 2007a). The aquifer discharge areas occur within the area impacted by longwall mining. Increased subsurface flow in the Hawkesbury Sandstone aquifer and the resultant water-rock interactions have caused changes to the chemical composition and ultimately the water quality (Jankowski 2007b).

Fluorescent dye injection technique

The technique presented in this paper is being used to verify the results of the previous environmental tracer test completed for the study area (PB, in progress). An advantage of the dye injection technique is the ability to produce real time results that can be monitored in the field and then later verified in the laboratory.

There are of course uncertainties associated with this technique. Firstly, when dye is added to the shallow groundwater system it is assumed that the dye is either remaining in the shallow aquifer system or returning to the surface further downstream. However, if partial amounts of dye are lost the pathway and mechanisms of this loss (which may be to deeper groundwater aquifers) will not be able to be analysed as there are currently no bores present in the deeper aquifers to monitor any such losses. Alternatively the lack of dye breakthrough further downstream may be a result of dye sitting at a lower depth in the bore than a fracture, of which water is flowing through.

A margin for error may be encountered when preparing and injecting the dye in the field. Small amounts of dye may be lost during the mixing and transport process, or may be lost to the surrounding surface water during injection. Steps will be taken to minimise this loss during the entire tracer test.

Methodology

Prior to this study a series of monitoring bores were installed by the Metropolitan Colliery at various points along the rivulet. These bores are located upstream, within and downstream of the main impacted zone along the valley floor. Sampling of monitoring bores and surface water from the rivulet was also undertaken to establish natural background levels of fluorescence in groundwater and surface water, and to determine the suitability of dye tracers for this investigation.

For the tracer testing program, fluorescent dyes (Fluorescein and Rhodamine WT) will be injected into a bore upstream of the main impacted zone (WRGW5) and in a bore located in the impacted zone (WRGW3) during low flow conditions. Fluorescein will be used for the tracer in the upstream bore (WRGW5) as this bore is at a greater distance from the sampling locations than the downstream bore (WRGW3). Rhodamine WT will therefore be used at the downstream bore. During the test monitoring will take place in bores (via both activated carbon samplers and Waterra 25 mm foot valves), along the rivulet at selected surface water locations where there is visible groundwater return and at the most downstream gauging station.

Sampling Regime

The sampling regime was devised with the knowledge that movement along the rivulet is extremely difficult and must be done on foot (with distances up to 3 km) and with limited resources, so cost effective measures must be employed. To compensate for this automatic samplers will be used at crucial sample locations and durable lightweight sampling housing devices will be engineered.

Figure 1 is a map of the study area and shows the upper and lower limits of the study area. The positions of the dye injection points are given, as well as the location of sampling sites and groundwater return sites. A further sample will be collected upstream of the dye injection test to provide a control background sample. These sites have been indentified through field reconnaissance.

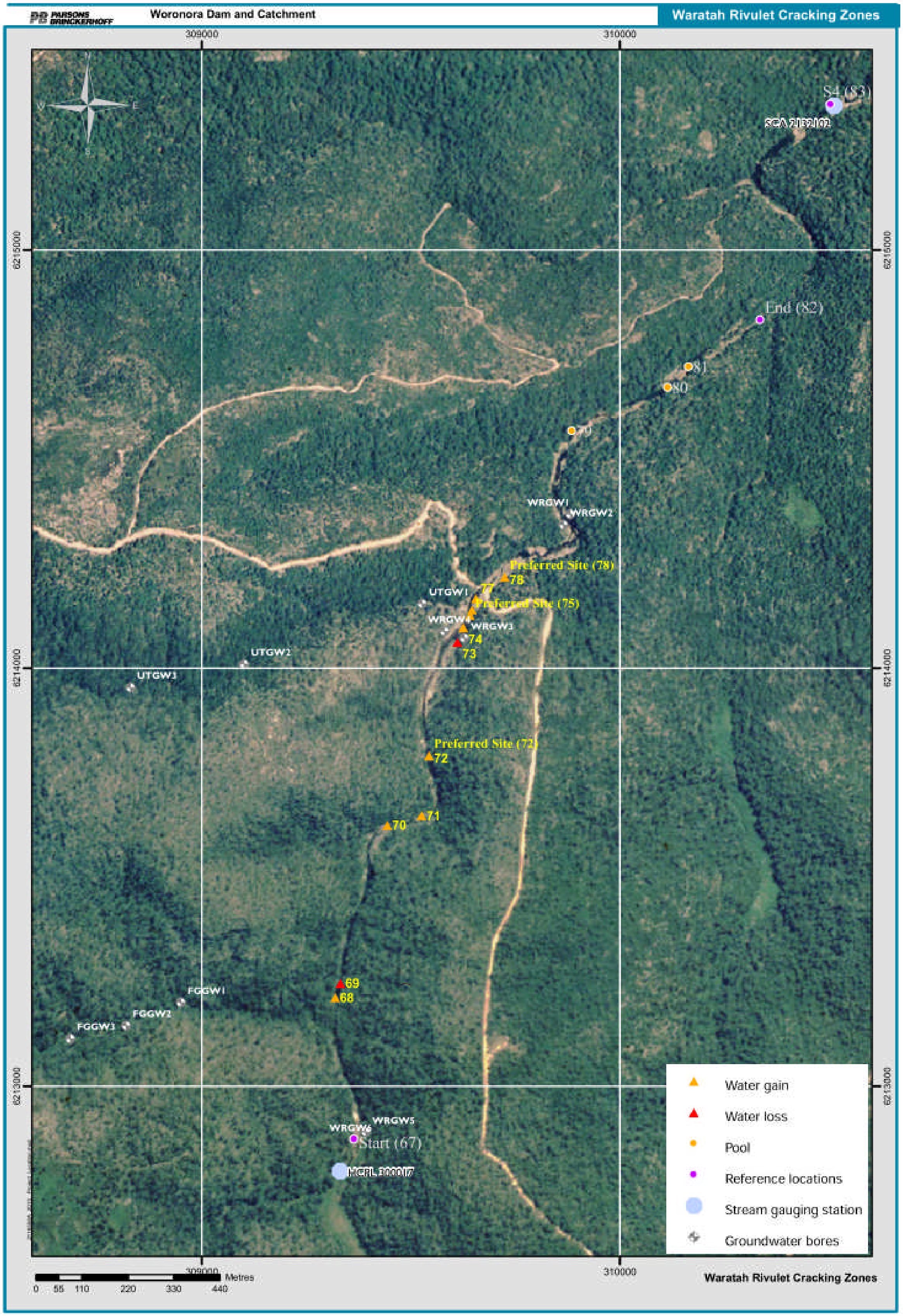
PARSONS BRINCKERHOFF
Woronora Dam and Catchment
Waratah Rivulet Cracking Zones
309000
310000
6215000
6214000
6213000
N
E
W
S
S4 (83)
SCA 2132102
End (82)
81
80
79
WRGW1
WRGW2
Preferred Site (78)
78
77
UTGW1
Preferred Site (75)
WRGW4
WRGW3
74
73
UTGW2
UTGW3
Preferred Site (72)
72
71
70
69
68
FGGW1
FGGW2
FGGW3
WRGW6
WRGW5
Start (67)
MCPL 2000017
Water gain
Water loss
Pool
Reference locations
Stream gauging station
Groundwater bores
0
55
110
220
330
440
Metres
Waratah Rivulet Cracking Zones

Figure 1: Location map

Samples will be collected by a variety of methods including:

- Two automatic sampling devices (Sigma 900 Series Portable Water Sampler) will be used to collect samples every 2 hours for the duration of the test. These samples will be analysed in the field using a portable flurometer.
- Surface water grab samples will be collected at various time intervals down the entire reach of the rivulet. These samples will be analysed in the field using a Turner Aquafluor portable flurometer, which will allow the concentration of dye to be calculated.
- Activated carbon sampling units will be positioned along the rivulet and in the groundwater bores. For surface water samples the activated carbon samples will be housed in devices that allow water to freely pass through, while restricting sunlight to prevent photodegradation of the dyes. These samples will be sent to Ozark Underground Laboratory in the United States for analysis.
- Sampling from groundwater bores will be carried out via Waterra 25mm foot valves and Waterra hose and analysed in the field using the portable flurometer mentioned above.

Quantity of dye required

The volume of dye used for both of the tracer tests was determined using information from the EPA (1988), Aley and Fletcher (1976) and Aley (2002). Based on this data 2 kg of Fluorescein and 0.5 kg of Rhodamine WT were determined to be appropriate amounts of dye.

Preparation of the dye solutions

Fluorescein: As Fluorescein dye is in a powder form it will be mixed with water from the rivulet before being added to bore WRGW5. Aley (2002) recommends the addition of water directly to the manufacturers supplied container (total volume 20 L, of which 4 kg is dye) until the container is 80 % full, giving a solution of around 250 g/L. For the purposes of this study 2 kg will be removed from the container and water will be added to make a total volume of 16 L. This will give a final dye concentration of approximately 125 g/L.

Rhodamine WT: Rhodamine WT dye is known to produce large amounts of foam when mixed with water. Therefore, the dye will be added in liquid form using a doser directly to the borehole. Rhodamine WT dye as a 20% solution (0.5 kg or 0.48 L) will be added slowly and below the water level and therefore should not require any additional mixing.

Dye injection

Due to the rugged nature of the catchment and the fact that all sampling devices and materials will have to be carried in manually lightweight gear is essential. The solution was found in lightweight fish tank pumps that were modified to run on 12V DC power and provide a constant flow rate.

The dyes need to be added at a rate of less than 5 L/min to prevent foaming and to allow sufficient mixing/dilution into the groundwater. The dyes will have to be injected below the groundwater level, preferably at or close to the screened interval of the bores.

Following the addition of the dye solution clean water will be pumped from Waratah Rivulet into the bore at a maximum flow rate of rate of 4.5 L/min. This will be carried out until the measured dye concentration in the bore is below the detection limits, thus ensuring the dye is flushed through the system. Up to 1,000 L of water is anticipated to be used during pumping and the outlet of the pump will be placed at the bottom of the bore (below the screened depth if necessary) to flush out residual trapped water. During this flushing process it may be necessary to monitor the amount of foaming. If excessive foaming occurs the pump will be shut off to allow the foam to dissipate. The water level in the bore will be monitored using a dip meter and the flow rate will be recorded to ensure that the water level does not change by more than 0.5 m.

Results interpretation

It is expected from this investigation that a detailed picture of groundwater- surface water interconnectivity and a further understanding of the impacts of longwall mining on the groundwater system will be obtained. The volume of groundwater lost may be quantified from the test, by measuring the volume of water and concentration of dye at both the injection and sampling points.

The data produced from this study will also be used in conjunction with hydrogeochemical data that has been collected monthly since February 2007.

Conclusions

Applied tracers have proven to be particularly powerful investigative tools in hydrogeology studies because the application and monitoring of the tracer can be designed and implemented in a controlled way and can therefore be used to quantify transport parameters and aquifer properties. Applied tracers have been used for an increasing number of hydrogeological applications over the last three decades, including the investigation of groundwater-surface water interaction.

An applied tracer test is being undertaken in the Waratah Rivulet sub-catchment to investigate the impact of longwall mining activities and subsequent subsidence on water flow and water quality in water supply catchments. Specifically the tracer test study will address the impacts to the hydrologic water balance and quantify the loss of surface water baseflows into subsurface fractures.

In the design of the tracer test a number of factors were considered and include: the rugged terrain, remoteness, and suitability of dye tracers in the groundwater and surface water system. The test has been designed to produce a cost effective, scientifically robust method to assess groundwater-surface water connectivity.

The tracer test will provide data that can be used to quantify groundwater-surface water interactions and ultimately will also give further information about fracture networks. The outcome of the study will be an enhanced understanding of the impact of longwall mining activities on drinking water supply catchments, particularly on surface water flow and quality and water balance. The results of the study will provide sound, scientific data which the SCA can utilise to develop future management options and a framework for monitoring and assessment of impacts of longwall mining on flow and water quality.

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Keynote address

Cracks in the Clay: The Role of Fractures and Macropores in Critical Zone Hydrology

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Abstract

Fine-grained geologic deposits often contain extensive networks of fractures, root holes and other macropores which can strongly influence groundwater flow and contaminant transport. The extent and depth of these features varies greatly according to the origin and geologic/pedologic history of the material. Rootholes typically persist to depths of only a few meters, although in some clays they can be found at much greater depths. Desiccation fractures, which are common in glaciolacustrine deposits, also tend to rapidly decrease with depth, but fractures caused by sub-glacial stresses may be pervasive throughout thick till seququences. Recent research in weathered clay-rich residuum developed on sedimentary rocks in east Tennessee show evidence of fractures and fracture-induced flow to depths of up to 40 m. Fractures and macropores can also act as pathways for transport of natural and anthropogenic constituents to underlying aquifers. Solutes are transported by advection along the fractures/macropores but can also be strongly attenuated by diffusion into the fine pore structure. In contrast, mineral colloids and microorganisms, are largely size-excluded from the fine-pore structure and hence can travel at much faster rates than solutes. Field tracer experiments in fractured clays in Canada, Denmark and Tennessee showed colloid transport rates of a few m/day to >100 m/day at sites where solute tracers were transported at rates that were 100s of times slower. Immiscible phase liquids, such as industrial solvents or coal tar, can enter some fractures or macropores, even in relatively low hydraulic conductivity materials and can

lead to extensive contamination. These immiscible liquids dissolve and diffuse into the fine pore structure, where they can act as long term sources of contamination to adjoining streams or underlying aquifers. Although there has been substantial progress over the past 25 years in developing a better understanding of the role of fractures in controlling flow and transport in clay-rich deposits, considerable work remains to be done. This includes better education of geo-environmental researchers and professionals, as well as development of better conceptual and numerical models of fracture origin, vadose and saturated zone flow, and contaminant transport.

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Investigating groundwater-surface water linkages using environmental and applied tracers

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Abstract

Some of the most important groundwater and surface water resources of the Sydney Basin occur across the Woronora and Illawarra Plateaus and the Southern Highlands south of Sydney. They support natural environments, and consumptive uses including raw water for potable water supply for the Greater Sydney area, water supply for irrigation and domestic use, mining and industrial/commercial uses. However, groundwater and surface water are not discrete water sources and the interaction between the two systems is complex, variable and often poorly understood. Exploration, development and use of one can affect the other and may have far reaching impacts on the environment and water users. Environmental and applied tracers are useful for assessing this relationship and the extent of potential impacts due to changes in human activity.

This paper describes the use of environmental and applied tracers as a tool for assessing groundwater-surface water interactions. The paper addresses some of the different methodologies which may be applied to assess interconnectivity in the context of a field trial undertaken in a water supply catchment in the Sydney Basin area to assess the impacts of groundwater extraction in a fractured rock aquifer system. This tracer study made use of various combinations of dissolved gas and fluorescent dye tracers as well as environmental isotopes (oxygen-18 ($\delta^{18}O$), deuterium (δD), tritium (^{3}H), carbon-14 ($a^{14}C$)).

The paper focuses on the benefits of using multiple techniques for assessing groundwater-surface water interactions. It examines what each methodology adds to the understanding of the processes occurring as a whole, and how combining these methods with typical water quality analysis can provide a cost effective, efficient method to obtain a comprehensive picture of the hydrogeological setting.

Keywords: applied tracers, environmental tracers, surface water-groundwater interaction

Introduction

Management of surface water and groundwater as a single resource with respect to water quantity and quality is currently increasing worldwide. However, to successfully achieve this detailed scientific data is required. Over time, a number of scientific methods have been developed for the assessment and quantification of groundwater-surface water connectivity however applied and environmental tracers are now often preferred for quantification of groundwater-surface water connectivity because of the shortcomings of other scientific techniques.

Applied tracers are non-natural constituents that are intentionally introduced into the groundwater or surface water system, such as dissolved gases and dyes, and they have proven to be particularly useful investigative tools for the assessment of groundwater and surface water connectivity. They are a powerful tool because tracer application is controlled and well characterised and can therefore be used to quantify groundwater-surface water interactions, and they can be used to provide information on groundwater flow paths, travel times, velocities, dispersion, flow rates and the degree of hydraulic connection (Divine & McDonnell, 2005). Environmental tracers are naturally occurring constituents and can provide independent estimates of groundwater flow and groundwater-surface water linkages.

This paper presents a case study from the Doudles Folly Creek catchment located in the Southern Highlands, NSW, involving the use of applied and environmental tracers to assess groundwater-surface water connectivity. The study was undertaken as part of the Sydney Catchment Authority's groundwater investigations in the Upper Nepean catchment investigating the suitability of the Hawkesbury Sandstone aquifer system for drought water supply (PB, 2009).

The study was undertaken to address two main objectives. The first objective was to determine the degree of connection between the fractured Hawkesbury Sandstone aquifers and surface water in the Doudles Folly Creek sub-catchment and to better understand flow in the fractured aquifers. The second main objective was to assess the sustainability of groundwater extractions in this area and quantify the impacts on creek flow if part of a large borefield were to be developed in this area.

Environmental Setting

The Doudles Folly Creek catchment is a sub-catchment of the Nepean River catchment and is approximately 5 km^2 in size. The catchment is located approximately 100 km south-west of Sydney. The geology of the area comprises the gently deformed sequence of Triassic sandstones and shales that form the upper sequence of the Sydney Basin sediments. Within the study area, the Hawkesbury Sandstone (a quartzose sandstone) is the outcropping geological unit, and has a thickness of up to 130 m. The geological structure of the study area is complex, with significant uplift and fracturing producing a series of north-northwest trending faults in the area.

The Hawkesbury Sandstone is a dual porosity, semi-confined aquifer and forms the main productive aquifer across the investigation area. Most of the regional groundwater discharge is to the incised (gorge) areas of the catchment located about 10 km north of the study area, and locally groundwater provides a continuous baseflow to Doudles Folly Creek.

In the local area, there is a great variation in the size, nature and distribution of fractures, and therefore the hydraulic properties of the aquifer. Fractures are both vertical and horizontal, and many are associated with bedding plane features. Downhole camera profiling was undertaken in test production bores to identify fracturing at the borehole wall. The profiling showed that fracturing was extensive, with up to 20 major fracture zones identified over 100 m thickness in bore 1A. The fractures varied in size from a few millimetres to nearly 0.5 m, with most fractures ranging from a few millimetres to centimetres. Fracturing in the catchment has resulted from different geological processes including uplift and faulting, and igneous intrusion. Airlift yields vary from 5 L/s to 40 L/s, depending on the degree of fracturing.

Doudles Folly Creek is a small perennial stream and is classified as a bedrock (sandstone) confined channel (SCA, 2007). In the study area, at least seven groundwater discharge zones have been identified along this portion of Doudles Folly Creek (SCA, 2007) and the stream is considered to be connected-gaining under natural conditions. The baseflow contributions from the sandstone aquifers are negligible compared to natural flows that are a mixture of catchment runoff, baseflows from basalt aquifers higher in the catchment, and inter-basin flows. The stream is used for water conveyance of Shoalhaven River water between Sydney water supply dams. Flows can be high during transfers (up to several thousand L/s) and the aquifer-stream flux temporarily changes in the near vicinity of the creek during these transfers. During the testing period flow rates were high, with Shoalhaven transfers (maintained at 200 ML/day for most of the period) along Doudles Folly Creek.

Methodology

In this study an applied tracer (dissolved gas, SF_6) was used in conjunction with environmental isotopes (^{18}O, D, ^{3}H and ^{14}C) during a long term (60-day) pumping test to assess the hydrologic impacts of pumping on groundwater water-surface water connectivity in the fractured rock aquifer system. An additional short term test using fluorescent dye tracer test was undertaken during pumping to constrain transport parameters, particularly those that are important in dual-domain (non-equilibrium) systems, as would be expected for fractured sandstone.

The pumping test was run on test production bore 1C for 60 days. For the first 30 days the bore was pumped at a rate of 25 L/s and in the second stage the bore was pumped at 32 L/s. Within the first few days, the stream dynamics change from connected-gaining to connected-losing and, as indicated by stream and groundwater hydrographs. Sulfur hexafluoride gas was continuously applied to Doudles Folly Creek during the test. Samples were collected regularly from the pumping bore, eight monitoring bores and five surface water locations and analysed for SF_6 on a gas chromatograph (Fig. 1). Groundwater samples were also collected from discrete fracture zones in an uncased monitoring bore (1A) for SF_6 analysis during the pumping test once SF_6 concentrations had stabilised in the pumping bore.

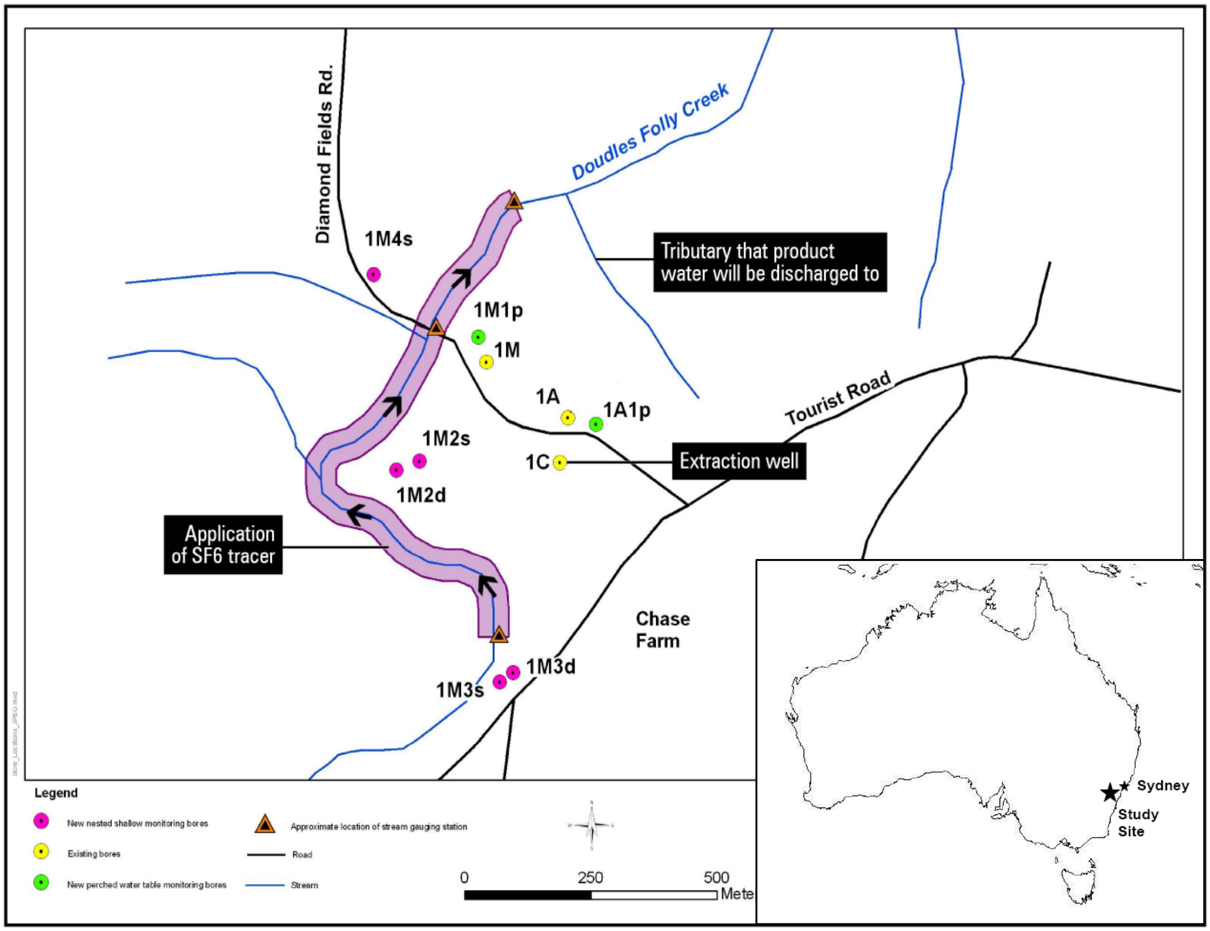

Figure 13 Site location, layout and monitoring network

The short term testing was undertaken by spiking 3,000 L of water with 120 g powdered fluorescein dye. The dye mixture was pumped into the uncased monitoring bore 1A and samples collected from pumping bore for dye analysis using a fluorometer.

Samples were collected for isotope analysis (^{18}O, D, ^{3}H and ^{14}C) from the pumping and monitoring bores, and the creek prior to pumping to establish baseline conditions and several times during the pumping test. The stable isotopes of water (^{18}O and D) were analysed at CSIRO Land and Water Laboratory, Adelaide. Tritium was analysed at GNS Science Tritium and Water Dating Laboratory, New Zealand and ^{14}C was analysed at Rafter Radiocarbon Laboratory, New Zealand.

Results

Dissolved gas tracer test

Tracer breakthrough curves for SF_6 for the pumping bore 1C is shown in Fig. 2 (note that bore 1C is the pumping bore). These results clearly verify stream loss occurred during pumping. Using potential theory (Charbeneau, 2000) the percent of extracted water derived from the stream after long periods of pumping can be calculated. It was calculated that approximately 5% of water produced at the pumping bore was derived from the SF_6 applied reach of Doudles Folly Creek in the later stages of the test.

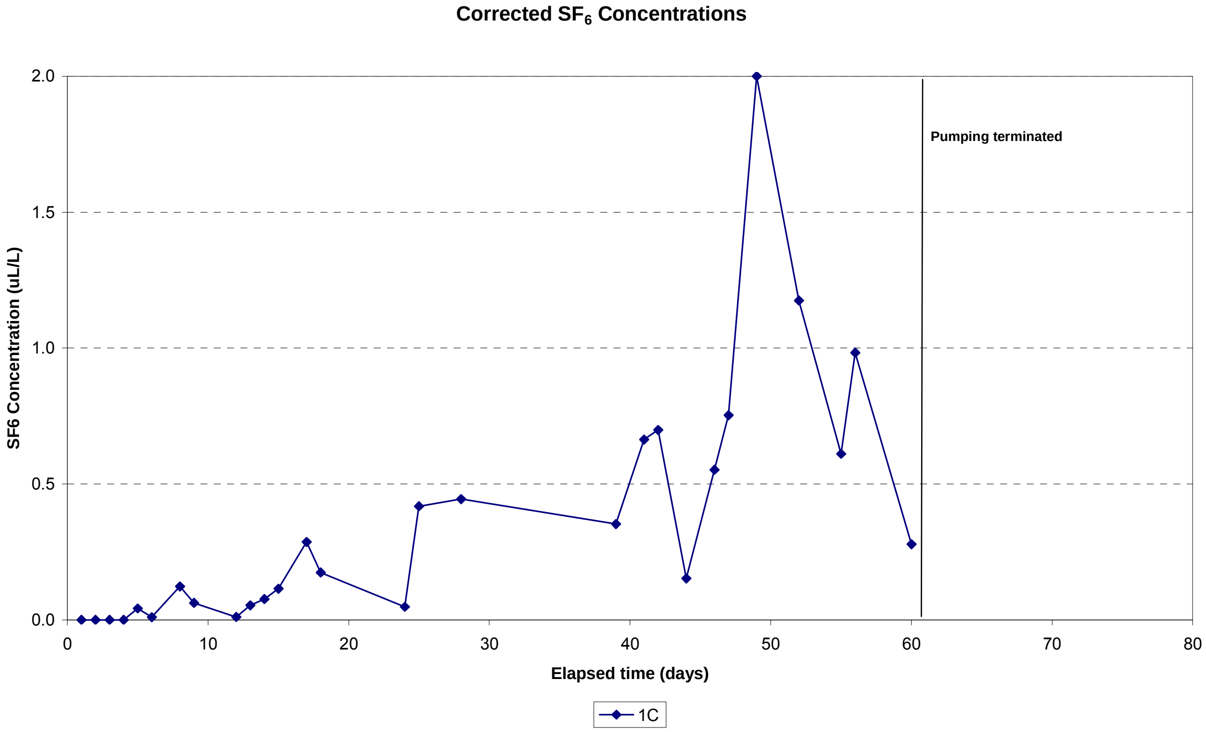

Figure 2 SF_6 tracer breakthrough curves for the pumping bore (1C)

The results also indicate that the pumping resulted in a strikingly fast transport velocity. The pumping bore is located approximately 260 m from Doudles Folly Creek and SF_6 was detected in less than 5 days, indicating a transport velocity within the primary pathways on the order of 60 m/day. Tracer breakthrough (appearance of tracer in groundwater) occurred in the deep pumping bore first and breakthrough times increased as bore depths decreased. The breakthrough times indicated that hydraulic connection between the creek and pumping/monitoring bores is dominated by a primary fracture zone. The speed of breakthrough suggests that this horizontal fracture zone must be connected to a vertical fracture(s) in the creek streambed. This is supported by the findings of the SCA creek bed survey (SCA, 2007) which identified seven groundwater discharge (fracture) zones in the reach of Doudles Folly Creek within the study area.

SF_6 concentrations were measured in discrete fracture zones in the adjacent monitoring bore 1A once during the pumping test. The lowest concentrations of SF_6 occurred in the deepest fractures. The highest concentrations were detected in the fracture zones at 51 m (2.107 µL/L) and 43 m (1.042 µL/L**)**. These results indicate that Doudles Folly creek is connected to bore 1A by a fracture system located predominantly between 43 and 51 m. Approximately 7% of the water present in the fracture zone at 51 m is surface water from Doudles Folly Creek.

Dye tracer test

A short-term (one day) dye tracer test was undertaken at bore 1A to estimate and constrain transport parameters. Dye breakthrough was monitored in the pumping bore

(1C). As with the SF_6 tracer test, fluorescein tracer arrived at the production bore quickly, within approximately 15 minutes. Based on the distance between the bores, this results in a transport velocity of approximately 3 m/min. The peak concentration arrived within approximately 60 minutes at a relative concentration of just under 0.01, or 10 %. Some minor "tailing" is present in the elution front of the breakthrough curve and data from a repeat test (not shown) confirms some limited mass exchange between the flowing fracture zone and the aquifer matrix. Numerical integration of the tracer breakthrough curves indicates that approximately 40 % of the fluorescein was recovered within 250 minutes. These results clearly indicate that hydraulic connection between the two bores is dominated by a single primary fracture zone, and supports the findings of the SF_6 packer test.

Environmental tracers

In the Doudles Folly Creek Catchment, groundwater from the Hawkesbury Sandstone aquifers under baseline (non-pumping) conditions has an average stable isotopic composition of –6.48‰ for $\delta^{18}O$ and –34.2‰ for $\delta^{2}H$ (n = 87). Groundwaters are interpreted to be of meteoric origin. Surface water has a more enriched isotopic signature, with an average $\delta^{18}O$ value of -5.20‰ and average $\delta^{2}H$ value of -28.3‰ (n = 33)

Under baseline conditions (non-pumping conditions), uncorrected radiocarbon ages in the Hawkesbury Sandstone aquifer system ranged from 3,550 yrs BP to 14,575 yrs BP, and corrected ages ranged from modern (<50 yrs BP) to 7,650 yrs BP. Groundwater ages increased along the regional flow path in a north and north-easterly direction, and also with depth. The average corrected radiocarbon age in the pumping bore 1C (prior to pumping) was 5,200 yrs BP.

Tritium concentrations in the Hawkesbury Sandstone aquifer system under baseline (non-pumping conditions) ranged from 0.015 TU to 0.827 TU, indicating that a small proportion of modern water is present in the aquifer system due to rainfall recharge. The tritium results were consistent with the radiocarbon results, with the monitoring bores with the youngest radiocarbon ages having the highest tritium concentrations. The average tritium value for the pumping bore 1C (prior to pumping) was 0.037 TU.

Stable isotope values became significantly more enriched during the 60-day pumping test in monitoring bore (1M) drilled to a depth of 42 m. The stable isotope values for 1M shifted from -6.39‰ for $\delta^{18}O$ and -35.3‰ for $\delta^{2}H$ prior to the pumping test to -5.77‰ for $\delta^{18}O$ and -29.1‰ for $\delta^{2}H$ at the end of the pumping test. This shift in isotopic signature towards that of surface water was due to induced recharge of surface water from Doudles Folly Creek. These results indicated this bore had a greater hydraulic connection with the creek than the other bores. Minor changes in stable isotope values were recorded in other monitoring bores and the pumping bore 1C but were not statistically significant.

During the 60-day pumping test radiocarbon ages significantly decreased in some monitoring bores and the pumping bore 1C, with the corrected ages ranging from <50 yrs BP (modern) to 4,750 yrs BP. The average corrected radiocarbon age in bore 1C was <1,000 yrs BP (n=6). Groundwater ages were younger with increased pumping due owing to induced recharge of surface water from Doudles Folly Creek and mixing with older groundwater.

Tritium concentrations increased significantly in the monitoring bores and pumping bore 1C during the 60-day pumping test, with values ranging from 0.046 TU to 0.861 TU. The tritium concentration in the pumping bore 1C increased from 0.140 TU two weeks into the pumping test to 0.172 TU at the end of the pumping test. Based on the concentration of tritium measured at the pumping bore during the latter portion of the test, an average of about 4% of the produced water from bore 1C was derived from Doudles Folly Creek.

Conclusions

The results of the environmental and applied tracer test indicate that there is a hydraulic connection between Doudles Folly Creek and the Hawkesbury Sandstone aquifer system. Under natural conditions, groundwater provides baseflow to the creek at several point source locations; however, this is reversed under pumping. The stream dynamics change from connected-gaining to connected-losing then to disconnected-losing.

The results of the gas tracer test showed that near the end of a 60-day pump test approximately 4-7% of water produced at the pumping bore was derived from Doudles Folly Creek, and these results were validated by the tritium concentrations in the pumping bore at the end of the test. The results of the applied tracer (SF_6 and fluorescein) and environmental tracers have shown that that a highly fractured and localised flow system between 40 and 60 m is the primary pathway for surface water movement during pumping.

This research study has concluded that the primary mechanism for groundwater-surface water interaction (both gains and losses) is through fracture zones within the creek bed, and connectivity is significantly limited where fractures are not present. The research study has also shown that where fractures are present in the Hawkesbury Sandstone aquifer, secondary porosity and permeability is the main source of water as opposed to primary porosity. The combination of multiple applied and environmental tracer techniques used in this study has proven to be a powerful toolbox for assessing groundwater-surface water linkages. Used in combination, these techniques were successful in quantifying linkages and validated the results of the applied tracer tests. The study provided quantitative data for understanding the groundwater-surface water system and the impacts pumping (up to 60 days) would have on baseflows. This study has also provided detailed information for borefield planning approvals and operational strategies should borefield development occur. The study has also shown that the creek is suitable for inter-basin transfers, with the surface water losses to groundwater measured during the study equating to between 0.04% (under transfers of 400 ML/day) and 5% (under lowest baseflows 3 ML/day) of the streamflow.

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Hydrochemistry of the Hawkesbury Sandstone Aquifers in Western Sydney and the Upper Nepean catchment

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Abstract

Hydrogeological investigations have been undertaken at three locations in the Sydney Basin as part of the New South Wales Government's Metropolitan Water Plan (MWP) strategy to assess the potential for use of groundwater during periods of severe drought. Extensive groundwater drilling and testing programs have been carried out since 2005 at Wallacia-Warragamba and Leonay-Emu Plains in western Sydney and in the Upper Nepean catchment in the Southern Highlands. Drilling and testing in the Wallacia and Leonay areas targeted the Hawkesbury Sandstone and a major regional structural feature, the Lapstone Structural Complex, which is known to have increased the fracturing and permeability of the sandstone. In the Upper Nepean catchment, drilling and testing targeted the highly fractured and faulted blocks of Hawkesbury Sandstone associated with the Mittagong Horst-Graben Complex.

This paper presents the findings of chemical and isotopic studies undertaken over a three year period as part of the drilling and hydrogeological testing programs in the three investigation areas. These studies were undertaken to determine baseline chemical characteristics of aquifers and surface water systems, identify groundwater-surface water linkages, and assess inter-aquifer linkages. Chemical and isotopic studies were also completed to confirm the age of groundwater and provide further information to assess the feasibility and long-term sustainability of potential bore field development.

This paper focuses on the variations in groundwater chemistry and age at the three locations which are related to the complexity of the geological structure. In the Upper Nepean catchment, groundwater is characterised by low salinity and relatively young "modern" water in the uplifted and highly fractured sandstone aquifers. At Wallacia and Leonay, brackish groundwater occurs in the upper part of the Hawkesbury Sandstone, downgradient of the Lapstone Monocline, while fresher and relatively older groundwater occurs at depth. Variations in water chemistry occur at Wallacia where igneous intrusions, such as the Nortons Basin Diatreme, are present, and where significant faulting has occurred along the Nepean Fault.

Keywords: hydrochemistry, environmental isotopes, Hawkesbury Sandstone

Introduction

In 2004 the New South Wales Government released the Metropolitan Water Plan (MWP), which was updated in May 2006. The MWP outlines measures for Sydney to achieve a sustainable and secure water supply for people and rivers for the next 25 years. The strategies to ensure Sydney's water future are through optimising water supplies from the existing system, recycling, tapping new water supplies and sustainable usage of industrial and domestic water supplies. Groundwater resource development that produces additional supplies during severe drought was part of the MWP initiative.

One of the drought management strategies set out in the MWP is to investigate the potential use of groundwater reserves in the Sydney Basin to supplement water supply during severe drought. Seven priority investigation sites were identified in an earlier desktop study (PB, 2003) and have since been investigated. The MWP was revised in early 2006 and groundwater was confirmed as one of the main drought water supply options for Sydney. In November 2006, Government announced that borefield development was to proceed at Kangaloon and pilot investigations at Leonay and Wallacia were to continue. If successful then borefield development would also be considered for these areas.

In June 2008 (primarily as a result of rising dam storage levels) Government announced the deferral of the construction of the Kangaloon borefield and that no further work would be undertaken at Leonay and Wallacia after the conclusion of the pilot testing program.

Extensive investigations of groundwater prospects from the Hawkesbury Sandstone were undertaken at three of the seven priority locations in the Sydney Basin from 2005-2008: Wallacia-Warragamba and Leonay-Emu Plains in western Sydney and in the Upper Nepean catchment at Kangaloon in the Southern Highlands. Drilling, geophysical logging and test pumping of multiple test production and monitoring bores were conducted to characterise the geology and hydrogeology of the three areas and to confirm the presence and variability of a groundwater resource within the Hawkesbury Sandstone strata with potential to supplement Sydney's water supplies during periods of severe drought.

Drilling and testing at the Wallacia and Leonay sites targeted the Hawkesbury Sandstone and a major regional structural feature, the Lapstone Structural Complex (LSC), which is known to have increased the fracturing and permeability of the sandstone. In the Upper Nepean catchment, drilling and testing targeted the highly fractured and faulted blocks of Hawkesbury Sandstone associated with the Mittagong Horst-Graben Complex (Fig.1).

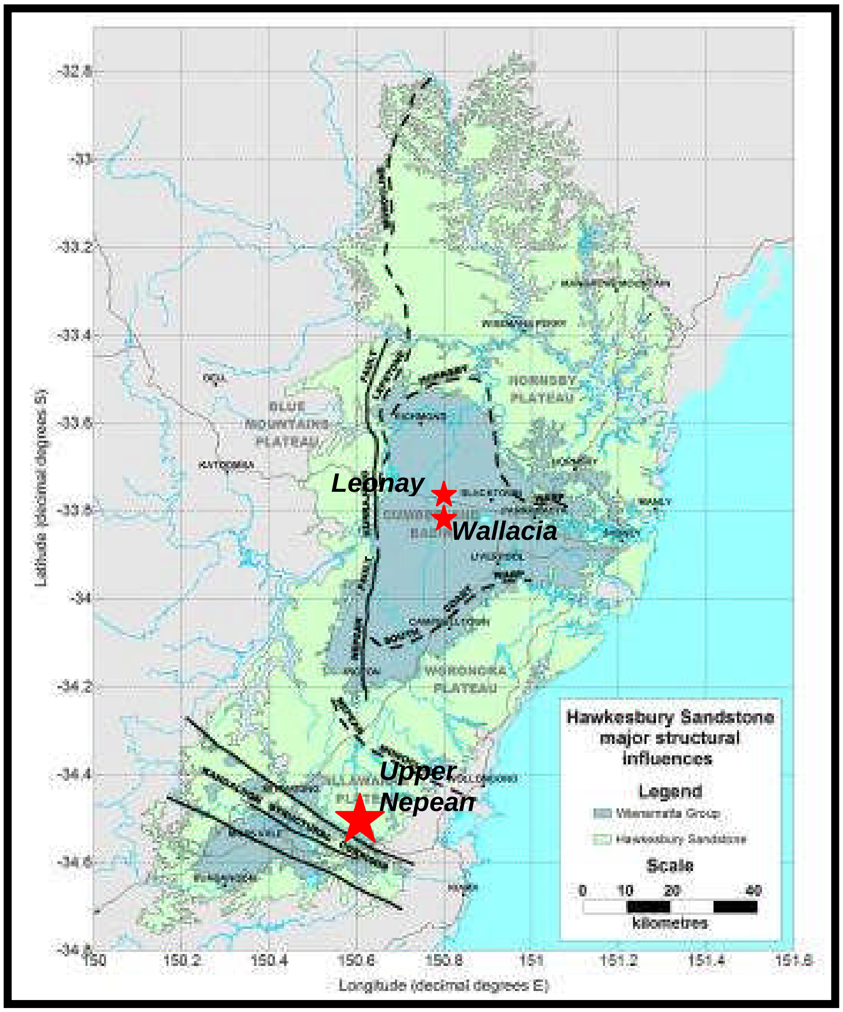

Figure 1. Hawkesbury Sandstone structural influences (after Russell, 2007)

As part of these groundwater resource investigations chemical and isotopic studies were undertaken to determine baseline chemical characteristics of aquifers and surface water systems, identify groundwater-surface water and inter-aquifer linkages, assess recharge mechanisms and groundwater residence times and provide further information to assess the feasibility and long-term sustainability of potential bore field development (PB, 2006a, 2006b, 2007a, 2007b, 2007c, 2008a, 2008c, 2008d, 2008e, 2009a, 2009b). This paper presents a brief summary the findings of chemical and isotopic studies undertaken over a three year period as part of the drilling and hydrogeological testing programs in the three investigation areas.

Physical setting

The Hawkesbury Sandstone is a dual porosity regional aquifer system that occurs across most of the central Sydney Basin. Groundwater flow is highly variable throughout the Hawkesbury Sandstone and is generally dominated by secondary porosity and fracture flow associated with structures such as faults and fracture zones. However, minor primary granular flow is also likely to occur. Bores that intercept major fractures can yield in excess of 40 L/s, whereas bores that do not intercept fractures yield <5 L/s. The Hawkesbury Sandstone was the target aquifer at the three groundwater investigation sites.

The Leonay and Wallacia sites are located in western Sydney in the central part of the Sydney Basin. The bores drilled during the Leonay and Wallacia investigations are located on the eastern side of the north-south oriented Lapstone Structural Complex at the foot of the Blue Mountains escarpment in Western Sydney. The bores at Leonay (to the west of the Nepean River at Penrith) are located at the base of the monocline, and at Wallacia (20 km south of Leonay), the bores are located on the eastern side of the Nepean Fault. The Mid Triassic Hawkesbury Sandstone is overlain by Quaternary alluvium, Triassic Ashfield Shale and Mittagong Formations and underlain by Early Triassic Narrabeen Group sediments.

The Lapstone Structural Complex is a major structural feature of the Sydney Basin, and overlies a deep seated basement structure (Branagan and Pedram, 1990). The Complex is indicated by structural lines that extend over 160 kilometres. The Leonay area differs from the Wallacia area in terms of how the basement geological structure is expressed within the overlying sedimentary rocks. Both areas have experienced extensional stresses, from the Triassic to the Tertiary, followed by compression post Jurassic. The Lapstone Structural Complex at Leonay forms a monocline, or series of monoclines, which has resulted in intense flexural fracturing, over the width of the monocline. At Wallacia, the development of the complex has been more brittle, and is expressed as the Nepean Fault (PB, 2008b). Therefore yields were generally higher at Leonay than Wallacia due to intense flexural fracturing (Hawkes et al, 2009; PB, 2008b, 2008e, 2009b). However high yields were obtained in bores in the Wallacia area where fracturing associated with secondary block movement (to the east of the Nepean Fault) or igneous intrusion (Norton's Diatreme) had occurred. In the Leonay area, a palaeochannel is thought to incise the Ashfield Shale beneath a small area of the Nepean River floodplain resulting in a direct hydraulic connection of the alluvium with the Mittagong Formation or Hawkesbury Sandstone. Under non pumping conditions some groundwater would discharge from the Hawkesbury Sandstone or Mittagong Formation to the alluvium under artesian conditions (Hawkes et al, 2009).

In both areas, groundwater recharge to the sandstone is likely to occur on the Blue Mountains plateau to the west of the Lapstone Structural Complex. Groundwater flow is then eastwards towards the Nepean River and the Cumberland Plain. There is a steep gradient across the Lapstone Structural Complex. In the Wallacia area, very shallow and some artesian water levels were measured in bores on the eastern side of the Nepean Fault. To the west of the Nepean Fault groundwater levels are deep (up to 100 mbgl). In both investigation areas, the deep sandstone aquifers are confined.

The Upper Nepean investigation area is located in the south western portion of the Sydney Basin. The geology of the area comprises the gently deformed sequence of Triassic sandstones and shales that form the upper sequence of the Sydney Basin sediments. Within the main investigation area, the Hawkesbury Sandstone is the outcropping geological unit, and has a thickness of up to 180 m. The geological structure of the area is complex, with significant uplift and fracturing producing a series of north-northwest trending faults in the area that are high permeability zones. Uplift has a produced a series of horst and graben structures associated with the Mittagong Horst-

Graben Complex (Lee, 2000). Groundwater exploration has targeted the known highly fractured zones.

Tertiary basalts (Robertson Basalt) cap the sandstone and shale on the Mittagong Ranges in the investigation area. A recent airborne geophysical survey identified an intrusive feature in the investigation area named the Mount Butler olivine intrusive (Webster, 2006). The intrusive is believed to be a laccolith, and several NE-SW trending structures which could represent high permeability zones, were found to be associated with this feature (Webster, 2006).

The Hawkesbury Sandstone is a dual porosity, semi-confined aquifer and forms the main productive aquifer in this area. Most of the regional groundwater discharge is to the incised (gorge) areas of the catchment located about 10 km north of the investigation area, and locally groundwater provides a continuous baseflow to creeks and rivers.

Methodology

Groundwater samples were collected for field parameters and laboratory analysis during the drilling and testing programs. Samples were collected at the completion of each hole following airlifting for hydrogeochemical analysis. Extra samples were collected for isotopic analysis using a stainless-steel double-valved bailer after airlifting, or after purging three well volumes using a submersible pump. Additional groundwater samples were collected during the pumping tests from either the wellhead or discharge pipe.

Samples collected were analysed for a range of physico-chemical field parameters [pH, electrical conductivity (EC), dissolved oxygen (DO), redox and temperature]. After filtration (0.45 μm), samples were processed in the field and stored under recommended preservation conditions until analysis for cations, anions, dissolved metals, nutrients, deuterium (δD), oxygen-18 ($\delta^{18}O$), tritium (^3H) and radiocarbon ($a^{14}C$). The stable isotopes of water (deuterium and oxygen-18) were analysed at CSIRO Land and Water Laboratory, Adelaide. This laboratory determined δD and $\delta^{18}O$ using a Europa Scientific Geo 20-20 isotope mass spectrometer and routine analytical procedures. Tritium was analysed at GNS Science Tritium and Water Dating Laboratory, Lower Hutt, New Zealand, using low-level liquid scintillation spectrometers, with a detection limit of 0.03-0.04 TU, Bq/kg (0.004-0.005) or at the Australian Nuclear Science and Technology Organisation (ANSTO) using liquid scintillation counting with a detection limit of 0.6 TU. The carbon-14 activity of groundwater and surface water samples was determined by atomic mass spectrometry (AMS), at the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences at Lower Hutt, New Zealand.

Discussion of results

A summary of the chemical and isotopic results for the three investigation areas is provided in Table 1 and discussed below. The upper Hawkesbury Sandstone is mostly cased and cemented off at Wallacia so no chemistry results are presented.

Table 6 Summary of groundwater chemistry in the Hawkesbury Sandstone (HS) – Leonay, Wallacia and Upper Nepean

		Leonay		Wallacia	Upper Nepean	
		Upper HS	**Lower HS**	**Lower HS**	**Upper HS**	**Lower HS**
EC (µS/cm)	Ave	787	375	1692	336	190
	Min	317	250	853	47	44
	Max	1661	593	4280	1213	836
pH (pH units)	Ave	6.21	6.13	6.18	5.85	6.12
	Min	5.44	5.02	5.16	4.58	3.71
	Max	7.84	7.83	7.32	7.12	8.36
Ca (mg/L)	Ave	14	12	70	11	6
	Min	6	3	17	1	1
	Max	25	48	225	29	17
Mg (mg/L)	Ave	17	8	54	14	5
	Min	7	5	5	1	1
	Max	45	12	126	50	22
K (mg/L)	Ave	3	4	12	2	2
	Min	2	2	6	1	1
	Max	5	16	49	3	4
Na (mg/L)	Ave	88	27	195	29	12
	Min	5	14	10	5	4
	Max	256	60	581	112	65
Bicarbonate alkalinity (as $CaCO_3$) (mg/L)	Ave	50	70	205	52	32
	Min	1	13	56	1	2
	Max	129	205	952	126	102
Cl (mg/L)	Ave	202	64	457	52	29
	Min	45	33	21	9	6
	Max	506	120	1420	259	245
SO_4 (mg/L)	Ave	17	3	41	9	3
	Min	6	1	2	1	1
	Max	56	8	235	35	25
Fe (mg/L)	Ave	27.27	17.7	21.63	9	12
	Min	0.58	0.16	1.57	0.1	0.05
	Max	49.1	30.3	60.4	18.1	47
Mn (mg/L)	Ave	1.45	0.95	0.896	0.52	0.63
	Min	0.19	0.12	0.22	0.01	0.02
	Max	3.17	1.45	2.26	1.04	3.44
Oxygen-18 (‰)	Ave	-5.28	-5.78	-5.91	-6.21	-6.36
	Min	-6.19	-8.13	-6.15	-6.57	-6.84
	Max	-4.14	-5.24	-5.46	-5.56	-5.73
Deuterium (‰)	Ave	-27.0	-29.6	-30.3	-32.5	-33.1
	Min	-33.5	-46.0	-33.3	-36.8	-37.3
	Max	-22.7	-25.2	-26.9	-26.5	-27.5
Uncorrected radiocarbon ages (yrs BP)	Ave	6050	10400	24850	4250	5650
	Min	1450	5300	8450	Modern	Modern
	Max	10600	25400	41750	7350	14650

		Leonay		**Wallacia**	**Upper Nepean**	
		Upper HS	**Lower HS**	**Lower HS**	**Upper HS**	**Lower HS**
Tritium (TU)	Ave	0.08	0.17	Na	0.66	0.4
	Min	0.05	0	Na	0.1	0
	Max	0.11	0.9	Na	1.7	1.79

Leonay

There are distinct differences in the geochemical composition of groundwater from the upper Hawkesbury Sandstone (at less than 100 metres depth) and lower Hawkesbury Sandstone (from 100–300 metres depth). Generally, the upper part of the Hawkesbury Sandstone sequence at Leonay-Emu Plains is more weathered and fractured, and has higher clay content than the lower part. Mudstone nodules and shale lenses are common. Therefore, higher groundwater salinity is encountered in the upper part of the aquifer, with EC values reaching a maximum level of 1700 µS/cm. At some sites where the Ashfield Shale overlies the Hawkesbury Sandstone, it is possible that leakage of saline groundwater from this aquitard contributes to the brackish salinity observed in the upper part of the sandstone.

Groundwater from the Ashfield Shale, which is part of the Wianamatta Group, is typically saline. The high salinity values are due to connate seawater trapped during deposition of the sediment (Old, 1942). Values up to 31,750 mg/L (total dissolved solids) have been recorded in groundwater from shale within the Sydney Basin (Woolley, 1991). The highest values are associated with groundwater in the central part of the Sydney Basin, where the base of the Wianamatta Group shale is located below sea level, natural drainage is restricted and flushing of salts is very limited.

The lower sandstone is more competent and is characteristically medium to coarse-grained, white to grey quartzose sandstone. Groundwater in the lower sandstone is generally fresh, with EC values in the majority of deep bores ranging from 250 µS/cm to 400 µS/cm, with little apparent spatial variability. The only exception was in the most downgradient test bore, where slightly brackish conditions were encountered (EC 593 µS/cm).

The pH of groundwater is variable and conditions vary from slightly acidic (pH more than 6) to slightly alkaline (pH less than 8) in all aquifers. In the upper sandstone pH values ranged from 5.44 to 7.84, while in the lower sandstone pH values range from 5.02 to 7.83 and showed no spatial trend.

The chemical composition of groundwater in the upper sandstone is dominated by sodium, magnesium and chloride reflecting the high clay content and possible leakage of saline groundwater from overlying shales. Groundwater in the lower sandstone sequence chemically evolves from mixed cation-Cl-HCO_3 type water to mixed cation-HCO_3-Cl type water along the flow path (Fig. 2). The increasing alkalinity is derived mainly from the dissolution of carbonate minerals, including calcite and siderite. Sulfate and potassium concentrations were low in both the upper and lower sandstone aquifers.

Groundwater from the Hawkesbury Sandstone had elevated concentrations of iron and manganese (McKibbin and Smith, 2000). Sources of iron include siderite (iron carbonate, $FeCO_3$) and iron oxyhydroxides and oxides. Siderite has been found to comprise an average 12% of the Hawkesbury Sandstone composition (Freed, 2005). Pyrite (iron sulfide, FeS_2) is not known as a common trace mineral in Hawkesbury Sandstone (McKibbin and Smith, 2000) and low sulfate concentrations confirm that this mineral is not a major source of iron. However, pyrite is a common mineral in shale and any mixing between shale and sandstone groundwater can supply iron into the upper part of the Hawkesbury Sandstone aquifer. The highest dissolved iron and manganese concentrations occur in the upper part of the Hawkesbury Sandstone. Dissolved iron and manganese were at concentrations up to 49.1 mg/L and 3.17 mg/L respectively. Iron staining and iron cemented fragments were observed in the upper part of the sandstone during drilling.

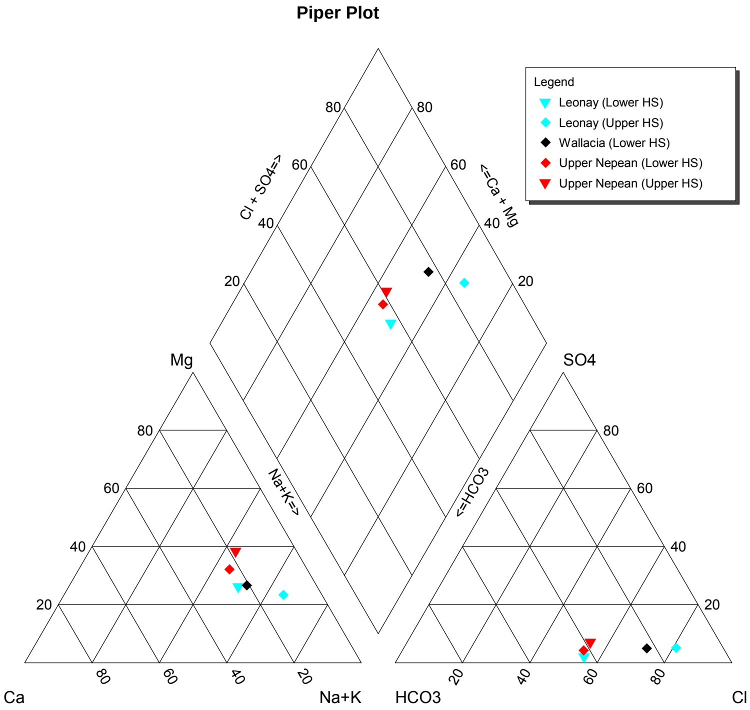

Figure 2. Piper diagram showing average chemical composition of groundwater from the Hawkesbury Sandstone

In the lower sandstone dissolved iron concentrations range from 0.17 mg/L to 30.3 mg/L. Dissolved manganese concentrations range from 0.12 mg/L to 1.45 mg/L. Iron and manganese are well correlated ($r^2 = 0.98$). No spatial trends in either iron or manganese were apparent. The concentration of dissolved iron and manganese is related to availability/reactivity of minerals and chemical processes in an aquifer and is dictated by pH, redox conditions and the distribution of iron and manganese-bearing minerals in the aquifers.

Stable isotope data for groundwater samples collected throughout the investigation indicate that groundwater is of meteoric origin with oxygen-18 values ranging from -8.13‰ to -5.24‰ and deuterium values ranging from -46.0‰ to -25.2‰ for groundwater samples collected from deep bores penetrating the Hawkesbury Sandstone.

Radiocarbon dating was used to give some indication of the age of groundwater in the sandstone aquifers and some insight into the recharge/discharge processes operating in the Leonay area. Radiocarbon ages for groundwater from the Hawkesbury Sandstone range from 5,300 years BP to 25,700 years BP (uncorrected) and 3,550 years BP to

21,600 years BP (corrected). There is generally an increase in groundwater residence time in the Hawkesbury Sandstone aquifer along the flow path (west to east). Groundwater age also increases with depth (Fig. 3). This is consistent with up gradient recharge areas in the lower Blue Mountains and down gradient discharge areas.

Tritium values were low in all bores penetrating the Hawkesbury Sandstone with the highest tritium value measuring 0.9 TU. Tritium values are in agreement with radiocarbon values, and indicate that the proportion of modern water present in the aquifer ranges from 3 to 30%.

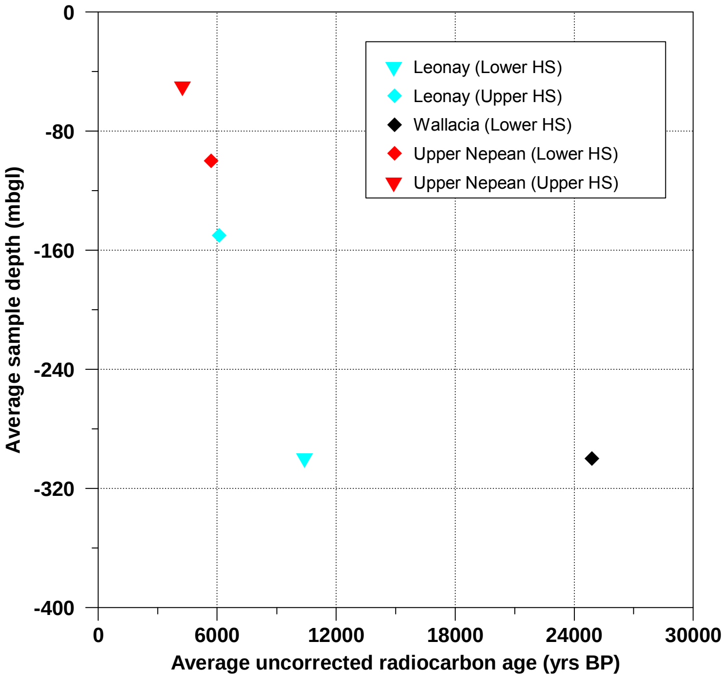

Figure 3. Average uncorrected radiocarbon age with average sampling depth of groundwater from the Hawkesbury Sandstone

Wallacia

Similar to the Leonay site, there are distinct differences in the geochemical composition of groundwater from the upper Hawkesbury Sandstone (at less than 150 metres depth) and lower Hawkesbury Sandstone (from 150–250 metres depth). Generally, the upper part of the Hawkesbury Sandstone sequence at Wallacia is more fractured, and has higher clay content than the lower part. As a result, higher groundwater salinity is encountered in the upper part of the aquifer, with EC values reaching a maximum level of ~4,300 µS/cm. Groundwater quality improves with depth, with EC values generally fresh to slightly brackish (400-1,600 µS/cm), but becomes more saline along the regional flow path from west to east. At some sites where the Ashfield Shale overlies or is immediately up gradient of the Hawkesbury Sandstone, saline groundwater from this aquitard contributes to the higher salinity observed in the upper part of the sandstone. Possible upward flow or migration of brackish to saline groundwater along fractures from underlying Narrabeen Group aquifers or Permian Coal Measures may be contributing to brackish conditions in the deeper Hawkesbury Sandstone on the eastern side of the Lapstone Structural Complex. Water quality results from the Mulgoa No.2 oil and gas exploration bore (to the north of the investigation area) confirm that salinity increases with depth in the Narrabeen Group formations and Permian Coal Measures (PB, 2009b).

The pH of groundwater is variable and conditions generally range from acidic (pH 5.3) to slightly alkaline (pH 7.3). Higher pH conditions are encountered in groundwater from the basaltic Nortons Diatreme.

The chemical composition of groundwater from the Hawkesbury Sandstone is Na-Mg-Cl type water in the recharge zone indicating the dominance of rainfall recharge. The chemical composition of groundwater evolves to a mixed cation-HCO_3-Cl or mixed cation-Cl-HCO_3 along the flow path. Sulfate and potassium concentrations were generally low. Dissolved silica concentrations range from 7-10 mg/L which is typical for the Hawkesbury Sandstone (Johnston and Johnston 1972). Dissolved silica is mainly derived from the dissolution of various silicates such as plagioclases or potassium feldspars, not quartz, as demonstrated in the study by Johnston and Johnston (1972).

Similar to the Leonay investigation area, groundwater contained elevated concentrations of iron and manganese. The dissolved iron concentrations ranged from 1.57 mg/L to 60.4 mg/L. Dissolved manganese concentrations ranged from 0.22 mg/L to 2.26 mg/L.

Groundwater chemistry in the area is strongly controlled by geology and geological structure. Variations in groundwater chemistry were noted in the Norton's Basin Diatreme (higher salinity, pH and dissolved silica concentrations). High dissolved carbon dioxide concentrations (1,000 mg/L) occurred at one deep bore, located near an east dipping fault on the eastern side of the Lapstone Monocline and may be attributed to ingassing from deep seated CO_2 sources, and/or from the Banks Wall Sandstone and underlying coal seams which are known sources of CO_2. High concentrations of other trace metals were detected at this location (other than iron and manganese) which are not characteristic of groundwater from the Hawkesbury Sandstone and suggest mixing with groundwater from underlying units is occurring (via upward movement along the fault or lateral movement from the west of the fault).

Higher salinities and high concentrations of trace metals in some of the other test production bores suggest that mixing with deeper groundwater may be widespread in the Wallacia area. Further investigation would be required to confirm this.

Oxygen-18 values ranged from -6.15‰ to -5.46‰ and deuterium values ranged from -33.3‰ to -26.9‰ for groundwater samples collected from test production bores penetrating the Hawkesbury Sandstone, indicating groundwaters are of meteoric origin. The uncorrected ages are older at Wallacia than Leonay, ranging from 8,542 yrs BP to 41,760 yrs BP and the corrected ages from 4,800 yrs BP to 30,600 yrs BP. The youngest radiocarbon age occurred in upgradient bores which are located on the western side of the Lapstone Structural Complex in the main recharge zone. Groundwater ages are significantly older on the eastern side of the Complex, and also generally increase in a northerly direction.

Upper Nepean

Groundwater in the Upper Nepean catchment is significantly fresher than at Leonay and Wallacia. The aquifer system is rapidly recharged by rainfall where the sandstone outcrops due to the enhanced fracturing of the Hawkesbury Sandstone. The lowest salinity values occur in the vicinity of an uplifted horst block in the middle of the investigation area and higher salinities occur where the Ashfield Shale overlies the Hawkesbury Sandstone. Recharge is relatively rapid through the highly fractured sandstone layers and water quality in the recharge zone is characterised by low salinity (<100 µS/cm), acidic pH conditions (pH<5), and a dominance of chloride due to recharge by coastal rainfall. Manganese and iron concentrations are low or non-detectable.

Along the identified groundwater flow paths (south to north) salinity increases up to 1,660 µS/cm (but is generally <400 µS/cm in the upper sandstone aquifer and 200 µS/cm in the lower sandstone aquifer), pH conditions become more neutral, and iron and manganese content of groundwater increases due mainly to the dissolution of siderite and iron oxides and hydroxides. Maximum dissolved iron and manganese concentrations were similar to Leonay and Wallacia, with maximum values being 47 mg/L and 3.44 mg/L, respectively. The major ion chemistry evolves from Na-Cl type water in the recharge zones to Na-HCO_3-Cl type water down gradient of the recharge zones, due predominantly to water-rock interaction with carbonate minerals in the aquifer system.

Oxygen-18 values for all groundwater samples range from –6.84‰ to –5.56‰ and deuterium values range from –37.3‰ to –27.5‰. Groundwater in the Upper Nepean catchment is interpreted to be of meteoric origin.

The measured radiocarbon activities of groundwater from the Hawkesbury Sandstone range between 16 pMC and 109 pMC and can roughly be divided into three groups: ^{14}C activities greater than 90 pMC suggesting these waters are very young, and may contain bomb radiocarbon indicating they are less than 50 years old; 40-90 pMC which are less than 5,000 years old (3,500 years old corrected) and 15-25 pMC which are >5,000 years old and <15,000 years old (3,500-8,000 years old corrected). Radiocarbon ages indicate that groundwater is “modern” (<50 years old) in the major recharge zone and shallow aquifer zones, but low permeability areas and areas downgradient of the major recharge zone to the north have ages up to 15,000 years old (uncorrected).

Tritium activities range from below quantification limit of the technique to 1.79 TU. In the major recharge zone, tritium and radiocarbon activities indicate modern water. Tritium and radiocarbon data indicates that groundwater is a mix of modern meteoric recharge water and older water, with the older waters associated with deeper fractures and the rock matrix. Shallow fractures act as conduits for modern meteoric recharge. Further along defined flow paths and at depth, tritium activities decrease below the quantification limit and correspond with radiocarbon ages >5,000 years old (uncorrected). This corresponds to the regional groundwater system.

Conclusions

As part of the drought management strategies in the NSW government’s 2004 and 2006 Metropolitan Water Plans the SCA has been investigating the possible use of groundwater in the Sydney Basin to supplement surface water supply sources during severe drought. Detailed hydrogeological investigations, including chemical and isotopic studies, have been undertaken at three locations (Leonay, Wallacia and Upper Nepean) in the Sydney Basin as part of the MWP.

Extensive groundwater drilling and testing programs have been carried out since 2005 at Wallacia-Warragamba and Leonay-Emu Plains in western Sydney and in the Upper Nepean catchment in the Southern Highlands. In the Upper Nepean catchment, drilling and testing targeted the highly fractured and faulted blocks of Hawkesbury Sandstone associated with the Mittagong Horst-Graben Complex. Groundwater is characterised by low salinity and relatively “modern” water in the uplifted and highly fractured sandstone aquifers.

Drilling and testing in the Wallacia and Leonay areas targeted the Hawkesbury Sandstone and a major regional structural feature, the Lapstone Structural Complex, which is known to have increased the fracturing and permeability of the sandstone. At both these locations, brackish groundwater occurs in the upper part of the Hawkesbury Sandstone, downgradient of the Lapstone Monocline, while fresher and relatively older groundwater occurs at depth. Variations in water chemistry occur at Wallacia where igneous intrusions, such as the Nortons Basin Diatreme, are present, and where significant faulting has occurred along the Nepean Fault.

With the exception of iron and manganese, groundwater at all locations was generally found to be suitable as a raw water source for potable supply.

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Soil and groundwater salinity in the shales of western Sydney

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Abstract

The Ashfield and Bringelly Shales, though primarily aquicludes, do include scattered zones of fracture porosity within the weathered bedrock and soil profile, and also at depth in the unaltered shale bedrock. The water within these fractures is generally saline, typically in the range 5,000-50,000mg/L. Although the shales have no value as sources of groundwater, they are associated with surface salting in parts of western Sydney. Much salt is believed to be stored within the soil B-horizon; it is added to by infiltration and depleted by throughflow and by deeper percolation. The probable source of this salt is not seawater trapped in the pores of the shale, according to the conventional wisdom, but rather windblown aerosols, which accumulate in the clay subsoil below the root zone.

1. Introduction

This paper is based on the results of soil and groundwater salinity investigations carried out by Sinclair Knight Merz (SKM) in shale bedrock areas of western Sydney over the period from about 1998 to the present. It is essentially a summary of the findings in a number of unpublished SKM reports, and those of other consultants, which are not within the public domain. It also presents a hypothesis based on field observations concerning the origin, accumulation and movement of salt through the soil profile and shale bedrock. Further details of these investigations have been previously published in McNally (2004, 2005a and 2005b). I have drawn upon the few published papers dealing with shale hydrogeology in western Sydney, especially Cox et al (2002), Dias and Thomas (1997), Hayward and Mitchell (2000) and the one that started it all, Old (1942). I would also like to acknowledge the unpublished reports of other consultants, particularly the many who have done valuable work on the former St Marys ADI site, in particular, from the early 1990s onwards.

The soil and groundwater investigations at the St Marys site have been by far the most thorough of their type completed in western Sydney. About 200 boreholes, half completed as piezometers, and more than 200 test pits have been used to study salinisation across this 15km^2 property, which is now being developed for housing and open space recreation. The work was carried out over a period of twenty years by ADI itself and a number of consultants, including SKM. These studies have established the existence of a shallow, low salinity soil aquifer of limited areal extent, which overlies a much tighter, saline, shale bedrock aquifer (of sorts). This dual aquifer system is widely present in other shale bedrock areas of western Sydney, as demonstrated by other SKM investigations at Orchard Hills, Castlereagh, Schofields, Bringelly, Marsden Park and elsewhere.

2. Origin of the salt

Since the publication of Old's seminal 1942 paper on groundwater in the shales of the Wianamatta Group, now referred to as the Ashfield and Bringelly Shales, the conventional explanation has been that these rocks are of marine origin, hence a certain amount of connate (inherent) salt is likely to be trapped in circulating pore water. I have argued (in McNally, 2004) that these rocks are not marine; that there is little pore space left to contain the salt; and that the present rate of weathering is too small to generate much salt. Furthermore windblown sea salt, in the form of saline rain, provides an adequate and continuing source for the soils of western Sydney (see Figure 1). This salt accumulates by evapo-transpiration following infiltration below the root zone, mostly in the B-horizon of residual soil profiles but also in the underlying weathered shale. The area's relatively low rainfall (800-1000mm/yr) is not sufficient to immediately flush the salt down to the water table, as would happen in sandstone areas, but is nevertheless enough to prevent salt crusts forming.

Although urbanization does not directly increase salinity in the soils of western Sydney, proposed irrigation using treated effluent could do so if adequate flushing is not provided. A warning against potential salt buildup in shale soil profiles from recycled water, even of low salinity (~500mg/L TDS) is given in a paper by Hird et al (2007).

3. The two aquifer system

Two aquifer systems are believed to coexist in the shale terrain of western Sydney (see Figure 2.). Neither is equivalent in hydraulic conductivity, storage capacity and groundwater quality to a normal producing aquifer, but each plays an important part in the salt cycle of the region. The upper or regolith aquifer is relatively fresh and pervious, but limited in area, while the deeper or shale bedrock aquifer is distinctly saline, much more extensive and considerably better known. They are not really independent bodies, but are poorly interconnected by narrow fracture networks and at most times the two waters are kept apart by pressure (hydraulic head) differences.

The existence of the upper aquifer explains why streams can run fresh in shale areas, despite most of the deeper groundwater being saline. It also explains why salinity can increase greatly in surface waters during droughts, or in certain reaches of streams such as South Creek, due to localised upward movement of salt water from the lower aquifer.

The regolith aquifers

The shallow aquifer system is composed of soil and soil-like materials, such as weathered shale, which have accumulated to depths of 3-12m on footslopes and valley floors of the Bringelly Shale terrain. Slow downslope creep of shale weathering products and alluvial reworking created this soil mantle, such that floodplain deposits (alluvium) merge laterally into slope deposits (colluvium). Relatively little is known of the hydrogeological properties of these inhomogeneous shallow soils, since most piezometers are located so as to respond to the lower (fractured shale) aquifer system, but it can be surmised that:

- The regolith aquifers, though predominantly composed of clay, are extremely variable in permeability and storage capacity, depending on the intensity of fissuring and the continuity of the fracture network within them. In places piezometer water levels may rise quickly and then fall after rain. Notional permeabilities could be in the range 0.1 to 20m/d, the latter being exceptionally high for clay.

- In places, however, the clay blanket is so tight that it acts as a confining layer over groundwater trapped in the fractured shale beneath and artesian pressures may develop. More commonly, slow upward seepage of salt water can occur, controlled by pressure differences and fissure connectivity between the two-aquifer systems.
- Water quality in the regolith aquifers is good, though not necessarily potable, and is similar to that in the nearby semi-perennial streams. These aquifers, it is believed, provide the baseflow which maintains the streams between major rainfall events.
- Recharge to the shallow aquifers is partly from direct rainfall infiltration, but mostly from shallow throughflow along the A/B soil horizon interface. This is not true groundwater because it moves mainly at depths less than 1m, parallel to the ground surface, and does not percolate down to the water table. In western Sydney shale terrain it is likely that throughflow amounts to 10-20 times the volume entering groundwater storage. It is also believed to be important in leaching salt stored in the soil B-horizon into local streams.

The shale bedrock aquifers

The deeper aquifer system consists of groundwater contained within fractures and bedding planes in the shale bedrock, below the base of weathering – say below 3-10m depth in most places. In fact the bedrock aquifer can be present at a depth of only metre or so below hill crests, with no ‘shallow’ aquifer above it. Compared to the shallow regolith system the bedrock aquifers are much more widespread, much more saline (say 5,000-30,000mg/L TDS) but have only about one-tenth of the hydraulic conductivity.

The bedrock aquifers are referred to as a system because they consist of stacked sub-aquifers (perched water tables) with intervening dry shale. Infiltrating water is successively stored within impersistent vertical joints and along bedding planes, between which flow may occur by ‘stepping’ for a short period after heavy rain. (This can be observed from the pattern of wet patches in cutting walls and quarry faces after rain.) Because of this sporadic distribution of saturated zones, SWLs may vary by a metre or more between adjacent boreholes and some of these boreholes may be quite dry.

There is some question about whether a true water table can be said to exist at all in shale rock masses. In this view the ‘water table’ is simply an artifact of the piezometers, whose response zone might extend from 1m below the surface to the base of the hole at 10-20m. The deeper the borehole, the deeper is the SWL. A composite SWL is eventually generated in a deep piezometer by seepage from a number of water cuts in perched water tables, each of which is more or less hydraulically independent.

As the shale rock mass tightens below the near-surface zone of stress relief, water movement becomes even more restricted. In deep quarries this is indicated by dry lower faces, although an apparently dry face in this situation may simply mean that the tiny amount of seepage is less than the rate of evaporation.

Why is the shale aquifer so salty?

Atmospheric salt, continuously added by rain and stored in the regolith, is periodically flushed down into the fractured shale aquifer system. Because the amount of salt that can be stored in the soil is large, in the order of 10-150 tonnes per hectare to 2m depth, and the infiltrating water volume is small (only 1-3% of precipitation), the recharge eventually reaching the water table is very saline, typically 10,000-30,000mg/L.

This salt leaching is presumed to occur mainly in wet years, when the soil profile becomes for a time saturated and is therefore at its most pervious. In this way salt buildup in the B-horizon is diminished from time to time – western Sydney would otherwise become a desert – but recovers during the intervening years. Much salt is also presumed to be removed laterally by throughflow at more frequent intervals. Because of the much greater volume of throughflow water, perhaps 10-20 times that reaching the water table, its salt content is less apparent. The relative proportions of salt leached vertically as groundwater recharge and laterally by throughflow are not known, but the latter is presumed to be greater.

Water level and salinity fluctuations

Where western Sydney observation boreholes have been monitored over 1-3 years, it is commonly found that water levels rise and fall by several metres (9m fall over three drought years is the largest SWL change known to me). A movement of 1-2m between seasons is more usual. Because of the low storage capacity within shale fractures they can empty and fill quickly; they are drained by tree roots or by downward percolation, but may fill rapidly after rain. The poor lateral connections between fractures mean that these fluctuations are neither uniform nor consistent. Water level peaks appear and disappear between monitoring rounds, which are generally several months to a year apart.

Salinities, too, can vary from say 1000mg/L to 20,000mg/L in the space of a few months. Saline spikes in shallow regolith piezometers and fresh water spikes in deeper shale wells are often observed during monitoring. Although these could be explained by evaporation from within the PVC tubing or by downward leakage of surface runoff around the piezometer seal respectively, the main cause is believed to be the pressure fluctuations between shallow fresh water and deeper salt water in the shale terrain.

Surface water, typically 500-1000mg/L TDS in western Sydney streams depending on the season, is also subject to salinity spikes. A general salinity rise within a stream reach would probably signal that the regolith aquifer there or upstream is depleted, but a localized spike might simply be due to an open joint in the stream bed acting as a conduit for deeper saline groundwater.

Is there a rising water table hazard?

A rising saline water table following many decades of urban development has created significant soil problems in Wagga NSW. The question naturally arises as to whether a rising water table, propelled by increased urban runoff, could become a threat in western Sydney. While the answer to this will depend on many site-specific factors and could take decades to resolve, there are reasons to feel optimistic.

First, the proportion of rainfall reaching the water table is much higher in Wagga, about 10% according to the CSIRO – up to ten times that in Sydney’s shale outcrop areas. All indications are that western Sydney’s shale bedrock is much tighter than the classic dryland salinity regions of WA and southwestern NSW, and that its rainfall is adequate to at least keep soil salinity within acceptable limits by periodic flushing from the soil profile

Second, although the regolith aquifers are generally unconfined and do indeed rise temporarily, their salinity is low – generally <1000mg/L and lower still following heavy rainfall infiltration. This water table rise would result in local waterlogging rather than long-term salinisation, possibly as a result of concentrated stormwater infiltration. The rise would be only temporary, because a mechanism exists to draw down these aquifers – the nearby stream, which is fed by this groundwater. Furthermore, because of the inhomogeneity, limited area and lack of hydraulic connection between the shallow aquifers such waterlogging would not be widespread. It could be controlled by careful stormwater routing or, as a last resort, by subsurface drainage.

Third, the shale bedrock aquifer is certainly saline, but it is generally confined or semi-confined, at least where it occurs low in the landscape. Pressures could indeed rise within this aquifer system (though not suddenly after rain, like the shallow regolith aquifers), and some upward leakage of brackish groundwater would probably result. Salinity spikes could be expected at discharge points along major streams such as South Creek.

4. Conclusion

This paper has been presented as an overview and a working hypothesis, based on more than ten years of field observations at many sites in western Sydney and numerous consulting reports, most of which remain confidential to clients and inaccessible to researchers. Some of the data on which it is based, omitted because of space limitations initially imposed by the conference organisers, can be found in the references below. Much remains in the category of plausible but unproven, and maybe unprovable. Although potential salinisation issues in western Sydney remain significant they are, in the author's recent experience, an order of magnitude less serious than those encountered in areas such as the southwestern slopes of NSW or the WA wheat belt.

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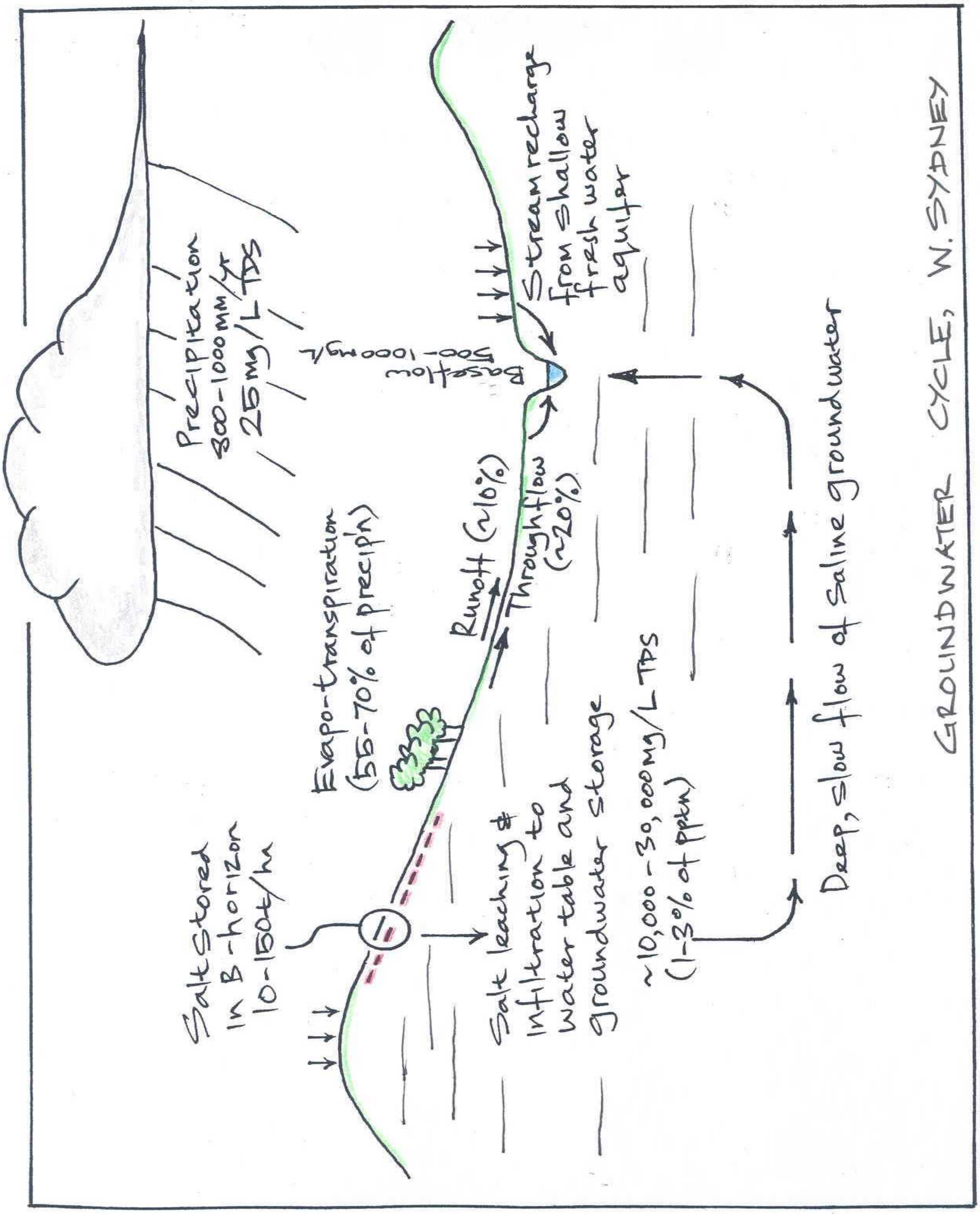

Figure 1. Presumed salt and groundwater cycle in western Sydney.

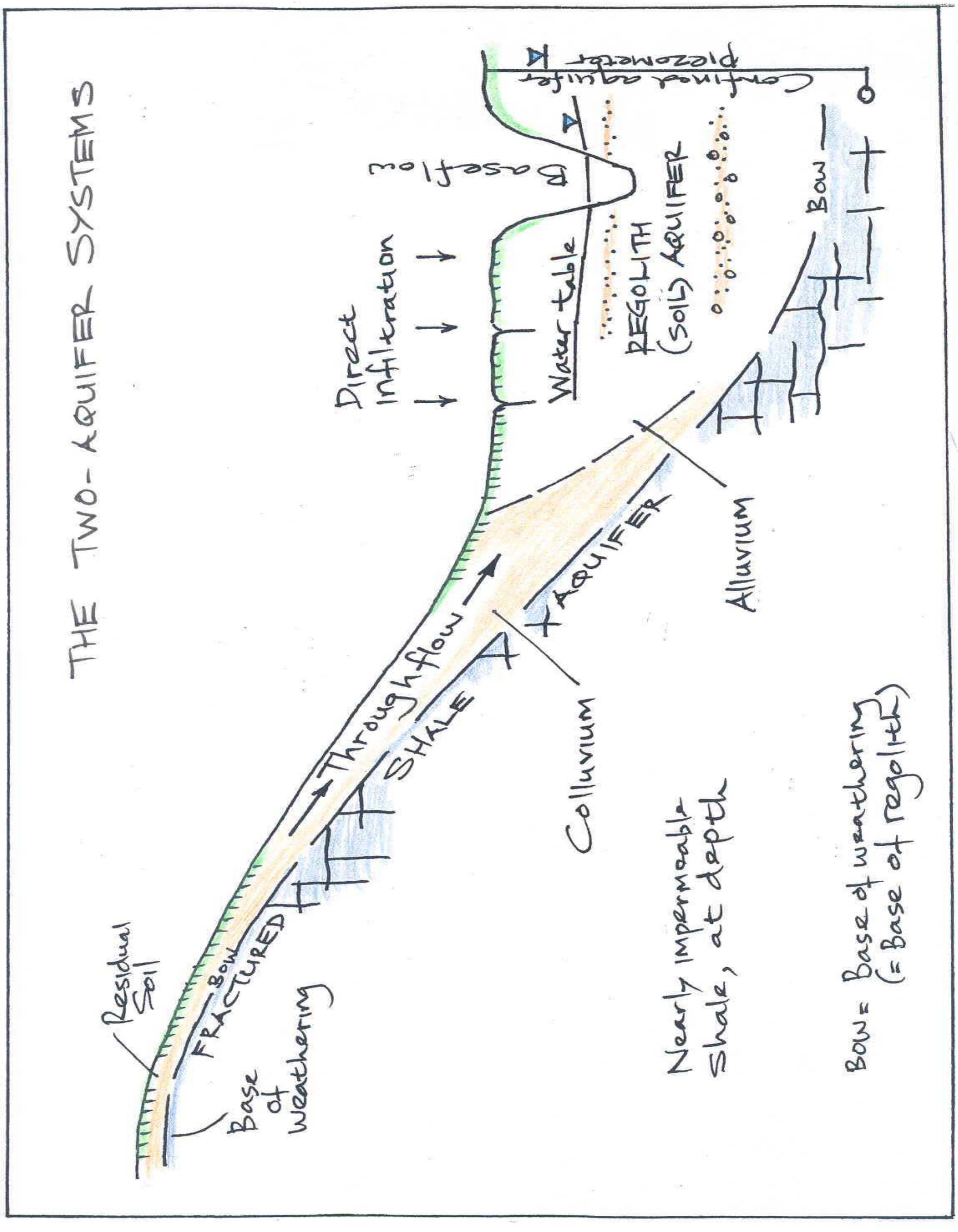

Figure 2. Relationship between the upper (regolith or soil) aquifer system and the lower (fractured shale) aquifer system, western Sydney.

Comparative modelling of longwall mining effects using Standard-MODFLOW and MODFLOW-SURFACT in the Southern Coalfield, New South Wales, Australia

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Abstract

Numerical modelling is an essential component of groundwater assessment for longwall coal mining for the Environmental Assessment process and subsequent Subsidence Management Plan approvals in New South Wales, Australia. Longwall mining causes a caved zone and a fractured zone immediately above the mined panels, with constrained and surface zones at higher altitude. The fractured zone varies in height according to panel width, seam height and the competence of overburden strata. The depth of cover determines whether the effects of fracturing at depth might cause environmental disturbance to shallow aquifers or to aquifer-stream interactions.

A comparative study has been made at the Metropolitan Colliery in the Southern Coalfield of New South Wales of modelling by Standard-MODFLOW and MODFLOW-SURFACT, an advanced version that is able to simulate variably saturated flow and can handle desaturation and resaturation of multiple aquifers. Standard-MODFLOW can handle depressurisation to some extent, but model cells that are dewatered (reduced below atmospheric pressure) are replaced by “dry cells”. During resaturation, Standard-MODFLOW re-wets previously dry cells by an algorithm that is approximate in nature. It remains unclear how much error in calculated heads and water fluxes occurs as a result of these approximations.

Estimation of time-varying fractured zone hydraulic conductivities is required for proper groundwater assessment. This is best done by inference from strings of multi-level vibrating-wire piezometers that monitor the changes in vertical hydraulic gradients before, during and after mining. It is standard practice in the coal industry to have about eight piezometers throughout the stratigraphic section at each hole.

Model calibration using PEST results in a median vertical permeability in the fractured zone that is higher than the host value by a factor of 8 to 14, for two alternative models. Regional groundwater level patterns in the Hawkesbury Sandstone (near-surface) are not affected by the choice of software, and shallow water levels calculated by Standard-MODFLOW are correct in cells adjacent to dry cells. However, substantial differences in simulated groundwater heads and depressurisation patterns occur beneath the Bald Hill Claystone over the mine footprint.

Keywords: longwall mining, groundwater, MODFLOW

1. Introduction

In part due to the poor resource potential of the deep Southern Coalfield aquifers, the limited potential for other groundwater users to be directly affected by underground mining, and the fact that coal mines are typically “dry”, the status of regional groundwater modelling is immature in the Southern Coalfield (NSW) compared with the modelling that is being done in other NSW coalfields. There have been several examples of 2D modelling of groundwater heads and pressures, but no 3D modelling until recently (2008). The introduction of best-practice groundwater modelling has been constrained by the short historical record and sparse spatial coverage of groundwater levels that are needed for regional model calibration. These issues were raised in the findings of the Southern Coalfield Inquiry in 2008 (NSW Department of Planning, 2008) (www.planning.nsw.gov.au).

Three-dimensional (3D) numerical modelling has been undertaken to support an application by Helensburgh Coal Pty Ltd (HCPL) for expansion of the existing Metropolitan Colliery in the Southern Coalfield (NSW). This is the first instance of 3D groundwater modelling in the Southern Coalfield (Merrick, 2007). The Metropolitan Colliery is located at a distance of approximately 30 km to the north of Wollongong, close to the Helensburgh township. The area of proposed underground mining (Longwalls 20 to 44; Figure 1) is situated to the north of the current longwall mining areas (Longwalls 14 to 19A; Figure 1). Longwall panel widths are relatively narrow (133-163 m), while depth of cover is substantial (400-560 m). This Project received approval from the Minister for Planning on 22 June 2009; see www.pac.nsw.gov.au or www.planning.nsw.gov.au.

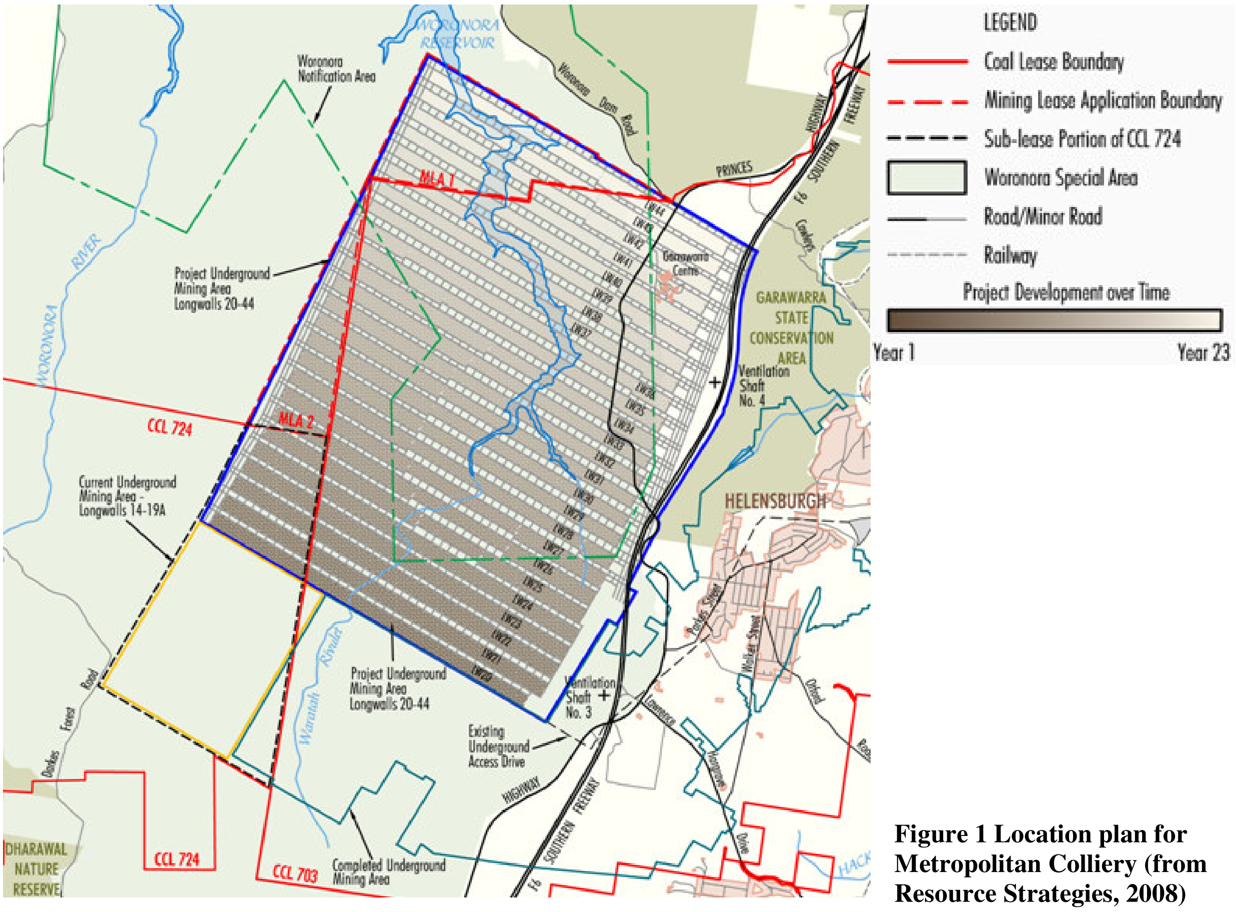

Figure 1 Location plan for Metropolitan Colliery (from Resource Strategies, 2008)

This paper addresses the issue of whether Standard-MODFLOW is adequate for modelling groundwater systems that are stressed by underground mining, and whether the errors due to the admitted limitations of MODFLOW are significant. Comparison is made with replicate modelling using more advanced MODFLOW-SURFACT software.

2. Conceptual model

2.1. Geology

The Southern Coalfield lies in the southern part of the Sydney Basin (Moffitt, 2000), which is infilled with sedimentary rocks of Permian age (<270 million years ago) and of Triassic age (<225 million years ago). At the top of the sequence in the area of interest is the Hawkesbury Sandstone. This consists of thickly bedded or massive quartzose sandstone (with grey shale lenses up to several metres thick), with a maximum thickness of about 170 m. Beneath the Hawkesbury Sandstone is the Narrabeen Group, a 230 m thick sequence of alternating sandstones and claystones. The Narrabeen Group does not outcrop within the Project area. The major formations within this group of rocks, from top to bottom, are the Bald Hill Claystone, Bulgo Sandstone, Stanwell Park Claystone, Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone. Immediately beneath the Narrabeen Group is the target Bulli Coal seam at the top of the Illawarra Coal Measures.

2.2. Hydrogeology

Apart from coal seam aquifers at depths of greater than 400 m, the recognised aquifers in the stratigraphic sequence are the Hawkesbury Sandstone and the sandstones of the Narrabeen Group. Whilst of low permeability, the Hawkesbury Sandstone has the relatively higher permeability compared to other units and is therefore capable of higher groundwater yields. Due to alternation of sheet and massive facies, groundwater flow is primarily horizontal with minor vertical leakage. Perched water tables are expected adjacent to cliff faces and within upland swamps.

Vertical hydraulic continuity with the underlying Narrabeen Group aquifer is mediated by a major aquitard, the Bald Hill Claystone, typically about 25 m thick. This unit will retard vertical groundwater flow downwards from the Hawkesbury Sandstone. The base of the Narrabeen Group, at the top of the Bulli Seam, is marked by the Wombarra Claystone. This unit is an aquitard that will limit vertical flow into mine workings. The Coal Cliff Sandstone lies between the two where it is developed.

The only recognised economic aquifer in the area is the Hawkesbury Sandstone. It is in general a low-yield aquifer of good quality, generally in the range 1000-3000 mg/L. It would be expected to be a productive aquifer, but land use status as a Water Supply Protection Area (for Sydney's water supply) prevents its development. The Metropolitan Colliery lies within the Hawkesbury Sandstone – South-East groundwater flow system (GFS) as defined by Grey and Ross (2003). This GFS extent tracks the Metropolitan Water Supply Catchment Area that includes the Nepean, Avon, Cordeaux, Cataract and Woronora Reservoirs. Only 82 bores are registered throughout the whole area of the GFS for stock and domestic use with total entitlements of 55 ML/year. This contrasts with a sustainable yield estimate of 58,000 ML/year (Grey and Ross, 2003). There are no high yield bores (>6 L/s) identified within the GFS.

The Narrabeen Group is a much poorer aquifer, and there is no known use of the aquifer in the Southern Coalfield for water supply. The very low permeability of the Narrabeen Group lithologies is substantiated by the common experience of "dry mines" in the Southern Coalfield.

At depth, groundwater sinks have developed at previous mine workings: Metropolitan Colliery (Longwalls 1 to 14 at the time of the study); Darkes Forest (to the south); Helensburgh (to the east); and North Cliff development headings (to the west).

Based on the available groundwater level data and to gain an impression of the regional water table pattern, a contour map of inferred groundwater level has been prepared for groundwater levels either measured at bores or equal to stream bed elevations and 10 m lower than measured perched levels in upland swamps (Figure 2). The main stream in the area to be mined is Waratah Rivulet, which drains into Lake Woronora (Figure 2).

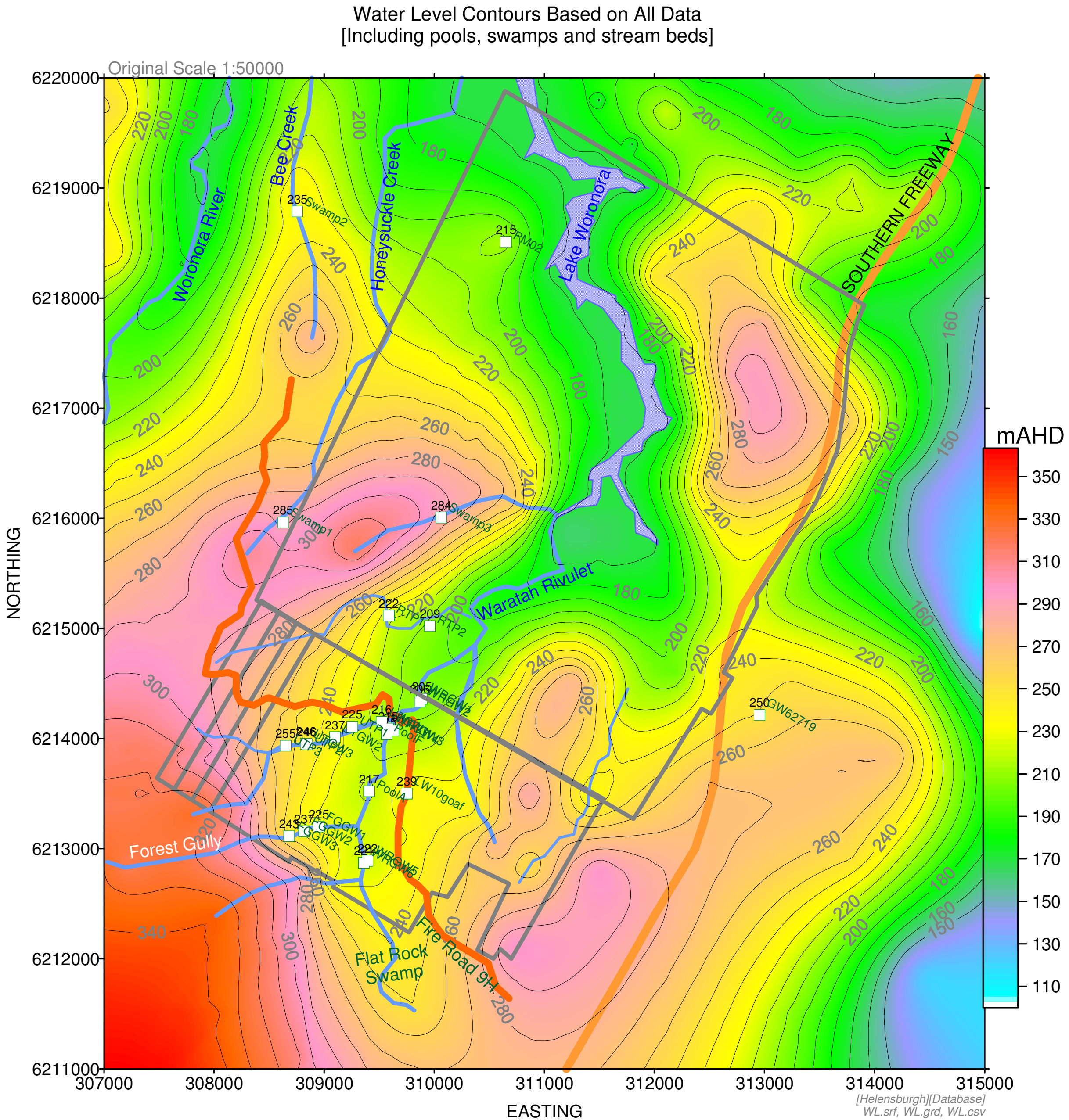

Figure 2 Inferred shallow groundwater level contours (mAHD)

[Helensburgh][Database]
WL.srf, WL.grd, WL.csv
Roads, FireRoad, StreamXYZ, WLxyz.csv
Drainage, Woronora.csv
LW1-17, LW18-19A, LW20-44.csv
[100m grid]

Groundwater in the upper part of the Hawkesbury Sandstone will flow from the ridges to the natural surface drainages. There is a clear potential for continuing groundwater discharge along Waratah Rivulet across the area already mined.

Groundwater pressures at depth have been measured at two locations (PM02 and LW10 goaf holes; Figure 2) in holes equipped with multiple vibrating-wire piezometers. The holes were drilled to depths of 327 m (LW10 goaf) and 575 m (PM02) at mined (LW10 goaf) and unmined (PM02) locations. The LW10 goaf hole terminated about 130 m above the mined seam at the top of the inferred fractured zone. The piezometric elevations and associated vertical hydraulic gradients are illustrated in Figure 3.

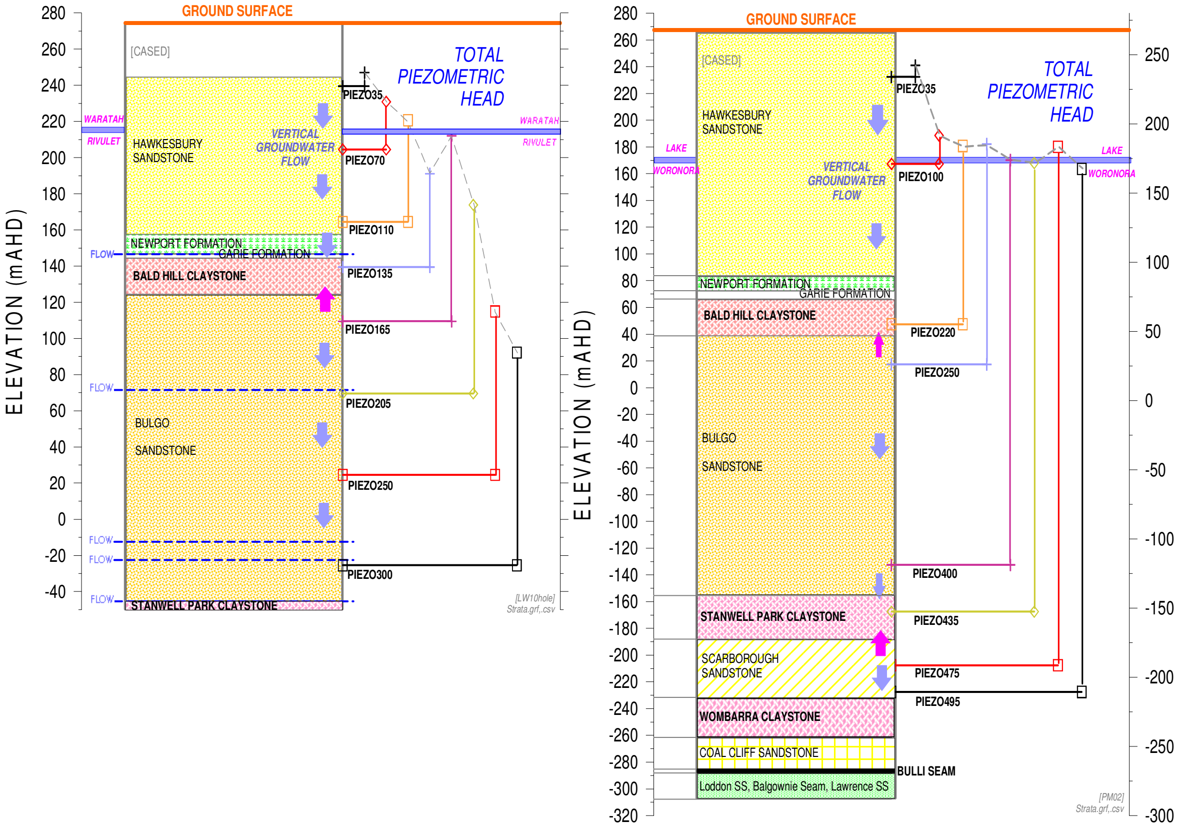

Figure 3 Vibrating-wire piezometer heads, vertical hydraulic gradients and inferred vertical flow directions at LW10 goaf hole (left, mined area) and PM02 (right, unmined area)

The conceptual model for the area of interest is presented in Figure 4. The data support three distinct groundwater systems: perched, shallow, and deep. Recharge to the groundwater system is from rainfall and from lateral groundwater flow at the boundaries of the study area. Local groundwater mounds develop beneath the sandstone hills with ultimate discharge to incised creeks and water bodies, and loss by evapotranspiration through vegetation within upland swamps and outcropping sandstone. During short events of high surface flow, streams can lose water to the sandstone aquifers that host the streams, but during recession the sandstone will discharge water slowly back into the stream from bank storage. Groundwater also discharges naturally to cliff faces and ultimately to the sea. In places where mining has occurred, groundwater discharge is expected to occur to the mined seam from above and below in proportion to local permeabilities.

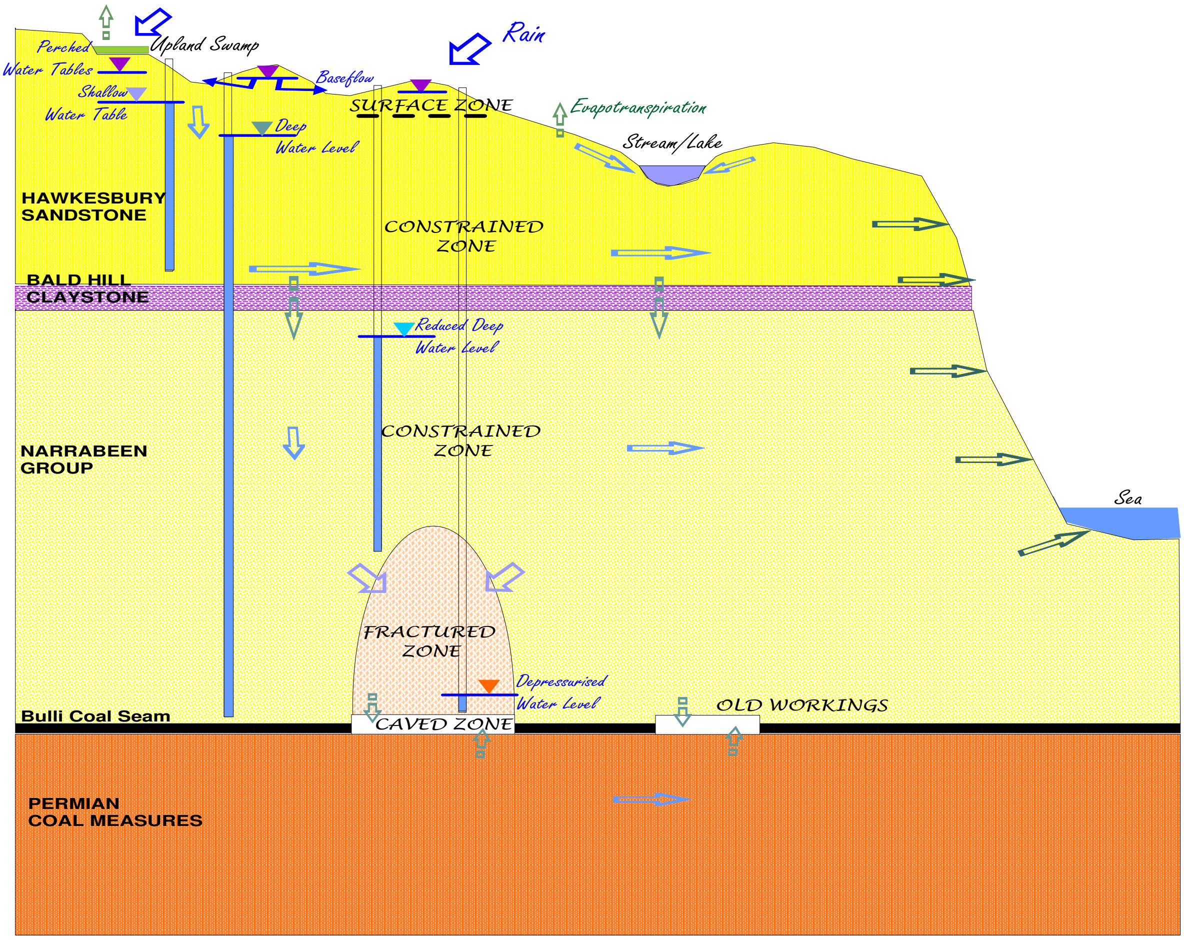

Figure 4 Conceptual model

Immediately above a mined coal seam, rocks will collapse into the void to form a caved zone and cause changes to aquifer permeability and porosity. As the mining proceeds, a fractured zone will develop above the caved zone and aquifer properties will change with time. The overlying rocks in the fractured zone will have a higher vertical permeability. Depending on the width of the longwall panels and the depth of mining, and alternation of thick sandstone/claystone lithologies, there will be a “constrained zone” in the overburden that acts as a bridge. Booth (2002) describes the “constrained zone” as “a continuous deformation zone which subsides coherently with little extensive fracturing”. This will mediate the connection between shallow and deep aquifers, but there could be enhanced horizontal permeability due to bed separation. At the substantial depths of cover at Metropolitan Mine, there will not be connective cracking from the ground surface to the mined seam. Groundwater pressures will reduce to atmospheric pressure and negative pressures within the fractured zone.

3. Numerical Modelling

3.1. Model Development

A numerical model was considered necessary to allow evaluation of near-field mine dewatering requirements and far-field environmental effects. To handle the observed vertical changes in groundwater head within a given formation, and expected goaf fracturing, the numerical model has 13 model layers. This includes subdivision of Hawkesbury Sandstone, Bulgo Sandstone and Scarborough Sandstone into two layers each. The model extent is 18 km from west to east and 14 km from south to north, with uniform 100 m cell size (140 rows, 180 columns).

The area has been simulated with two versions of MODFLOW software: MODFLOW96 (here called Standard-MODFLOW) and MODFLOW-SURFACT - an advanced version that is distributed commercially by Hydrogeologic, Inc. (Virginia, USA). It is able to simulate variably saturated flow and can handle desaturation and resaturation of multiple aquifers without the "dry cell" problems of Standard-MODFLOW. This is pertinent to the depressurisation that occurs in the caved zone and fractured zone above mined coal panels, and to possible dewatering of the uppermost model layer(s). Standard-MODFLOW can handle depressurisation to some extent, but model cells that are dewatered (reduced below atmospheric pressure) are replaced by "dry cells". During resaturation, Standard-MODFLOW re-wets previously dry cells by an algorithm that is approximate in nature. It remains unclear how much error (in calculated heads and water fluxes) occurs as a result of these approximations.

The vertical head profile data at the LW10 goaf hole and at PM02 (Figure 3) were submitted to specialised parameter estimation inversion software (PEST) as the primary targets for a Standard-MODFLOW zoned-parameter automated calibration. The resulting parameterisation was preserved in the MODFLOW-SURFACT model, the only difference being the addition of four unsaturated zone parameters.

3.2. Total Piezometric Head

Comparative piezometric heads are illustrated for steady-state simulations at the end of mining for each model code. Figures 5 and 6 show the head patterns for Layer 1 (Upper Hawkesbury Sandstone) and Layer 6 (Lower Bulgo Sandstone). Regional patterns are in good agreement in each of the 13 model layers.

Layer 1 (Figure 5) shows many dry cells with Standard-MODFLOW (as purple blotches), whereas MODFLOW-SURFACT reports unsaturated heads in corresponding cells. The dry cells have not had a deleterious effect on heads calculated in nearby wet cells, but the levels on the ridges are slightly elevated with MODFLOW-SURFACT. As Layer 2 (not shown here) is almost free of dry cells, the head patterns produced by the two software alternatives agree closely.

Substantial head differences commence in the Bald Hill Claystone (Layer 4) along the upstream reaches of Lake Woronora (refer to Figure 2 for location), and the differences continue with depth over the mine footprint and adjacent to it. The most pronounced disagreement occurs in the Lower Bulgo Sandstone (Figure 6) where Standard-MODFLOW gives misleadingly high piezometric heads over the mined area.

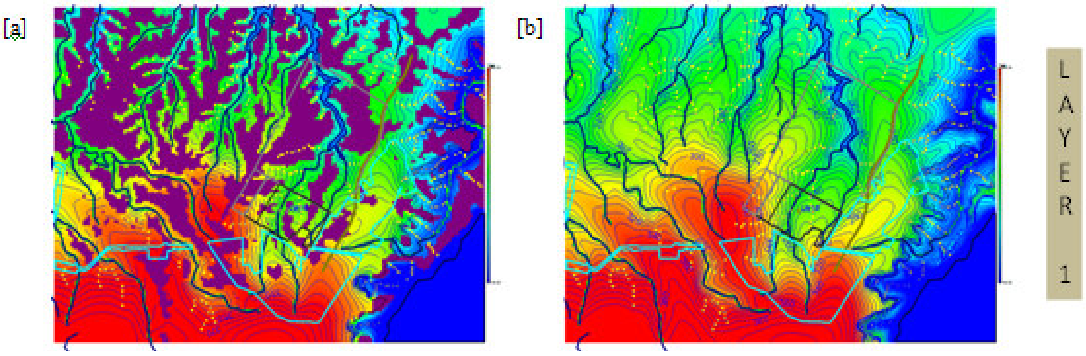

Figure 5 Simulated Upper Hawkesbury Sandstone regional water table for final mining: [a] Standard-MODFLOW; [b] MODFLOW-SURFACT.

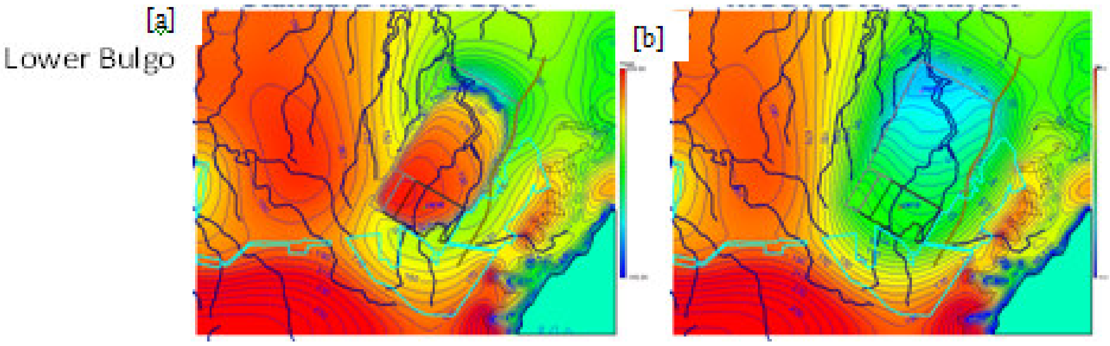

Figure 6 Simulated Lower Bulgo Sandstone groundwater elevation for final mining: [a] Standard-MODFLOW; [b] MODFLOW-SURFACT.

3.3. Vertical Head Profiles

Although the same parameterisation was used for both models, they differ in calibration performance (due to the additional unsaturated zone process in MODFLOW-SURFACT). The RMS statistic for vertical profile heads deteriorated from 9.9% to 14.4% (Figure 7). This unavoidable difference between the two models complicates direct comparison of the software alternatives.

The two software approaches suggest different vertical hydraulic head profiles over the mine footprint. At the LW10 goaf hole, MODFLOW-SURFACT gives an exaggerated gradient below 300 m, the limit of piezometer monitoring, compared with Standard-MODFLOW (Figure 7). There is no field evidence as to which is right. In the upper 300 m, MODFLOW-SURFACT tends to underestimate the known heads. At PM02, MODFLOW-SURFACT reports heads at depth that are consistently about 5 m lower than those simulated with Standard-MODFLOW. However, one approach is not better than the other in reproducing measured heads at depth.

The mining-affected vertical head profile at the LW10 goaf hole allows estimation of enhanced hydraulic conductivity in the fractured zone. Model calibration using PEST results in a median vertical permeability in the fractured zone that is higher than the host value by a factor of 8 to 14, for two alternative models.

Another control on calibration was the amount of mine inflow into current workings. Standard-MODFLOW reports 0.14 ML/day while MODFLOW-SURFACT reports 0.46 ML/day. As the latter figure is considered too high, there is a case for re-calibration of the MODFLOW-SURFACT model. The reported MODFLOW-SURFACT results can be considered as overly conservative with respect to environmental effects, as this model is producing a higher degree of depressurisation than is likely to occur.

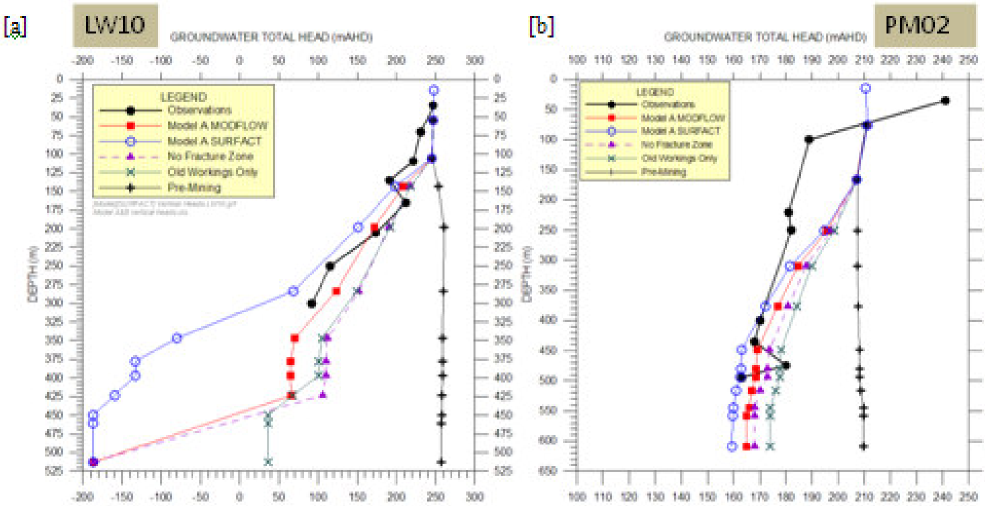

Figure 7 Observed and simulated vertical head profiles:
[a] Standard-MODFLOW; [b] MODFLOW-SURFACT.

The MODFLOW-SURFACT model has been re-calibrated by use of 40 additional vertical head difference targets, one quantitative mine inflow target (0.1 ML/day), and lower rainfall infiltration as suggested by a sensitivity analysis. The calibration performance improved to 12.2 %RMS but mine inflow remained high at 0.38 ML/day. *[Due to lack of space, detailed results for the re-calibration are not reported here.]*

3.4. Pressure Head Sections

The height of a simulated fractured zone can be illustrated on cross-sections of water pressure head (by subtracting model cell elevation from the simulated head value). The zone of free drainage will be marked by the line of zero (atmospheric) pressure.

Figures 8 and 9 show south-north pressure head sections for MODFLOW-SURFACT and Standard-MODFLOW models, respectively. MODFLOW-SURFACT gives the more realistic pattern (Figure 8) as a result of mining and projected mining, showing an unsaturated zone (negative pressure) extending upwards to include the Stanwell Park Claystone. The Standard-MODFLOW section (Figure 9) has been produced by replacing all dry cells by zero pressures. The pattern differs significantly from that given by MODFLOW-SURFACT. There is less effect above the mine, with positive pressure apparently maintained in the Scarborough Sandstone, and anomalously high pressures in the Lower Bulgo Sandstone (as observed earlier in Figure 5). Unsaturated conditions propagate up to the Stanwell Park Claystone, as they do for MODFLOW-SURFACT. Significant numerical instability is apparent, as there are periodic occurrences of low pressure in the Bulgo Sandstone (between the Stanwell Park Claystone and the Bald Hill Claystone), and shallow dry-cell effects above the Bald Hill Claystone (in the Hawkesbury Sandstone).

4. Conclusions

A direct comparison between Standard-MODFLOW and MODFLOW-SURFACT models with the same parameterisation is problematic because the two software approaches differ in their handling of unsaturated conditions which occur in the near-surface and in the fractured zone above mined coal panels. A consequence is that the models will differ in calibration performance. In the present study, Standard-MODFLOW has the better calibration performance, measured against observed heads only, but the occurrence of dry cells causes unrealistic heads in some cells within the model, particularly at depth in the vicinity of mining. Regional groundwater level patterns in the Hawkesbury Sandstone (near-surface) are not affected by the choice of software, and shallow water levels calculated by Standard-MODFLOW are correct in cells adjacent to dry cells. MODFLOW-SURFACT gives sensible piezometric heads and pressure heads everywhere, and predicts gradational negative pressures within the fractured zone generated by roof caving.

It is clear that near-field mining effects are well simulated by MODFLOW-SURFACT but Standard-MODFLOW can give anomalous heads. Far-field mining effects, however, such as changes in baseflow due to deep mining, are simulated equally well by the two software approaches. On the whole, it is recommended that a code capable of simulating variable saturation (such as MODFLOW-SURFACT) is preferable for modelling of the effects of underground mining on aquifers and their interactions with surface water bodies.

5. Acknowledgements

The author would like to acknowledge and thank Helensburgh Coal Pty Ltd and the staff of Resource Strategies Pty Ltd for commissioning this study and making available the data and modelling results.

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A Geologist’s View of the Hydrogeology of the Hawkesbury Sandstone in the Southern Sydney Basin.

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Abstract

Hydrogeological assessments of the Sydney Catchment Authority’s (SCA) proposed Upper Nepean Borefield, near Robertson in the Southern Sydney Basin, emphasised the existence of fracture zones and the increases of aquifer flows from within those zones. The SCA Consultants associated diameter increases in their early water bores, revealed by Caliper Logs, with significant aquifer flows. They concluded that the enlargements were due to fractures and, therefore, that fractures were significant aquifers.

Their conclusions are in agreement with a previous study of the Hawkesbury Sandstone within the Southern Highlands, in which Lee (2000) highlighted the association of increased water flows with Mesozoic Horst – Graben Tectonics.

The borehole enlargements also coincide with changes of lithology, where low gamma, porous sandstone beds are above more-impervious (higher gamma) shaly sediments. It will be argued that erosion of these porous sandstone beds, during deeper drilling and water-flow testing of lower aquifers, is the most likely cause of the borehole enlargements. Porous beds, not fractures, produce the recorded water flows. Fractures are present but not to the extent of the SCA assessments.

Lee defined Units ‘A’, ‘B’ and ‘C’ of the Hawkesbury Sandstone, based on their varying characteristics within geophysical logs. The units produce differing quantities and qualities of groundwater. Generally, the lower Unit ‘A’ is the most productive but it is not reached by most of the shallower, lower-yielding bores in the Southern Highlands.

The increased yields in uplifted areas, Lee’s Mittagong Horst-Graben and the SCA Consultants’ Mt. Murray Monocline, are not due to the existence of fractures but to Unit ‘A’ being more accessible to the surface. Uplifts in both areas make Unit ‘A’ amenable to recharge at the surface and to penetration by water bores at relatively shallow depths.

Keywords: hydrogeology, Hawkesbury Sandstone, Sydney Basin.

Introduction

The hydrogeology of the Hawkesbury Sandstone, in the southern portion of the Sydney Basin, has been described by McKibbin and Smith (2000). Lee (2000) reported in more detail on the more southern portion of that area, i.e. within horst-graben structures at Mittagong and extending eastward towards Robertson.

McKibbin and Smith generally described the Hawkesbury Sandstone as exhibiting “dual porosity/permeability characteristics” where “the original pore space porosity is overprinted by fracture or solution porosity”. Elsewhere, they refer to its “so-called dual porosity”, the primary porosity being that of the compacted material within the aquifer and dual porosity being the “void space” caused by later tectonic events, e.g. bedding planes, joints, shear zones and solution cavities. Other hydrogeologists have generally described the Hawkesbury Sandstone as a “fractured sandstone aquifer” (e.g. Douglas Partners, 2003).

Lee provided details of the varying geology within the Sandstone. He defined three units within the Formation (Fig. 1), which he recorded as up to 160 metres thick within the Southern Highlands. Using a suite of geophysical logs in existing water bores, he separated the mainly sandstone sequence into:-

- a lower Unit ‘A’, about 70 metres thick and summarised as “sandstone medium to coarse, minor shale”,

- a central Unit ‘B’, about 50 metres thick and comprising “argillaceous sandstone and siltstone”, and
- an upper Unit ‘C’, about 40 metres thick and including “sandstones, medium to coarse”.

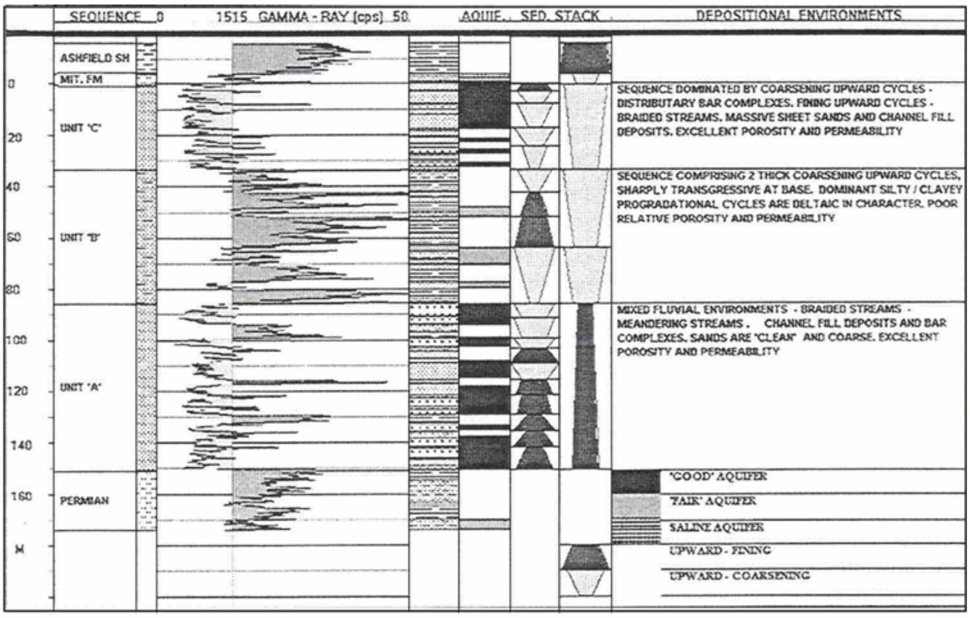


Figure 1 - Stratigraphic correlation of the Hawkesbury Sandstone in the Southern Highlands region. *(From Lee, 2000)*

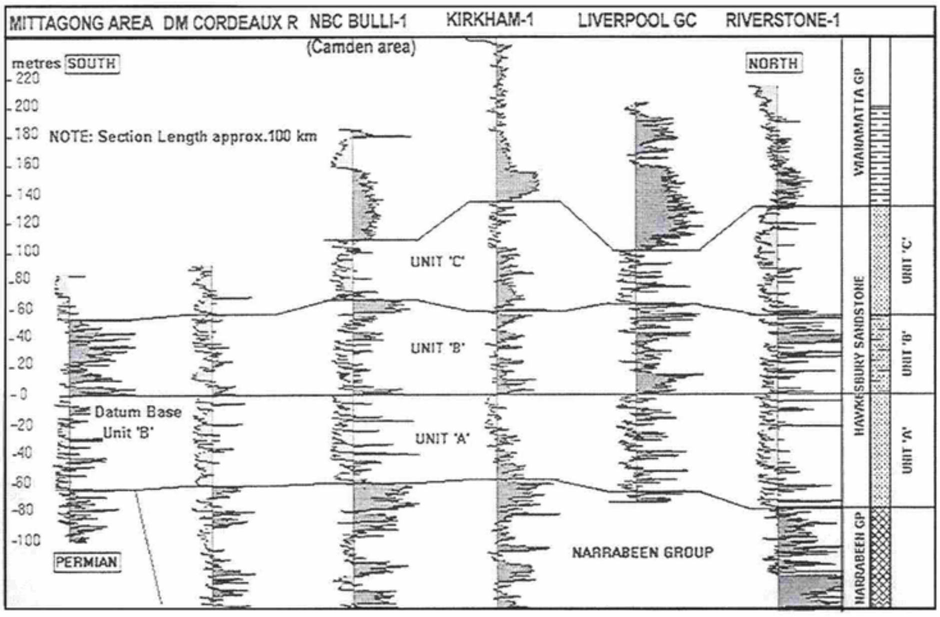


Figure 2 - Gamma-ray log correlation, Mittagong to Riverstone / Sydney region. *(From Lee, 2000)*

He used Gamma Logs, as on Fig. 2, to illustrate the higher gamma – more shaly nature of Unit ‘B’ and to indicate the existence of many individual sandstone beds within all of the Units. Those beds have low gamma responses and are separated by beds with higher and, in Units ‘A’ and ‘C’, sometimes very high gamma responses. The general lithological log, on Fig. 2, confirms that most, if not all, of the high gamma beds comprise shale or mudstone or are at least shaly or “muddy”. They separate the many intervening beds of sandstone, which include the aquifers.

This paper discusses some of the aspects of a recent assessment, by the Sydney Catchment Authority (SCA), of aquifers within the Hawkesbury Sandstone, which ignored the basic principle that Lee expounded but adopted his conclusion, which does not appear to be valid. Variations of the quantity of groundwater throughout the Hawkesbury Sandstone are considered and an alternative interpretation of the hydrogeological assessment is suggested.

The Kangaloon Borefield

The SCA assessed the hydrogeology of the Upper Nepean (Kangaloon) Area, north of Robertson, NSW, for about 3 years. The area was selected by their geological consultants (Parsons Brinckerhoff, 2003) because it was within their Catchment Area but, primarily, because it was considered that fracturing was more likely within the vicinity of the Mount Murray Anticline/Fault. It was assumed that movement of groundwater along the fractures or fault planes would enhance the flow of water within the sandstone and, similarly, that there would be greater recharge of water from the surface and along the fractures.

Their reasoning was not dissimilar to that of Lee, who stated that "Increased rates of groundwater recharge are expected - - - - - from within fracture zones and faults. The production potential of these aquifers is enhanced within zones of major fracturing and faulting associated with the Mittagong Horst-Graben Complex" (Fig. 3), which he extended to the Kangaloon Area.

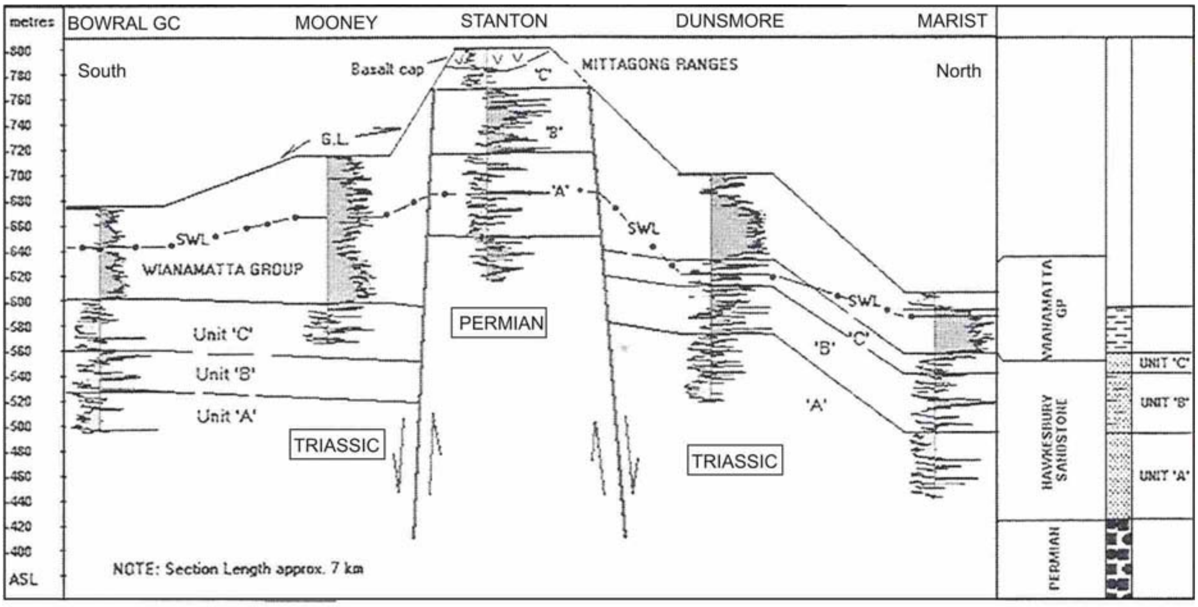
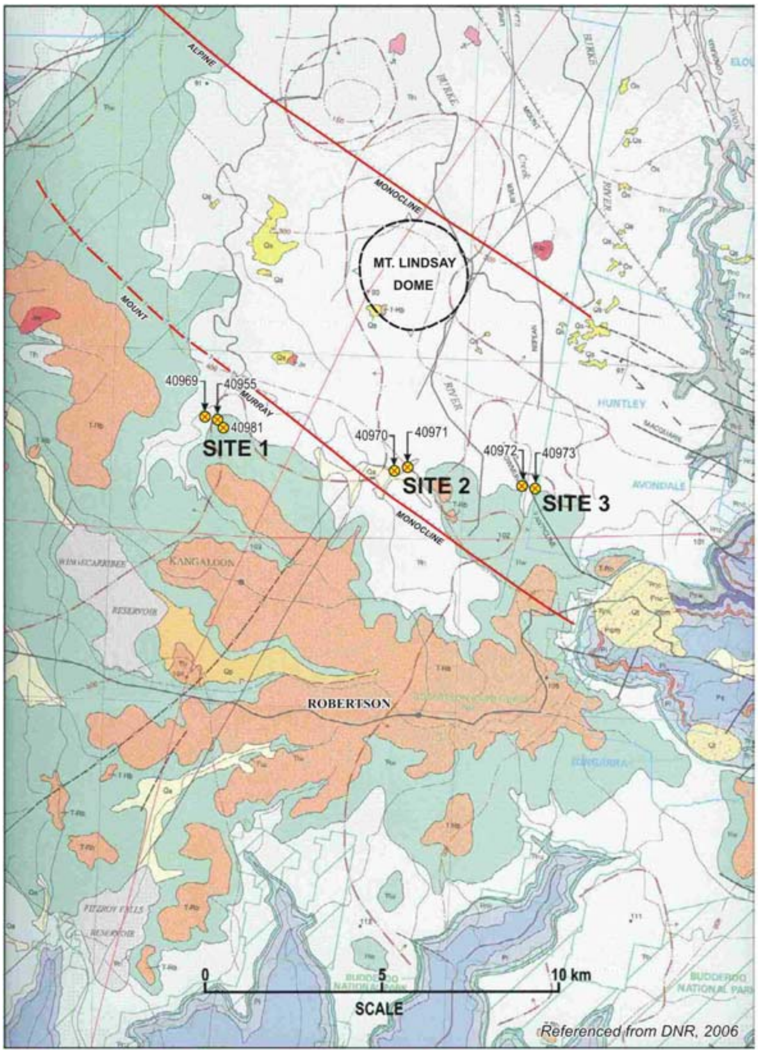


Figure 3 - North-South gamma-ray log correlation across the Mittagong Horst-Graben Complex. *(From Lee, 2000)*

Fig. 4 shows the location and surface geology of the proposed Kangaloon Borefield and the initial three drilling sites. The borefield is north of the basalt-covered area of Robertson, is essentially within only the Hawkesbury Sandstone and the likely re-charge of water to, and discharge of water from, the aquifers is essentially within that Formation.

Many bores have been completed, as part of the assessment process. Most fully penetrate the Sandstone sequence, proving thicknesses of more than 120 metres. In the uplifted area of a horst between two north-westward trending normal faults (the Mt. Murray Anticline/Fault System) only the basal section of the Sandstone is present (e.g. at site 2 on Fig. 4).

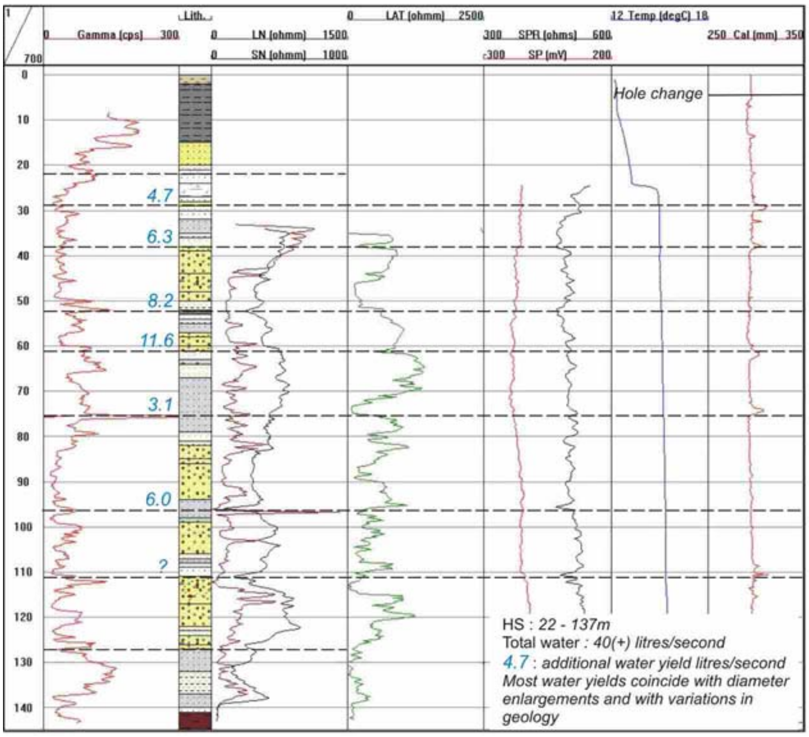
This paper discusses only the initial bores drilled, at Sites 1 to 3, as they are adequate to illustrate the sub-surface geology, the possible association of aquifers with that geology and the variation of the extractable quantity of water within the geological sequence.



LEGEND		GROUP	FORMATION
QUATERNARY	Qa		
	Qs		
	Qp		
TERTIARY	Tb		
	T-rb		Robertson Basalt
JURASSIC	Jv		
	Jes		
TRIASSIC	Rw	Wianamatta Group	
	Rh		Hawkesbury Sandstone
	Rnz	Narrabeen Group	Newport Formation/ Garie Formation/ Bald Hill Claystone
	Rnc		Colo Vale Sandstone/ Bulgo Sandstone
PERMIAN	Pi	Illawarra Coal Measures	
	Ps	Shoalhaven Group	

After Mineral Resources (1999)

Figure 4 - Regional Geology & SCA Drilling Sites



HS : 22 - 137m
Total water : 40(+) litres/second
4.7 : additional water yield litres/second
Most water yields coincide with diameter enlargements and with variations in geology

Logging Data		Borehole Data		Construction Details				
				Casing Record				Cementing details
Project:	Sydney Catchment	Date Drilled:	13/9/05	Size	Type	From	To	
Date Logged:	13/9/05	Elevation:		340mm	Steel	0	6m	Tremmie cement 0 - 6m
Area:	Southern Highlands	Easting:	272624					
Property:	Upper Nepean	Northing:	6178000					Comments:
Operator:	B Finch	Hole Diameter:	300mm					
Fluid Type:	Water	Depth (driller):	143m					
Fluid Level:	24.65m	Bore Type:	Production					
Fluid Salinity:								

Sandstone (fine,medium)	Sandstone (fine)	Sandstone (medium)	Sandstone (coarse)	Claystone (red brown)
Sandstone (fine,medium, shale)	Sandstone (fine, white)	Sandstone (medium)	Sandstone (fine to coarse)	Siltstone
Clay	Sandstone (fine, light grey)	Sandstone (medium coarse)	Shale (grey)	

Figure 5 - Downhole Graphic & Geophysical Logs - Bore GW040981Upper Nepean Site 1C *(from DNR, 2006)*

Aquifer Identification

Fig. 5 includes details of Bore GW040981, at Site 1C. From left to right, it includes:-

- a Gamma Log,
- a graphic representation of the lithology, based on cuttings from the non-cored borehole,
- Resistivity Logs at various scales,
- Self Potential Logs at various scales,
- a Temperature Log within various temperature ranges,
- a Caliper Log, with a diameter recording range of 250 to 350mm. As it shows, the nominal borehole diameter is approximately 300mm, plus
- the additional water flows recorded at each significant aquifer

The Standing Water level in the borehole is best determined by the sharp increase in Temperature at 24 metres below ground level (mbgl). Most of the electric logs commence at that level.

During drilling of the boreholes, penetration ceased when each significant aquifer was indicated by an increase of water in the airlift of drilling fluid. The cumulative flow at that depth was determined by airlift and recorded as litres per second (l/s). For example, at Site 1C, the total **cumulative** flow was more than 40 l/s over the whole Hawkesbury Sandstone sequence and the estimated **additional** water flow from each major aquifer is shown at the recorded depths. The additional flows range from 4.7 l/s at about 30 metres below ground level (mbgl), to 11.6 l/s at 60 mbgl and to an unrecorded flow at about 110 mbgl.

The bore includes 7 significant aquifers. They can be related to sandstone beds recorded in the Lithology Log, to low responses in the Gamma Log and, usually, to some change of the Resistivity and Self Potential Logs. Gamma Logs had been used by Lee to define the many sandstone aquifers and their underlying finer-grained beds throughout the Hawkesbury Sandstone.

Caliper Logs were also used by the SCA Consultants and Fig. 5 records a number of increases of diameter of the borehole. They were interpreted as being due to fractures in the sandstone and, because they coincide with the recorded levels of some aquifers, were assessed as being the sources of water.

Comments which accompanied the Geophysical Logs shown on Fig. 5 (DNR 2006, Appendix 6) stated that "significant variations in borehole diameter at 28-38m, 60-62, 74-75 and 109-115 may indicate water bearing fractures at these depths, which is supported by information given in the driller's log". The Driller reported Water Bearing Zones commencing at 27, 37, 52, 61, 75, 97 and 110mbgl. Five of the so-called fracture zones correlate approximately with additional flows of 4.7 l/s at about 27m, 6.3 l/s at 37m, 11.7 l/s at 61m, 3.1 l/s at 75m and an unknown quantity at 110m. The other significant flows of 8.2 l/s at 52m and about 6 l/s at 97m do not coincide with borehole enlargements. Despite that, the comments on the Geophysical Log were summarised as "Fractured sandstone from 28-38m, 60-62m, 74-75m and 109-115m **has been clearly defined and is reported to be the main water supply zone for this bore".** (emphasis added).

Fractures have been recorded in the Lithology Logs of some other bores but none were reported in the log for Bore GW040981. Elsewhere, some references to fractures appear to have been added only because of the results of the Caliper Logs. Occasionally, a fracture is recorded together with iron-staining and an iron-filled joint or fracture may have been indicated. Generally, the occurrences are more prevalent later in the drilling programme, possibly because the initial assessment emphasised the significance of the fracture zones.

The association of factures to significant flows from aquifers continued during the subsequent investigations, as the SCA Consultants appeared to accept that enlargements of the borehole were due only to fracturing of the strata and concluded that the fractures were the reason for the significant water flows.

An alternative explanation for the borehole enlargements is that the aquifers with significant water flows are within sandstone beds and have little if any relevance to fractures. The sites of increased bore diameters also coincide with apparent changes of lithology. In Bore GW040981, the more significant enlargements are at levels of low-gamma responses, indicating sandstone beds, which are underlain by beds with higher gamma response, indicating more impervious and, probably, shaly beds. Such impervious layers would semi-confine the aquifers, which are within porous sandstone beds. They tend to be “soft” and friable and very prone to erosion, particularly during the violent agitation of the water in the borehole during airlift tests of subsequent aquifers.

The scale for the Caliper Log on Fig. 5 is assumed to be linear. If so, the maximum borehole enlargement recorded in Bore GW040981, is 8.5mm, which occurs over a vertical thickness of up to 3.5 metres. Such relatively minor enlargements over a number of metres appear to be related more to erosion of a porous sandstone bed than to a fracture of the wall of the hole.

Some of the enlargements may be due to fracturing, and fractures have been observed by down-hole cameras (John Ross, pers.com.). However, as later discussed, they usually are iron-filled and not “open” to significant water flows.

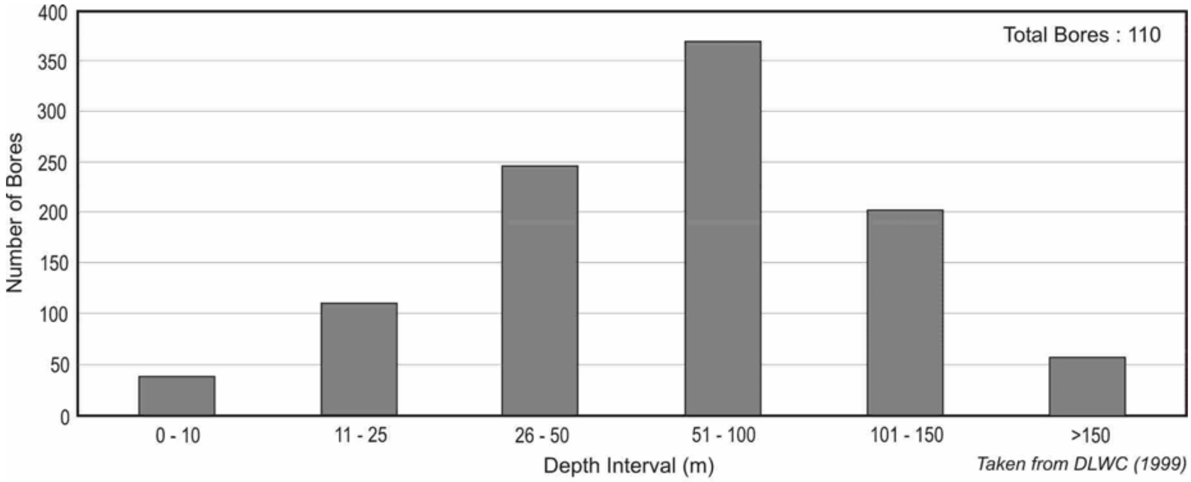
Aquifer Distribution

Observations of water seepages from the Hawkesbury Sandstone, in the many exposures along Freeways, provide convincing evidence that the significant aquifers within the Formation are porous sandstone beds above a more impervious layer; either a shaly bed or, perhaps, only a less porous sandstone bed. Fractures within the sandstone are not frequent and usually are not “open”. Older joints and fractures invariably are in-filled with iron or other minerals. Within the fractures, some down-flow of water is possible, and can be seen after significant rainfall, but up-flow of groundwater within those features, even under pressure, is most unlikely.

The SCA Consultants have reported that the greater aquifer flows are in fractured areas within the Sandstone. However, there is another possible interpretation of the increased flows in some of their bores, within the influence of the Mount Murray Anticline/Fault, just as it is possible to re-interpret the conclusions of John Lee.

Lee proved three major sedimentary units within the Hawkesbury Sandstone, correlated them across the Southern Highlands and concluded that the largest groundwater flows were associated with uplifted areas, due to the fractures and faults within them.

He did not discuss the vertical variation of water flows but it is known, and the SCA have proved, that flows vary considerably from Unit to Unit. Usually, Unit ‘A’ has a considerably higher yield than the other units and flows of less than about 6 l/s are normal, when Unit ‘A’ is not penetrated.



Taken from DLWC (1999)

Figure 6 - Total depth of bores - Southern Highlands

The Department of Land and Water Conservation (DLWC, 1999) recorded that, of the 1023 water bores registered at that time, 764 or about 75% had depths of less than 100 metres (Fig. 6). As Unit 'A' commences about 90 metres into the Hawkesbury Sandstone and most of the bores are within areas also covered by Wianamatta Shale, and/or Robertson Basalt, relatively few bores extend to Unit 'A'. As the DLWC state, "Termination of a bore is usually dependent on either successful intersection of an aquifer or economic grounds", the Licensee stops the drilling as soon as sufficient flow has been recorded. Usually, that quantity is much less than 6 l/s. Parsons Brinckerhoff (2003, page 8-1) reported that only 12.4 % of bores in the Southern Highlands "recorded yields of 6l/s or better".

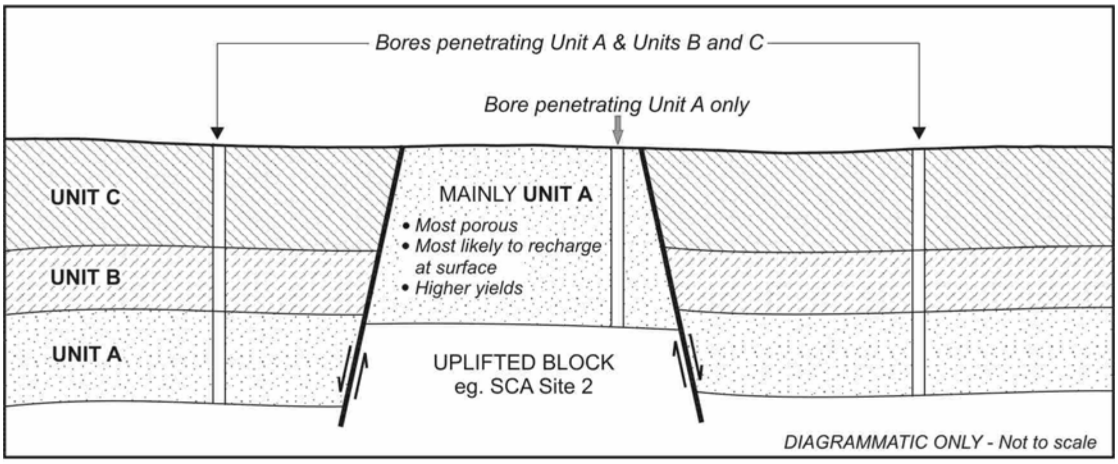


Figure 7 - An explanation for additional aquifer flows within uplifted areas

Fig. 3, from Lee, indicates that Unit 'A' is closer to, or at the surface, in the uplifted areas of the Mittagong Horst-Graben. Figure 7, based on SCA's structural interpretation, suggest that their Site 2 is similarly within an uplifted area, within the Mt. Murray Monocline/Fault. In both areas, the more significant water flows from Unit 'A' are more accessible to the surface and are more likely to be penetrated by water bores. In the Kangaloon Borefield, the very porous sandstones of Unit 'A' also outcrop at Site 2, where they are more amenable to recharge, in an area where annual rainfall is more than 1500mm.

Conclusions

The Hawkesbury Sandstone has long been regarded as a "fractured aquifer" and the conclusions of Lee (2000) and of the SCA Consultants were that the fracture zones, associated with uplifted areas, enhanced groundwater flows. The local enlargements of borehole diameters, in the initial SCA assessment bores, were interpreted as being due to such fractures.

The fractures in the SCA bores also coincide with porous (low gamma) sandstone beds, as identified by Lee (2000). This paper concludes that erosion of the sandstone, during later airlift pumping tests, is the prime reason for the enlargements, not the existence of fractures. The significant water flows are from porous sandstone beds, semi-confined by more impervious strata.

Larger water flows do occur in bores located within uplifted areas, but the penetration of the more porous, basal Unit 'A' is the prime reason for the increased flows.

Acknowledgements

The writer was a Member of the Upper Nepean Community Reference Group, appointed by the Sydney Catchment Authority. Virtually all of the Consultants' reports on the assessment of their Upper Nepean Borefield were provided to Members. The results of their assessment programmes were made available, usually in presentations by John Ross, Groundwater Project Manager. At those meetings, the writer’s conflicting geological assessments, expressed in this paper, also were discussed. The cooperation of the SCA and its Consultants in allowing discussion of these conflicting arguments and for allowing reproduction of some of their data is acknowledged

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Modelling Dewatering Effects on Groundwater Dependent Ecosystems at Raymond Terrace, Newcastle

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Abstract

Dewatering was required in order to abstract groundwater discharging into excavations during construction of a new clarifier and digestor. Groundwater model indicated that between 0.34 ML/day and 0.30 ML/day needed to be abstracted during construction of the clarifier in order to maintain a water level of -2.3 m Australian Height Datum (AHD). Between 0.15 and 0.16 ML/day needed to be abstracted during construction of the new digestor in order to maintain a water level of -0.5 m AHD. While simulation results indicated that dewatering activities lead to a reduction in the rate of groundwater discharge to the wetlands area (between 60 and 74 kL/day at the end of construction of the clarifier and digestor, respectively), the total volume discharged to the wetlands was expected to increase due to the dewatering volume being subsequently treated and discharged to the wetlands. Mass balance results indicated that the input volume to the wetlands area was unaffected during dewatering activities and were unlikely to have a significant impact on the overall mass balance of the wetlands system. The presence of groundwater dependent ecosystems (GDEs) was confirmed through an ecological survey conducted in the study area. Three broad classes of GDEs were identified based on the depth of the groundwater and level of dependency. Based on the model results, proposed dewatering volumes and ground-truth ecological survey it was concluded that there would be no significant increase in the depth to groundwater below the obligate and obligate/facultative GDEs identified from this study (i.e. average 200-300 mm). Therefore, the volume and length of dewatering was not expected to impose a significant impact on GDEs in the study area in the medium to long-term.

Keywords: Dewatering, Groundwater Modelling, Groundwater Dependent Ecosystems.

Introduction

Dewatering was required as part of upgrade works to construct a new clarifier[1] and digestor[2]. A licence was required from the Commonwealth Government Department of Water and Energy (DWE) under Part 5 of the Water Act to undertake dewatering activities. Prior to approving and issuing the licence, DWE requested additional

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[1] A clarifier is any large circular or rectangular sedimentation tank used to remove settleable solids in water or wastewater.

[2] A digestor is a tank or other vessel for the storage and anaerobic or aerobic decomposition of organic matter present in the sludge.

information to better understand the potential impact of the proposed dewatering activities on GDEs at the site and surrounding area.

This paper describes the groundwater modelling methodology used by Sinclair Knight Merz (SKM) to predict water levels and abstraction requirements to assess the potential impacts of dewatering activities on GDEs.

Site Description

As shown in Figure 1 the site is located to the south of Raymond Terrace Township, approximately 20 km north of Newcastle.

Figure 1 - Site Location

The site is bounded to the north by the Grahamstown Drain which in turn discharges to Grahamstown Dam to the northeast, to the east by private farm land, to the south by Windeyers Creek and to the west by a quarry. The surrounding area is generally agricultural with a residential area located approximately 250 metres north of the site and the Pacific Highway approximately 500 metres to the east.

The site is generally flat with a gentle slope towards the east. Ground elevation in the site is between 5 and 6 m AHD, with the ground surface sloping to 2 m AHD immediately to the north and west of the plant. These areas consist of low lying wetlands as they approach Grahamstown Drain to the north.

Geological and Hydrogeological Setting

The site is situated on the Tomago Sandbeds Aquifer, which is used as one of the three main drinking water supplies for the Newcastle region. The aquifer supplies approximately 25% of the region's potable water and covers an area of approximately 183 square kilometres (Crosbie, 2003).

The Tomago Sandbeds Aquifer is an unconfined coastal aquifer located in a coastal barrier setting. The aquifer consists of fine to medium grained sand of Aeolian origin that extends from the ground surface to depths of at least 30 m bgs. The sands have a high degree of porosity and permeability, allowing high transmissivity for water.

The water table is relatively shallow throughout much of the aquifer, and its elevation responds rapidly to rainfall recharge. The aquifer is recharged entirely by rainfall infiltration, with water levels controlled by rainfall and evapotranspiration. Aquifer recharge is strongly influenced by the thickness of the unsaturated zone between the water table and ground surface, with the rate of recharge increasing with shallower water levels. Groundwater actually approaches and inundates the ground surface in low lying areas and during significant rainfall events. Based on water level and topographic data for the site, this scenario is expected to occur in the low lying wetland areas to the north and west, with groundwater levels exceeding the ground surface and supplying the wetlands. Nearby surface water bodies Grahamstown Drain and Windeyers Creek both flow to the west towards the Hunter River, and inferred groundwater contours for the site indicated groundwater flow is in the same direction.

Numerical Model Development

A numerical groundwater model for the site was developed using the MODFLOW 2000 modelling code (Harbaugh et al, 2000). The model was constructed from a previous model built by SKM for the Tomago Sandbeds Aquifer (SKM, 2006), which included the site location. The original Tomago Sandbeds Aquifer model (SKM, 2006) was constructed using a single layer and 100 m by 100 m grid across the entire aquifer area, which had dimensions of approximately 35 km by 12 km. The surface and base of the original model were obtained from the model constructed by Crosbie (2003).

The site groundwater model domain was initially defined by focusing the existing Tomago Sandbeds Aquifer model (SKM, 2006) on the region that includes the site. The model extents were then set by aerial photography, contour data and relevant hydrogeologic features in the vicinity of the site. The resulting model grid contained approximately 21,000 grid cells in 128 rows and 164 columns, covering an areal extent of 5 km (east-west) by 3 km (north-south). The orientation of the model was also adjusted to correspond with true north. The model grid was refined in the vicinity of the site in order to achieve better resolution for groundwater flow in the area. Relevant hydrogeologic features in the vicinity of the site, such as Grahamstown Drain, the Rocla quarry, and the wetlands to the west of the site, were also accounted for in the model.

The model was constructed with five vertical layers in order to achieve better vertical discretisation for groundwater flow. The base of the model (bottom of layer five) was defined by the aquifer base used in the original Tomago Sandbeds Aquifer model (SKM, 2006), while the ground surface was shaped using topographic contour data for the site and surrounding area.

Boundary Conditions

Boundary conditions for the model were defined by the Hunter River and groundwater head results for the model domain from the Tomago Sandbeds Aquifer model previously developed by SKM (2006). Grid cells corresponding to the Hunter River were assigned as constant head cells with a head of 0 m AHD, and all cells to the north and west of the Hunter River were made inactive as they do not take part in the groundwater flow regime for the site. Constant head cells were also assigned at the northern, eastern, and southern boundaries of the model domain, with head values defined by the results of the original Tomago Sandbeds Aquifer model under steady state conditions. The values were determined by overlaying the site model domain on the original Tomago Sandbeds Aquifer model and assigning the hydraulic head results under steady state conditions to the corresponding boundaries of the model domain.

Model Parameters

Site specific values for hydraulic conductivity were calculated from field tests conducted by SKM at the site. All other aquifer parameters were taken directly from the previous model developed by SKM for the Tomago Sandbeds Aquifer (SKM, 2006), with the exception of specific storage, which was adjusted according to literature data as the original Tomago Sandbeds Aquifer model included only one vertical layer. Table 1 summarises the aquifer properties used in the model.

Table 1 - Property Input Data for Groundwater Model

Aquifer Property	Value	Source
Hydraulic Conductivity, $K_x = K_y = K_z$	3 m/d	SKM field data
Specific Storage, S_s	5×10^{-6} 1/m	
Specific Yield, S_y	0.15	SKM, 2006
Total Porosity	0.4	SKM, 2006
Effective Porosity	0.4	SKM, 2006

Hydraulic Conductivity

Hydraulic conductivity values input in the model were determined from aquifer slug test data collected by SKM at the site. Slug tests were undertaken at three existing groundwater wells and water level data recorded on data logger for the falling and rising head slug tests was analysed using the Hvorslev (1951) method to determine hydraulic conductivity. A minimum of two falling head and two rising head tests were conducted at each groundwater well. The hydraulic conductivity values determined for each borehole and for each slug test were consistent, and the average value of 3 m/d was used as input for hydraulic conductivity in the groundwater model.

Recharge

Due to the shallow nature and physical characteristics of the Tomago Sandbeds Aquifer, recharge became one of the most important parameters influencing water levels in the model. Recharge was initially assigned according to the recharge determined for the site in the Tomago Sandbeds Aquifer model previously developed by SKM (2006), and a single recharge zone was applied across the entire model domain. Recharge was adjusted during calibration of the steady state model to better simulate hydraulic heads observed at the site. Following calibration of the model, recharge was then adjusted according to average monthly rainfall data collected by the Bureau of Meteorology's (BOM) Raymond Terrace (Kinross) weather station, which is located less than 3 km from the site, for the transient state model simulations (refer Sec 8).

Evapotranspiration

In MODFLOW 2000 evapotranspiration is defined as a discharge from groundwater that is inversely proportional to the depth from ground surface to the water table. The inputs required to define evapotranspiration in the model are the maximum evapotranspiration rate, which is based on the evaporation rate for the area, and an extinction depth. The rate of evapotranspiration in a given cell at a given time is then calculated by linear interpolation between the maximum evapotranspiration rate when the water table is at the ground surface, to an evapotranspiration rate of zero when the water table is at (or below) the extinction depth. Similar to recharge, a consistent evapotranspiration function was applied to all cells in the model domain. A maximum evapotranspiration rate of 1000 mm/year was input into the model, which corresponds to approximately 60% of the average yearly evaporation rate observed at the BOM's Williamtown RAAF weather station. An extinction depth of 2 m was also used in the model, taken from SKM's original Tomago Sandbeds Aquifer model (SKM, 2006).

Model Setup

Specific features included in the groundwater model for the site included the wetlands area to the west of the plant (where treated effluent from the site is discharged), the quarry on the adjacent property to the west, and Grahamstown Drain to the north of the site. The quarry and wetlands area were nominated as MODFLOW RIVER cells to allow these areas to interact with groundwater in surrounding cells. Water levels in the quarry and wetlands area were set at 1 m AHD, based on available surface contour data. Grahamstown Drain was defined in the model using MODFLOW DRAIN cells, which act to remove water from the aquifer in proportion to the difference between the groundwater potentiometric head and the assigned water levels in the drain cells. This behaviour is consistent with the purpose of Grahamstown Drain, which was constructed to alleviate surface flooding caused by groundwater levels intercepting the ground surface (SKM, 2006). The water level in Grahamstown Drain was set at 100 mm below the ground elevation of the respective cell.

It is noted that using river cells for the wetlands area imposes a boundary condition of the specified head (in this case 1 m AHD) for those particular cells in the model. The model adjusts hydraulic heads in surrounding cells to meet this boundary condition. While topography and water level data suggested the wetlands area was likely fed by groundwater, and as a result water levels in the wetlands were likely subject to groundwater levels in the surrounding area. It is noted that using this model setup the water level in the wetlands is constant and influences groundwater levels in the surrounding cells, rather than the other way around. In spite of this, simulating the wetlands as river cells was considered appropriate due to the non-natural inputs and outputs for the wetlands area, namely being the treated effluent discharged to the wetland from the treatment plant, and the constructed outlet weir(s) subsequently discharging water from the wetlands to Grahamstown Drain. These additional inputs and outputs served to artificially control the water level in the wetlands, making the use of river cells in the model appropriate for simulating actual conditions.

Model Calibration

Due to the limited amount of site specific data available, the model was calibrated only in steady state mode. Steady state model calibration involved the matching of hydraulic heads under steady state conditions to water levels observed at the site. Available water level data consisted of three groundwater monitoring events previously conducted at the site. Water level data available for the site exhibited considerable fluctuations between gauging events, with water levels changing by as much as 0.7 m for the same well between events. These fluctuations likely reflect the influence of rainfall on water levels at the site. In order to calibrate the steady state model to conditions less likely to be influenced by high rainfall events, the date of each monitoring event was compared to rainfall data collected at the site. Three of the four monitoring events (28 April and 1 May 2008, and 17 February 2009) were conducted within 15 days of heavy rainfall at the site, as shown in Figure 2. As a result the water level data collected on 16 April 2008 was used for model calibration in order to better establish groundwater levels under 'normal' conditions.

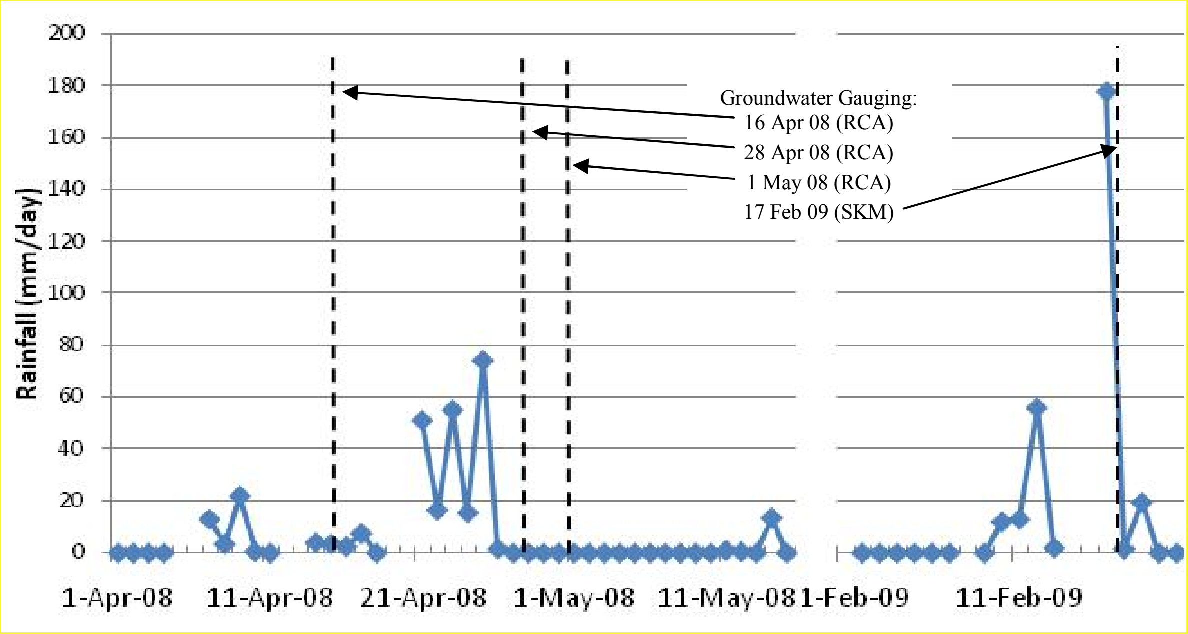

Figure 2 - Rainfall Data for Raymond Terrace

The calibration process involved trial and error matching of potentiometric heads determined by the model at observation bores within the site with observed water levels. Recharge in the model was adjusted to better simulate the observed heads, and the resulting steady state model predicted water levels at the wells within 0.1 m AHD of the observed levels. The recharge value determined during model calibration (550 mm/yr) fell within 10% of the average recharge determined for the site in the Tomago Sandbeds Aquifer model previously developed by SKM (510 mm/yr), which was calculated using rainfall data and a Soil Moisture Balance Model over a ten year period.

Dewatering Scenarios

Design

Following calibration of the model under steady state conditions, transient simulations were run to investigate the effect of dewatering during the proposed construction works on groundwater at the site and surrounding areas. The groundwater head results determined by the steady state model simulations were used as initial heads for the transient simulations. Transient model simulations were initially constructed to account for seasonal variations in rainfall at the site and the corresponding effect on groundwater levels. Average monthly rainfall data for the BOM's Raymond Terrace (Kinross) weather station was used to determine monthly variations in recharge for the model. The relationship between rainfall data for the local area and recharge values used in the model was based on the long term average annual rainfall for the Raymond Terrace (Kinross) station and the recharge value determined during the steady state model calibration.

Dewatering in the model was simulated using MODFLOW DRAIN cells. The drain cells were placed in those areas scheduled for construction of the clarifier and digestor, respectively. Target water levels were input as -2.3 m AHD and -0.5 m AHD for the clarifier and digestor, respectively, based on the dewatering plans for the construction works. In addition, hydraulic conductivity values were adjusted in the drain cells for the clarifier and digestor to simulate the use of sheet piling during construction to limit horizontal groundwater flow into the construction area. Horizontal hydraulic conductivity values for the drain cells were adjusted to 1 x 10-5 m/d.

Transient simulations were run using time steps that accounted for 100 days (approximately 14 weeks) of dewatering at the proposed clarifier, followed by 100 days of dewatering at the proposed digestor, in accordance with the proposed construction programme. The simulations were run assuming construction and dewatering works would begin on the first of April. Table 2 summarises the time steps, recharge, and dewatering activities simulated in the model.

Table 2 - Time Steps for Transient Model Simulations

Time Step (days)	Calendar Month	Avg Rainfall by Month (mm/mth)	Model Recharge (mm/yr)	Dewatering Activity	Target Level (m AHD)
0 – 30	April	1168	612	Clarifier	-2.3
30 – 60	May	1244	652	Clarifier	-2.3
60 – 90	June	1417	742	Clarifier	-2.3
90 – 100	July	1268	664	Clarifier	-2.3
100 – 120	July	1268	664	Digestor	-0.5
120 – 150	August	1132	593	Digestor	-0.5
150 – 180	September	1249	654	Digestor	-0.5
180 – 200	October	866	454	Digestor	-0.5
200 – 210	October	866	454	Digestor	-0.5
210 – 240	November	770	403	None	N/A
240 – 270	December	759	397	None	N/A
270 – 300	January	835	437	None	N/A
300 – 330	February	843	442	None	N/A
330 – 360	March	1053	552	None	N/A

Notes:
Avg Yearly Rainfall (Raymond Terrace): 1050 mm/yr
Calibrated Model Recharge: 550 mm/yr
Ratio of Model Recharge to Actual Rainfall: 0.52

Results

Results of transient model simulations indicated that the proposed dewatering would have an effect on the quantity of water fed to the wetlands from groundwater, as expected. The model indicated that between 0.34 ML/day (April) and 0.30 ML/day (July) would need to be pumped out for dewatering during construction of the clarifier in order to maintain a water level of -2.3 m AHD. The fluctuation in dewatering rates for the different months was due to variations in rainfall, and consequently recharge, during the construction program. Between 0.15 and 0.16 ML/day would need to be pumped for dewatering during construction of the new digestor in order to maintain a water level of -0.5 m AHD. The dewatering would in turn reduce the natural discharge of groundwater to the wetlands by approximately 90 and 74 kL/day at the end of the construction periods for the clarifier and digestor, respectively.

The model simulations presented in this paper assumed that the water pumped out of groundwater during dewatering was subsequently discharged to the wetlands area (whether via the treatment plant or direct). This scenario allowed the specified water level for the river cells that represented the wetlands in the model to continue to apply during the dewatering phases. Therefore, as long as the groundwater pumped out during dewatering is returned to the wetlands, the water level in the wetlands would not decrease, and the water level used in the model would continue to be valid. For this reason the water table drawdown determined in the simulations did not extend in to the wetlands area, a result of the wetlands being modelled as river cells with set water levels. However, should the groundwater pumped out during dewatering not be returned to the wetlands, the water level in the wetlands was expected to decline. Additional model simulations that did not account for the discharge of the dewatering volume to the wetlands to the west of the site have indicated static water levels in this area would decrease.

Figures 3 shows the GDEs and the radius of influence of groundwater drawdown as a result of dewatering activities reaching a maximum at the end of dewatering for the clarifier construction (100 days). The drawdown of the water table at 210 days indicated that groundwater levels returned to within 400 mm of normal levels within ten days of stopping dewatering activities, reflecting the high transmissivity and rapid response characteristic of the Tomago Sandbeds Aquifer.

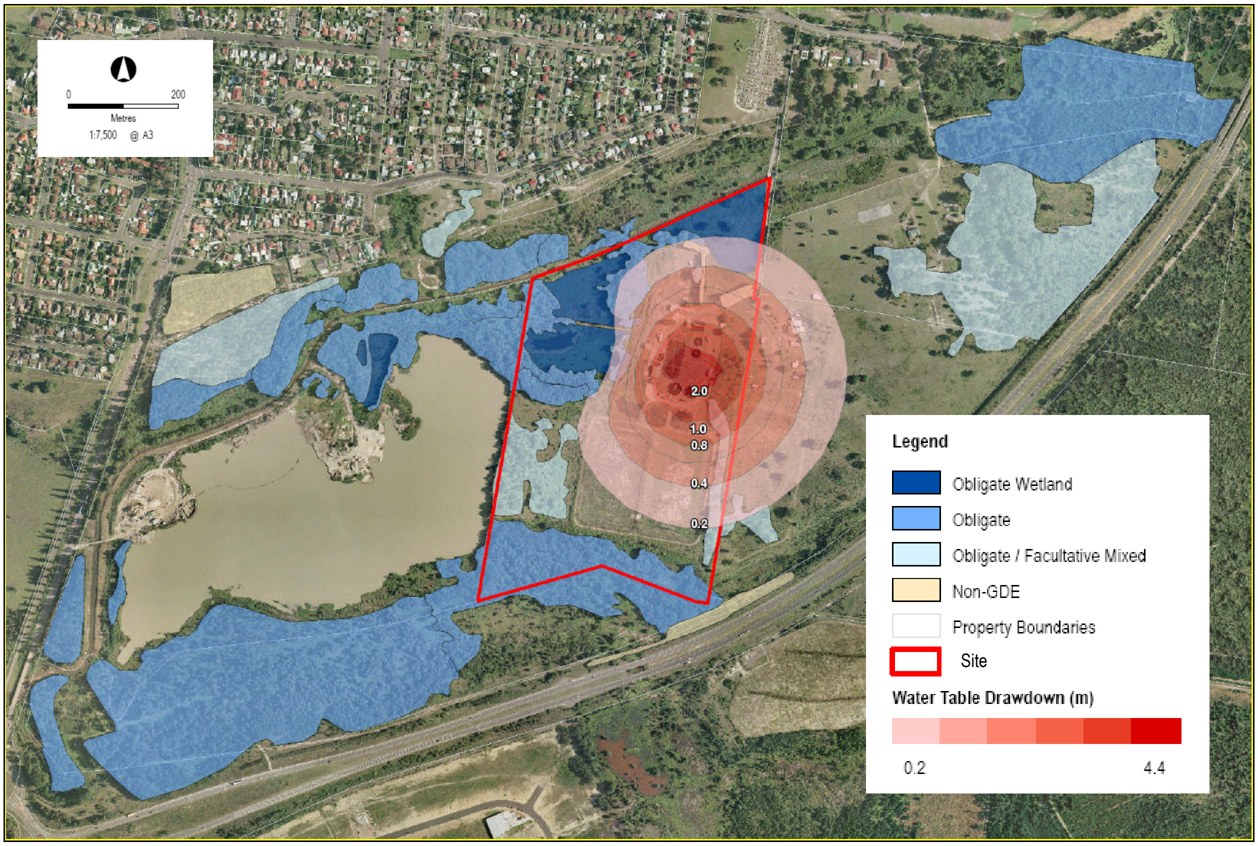

Figure 3 – GDEs and Groundwater Drawdown at T = 100 days

The presence of GDEs was confirmed through an ecological survey conducted at the site and the surrounding area. Three broad classes of GDEs were identified based on the depth of the groundwater and level of dependency. These included:

1) A wetland ecosystem (obligate wetland) dependent on the direct uptake of groundwater and surface expression of water (0-1 m depth);
2) Swamp forest ecosystems and wet meadow wetland (obligate) dependent on the subsurface presence of groundwater which is being accessed via the capillary fringe located above the water table (1-2 m depth); and
3) Sclerophyll forest and woodland (obligate/facultative mixed) adapted to accessing groundwater through the capillary fringe when it is available but not dependent in the medium and long term (2-3 m depth).

The swamp forest and wetland communities were consistent with the definition provided for high priority GDEs in Schedule 5 of the Water Sharing Plan for the Tomago-Tomaree Stockton Groundwater Sources 2003.

Further interrogation of the model predicted the potential impact of dewatering activities on the wetlands area to the west of treatment plant from a mass balance perspective. While simulation results indicated that dewatering activities would lead to a reduction in the rate of groundwater discharge to the wetlands area (between 60 and 92 kL/day), the total volume discharged to the wetlands was actually expected to increase due to the dewatering volume being subsequently discharged (via the treatment plant) to the wetlands. Figure 4 shows the input volume to the wetlands area under normal conditions and during dewatering activities. Data for the discharge volume from the treatment plant to the wetlands for the 2008 calendar year was used for this prediction. The plot (Fig. 4) showed that during the period of dewatering activities (assumed to commence at the beginning of April), the overall change in volume input to the wetlands area still fell within the minimum and maximum fluctuations observed under normal conditions. The data suggested that the dewatering activities were unlikely to have a significant impact on the overall mass balance of the wetlands system.

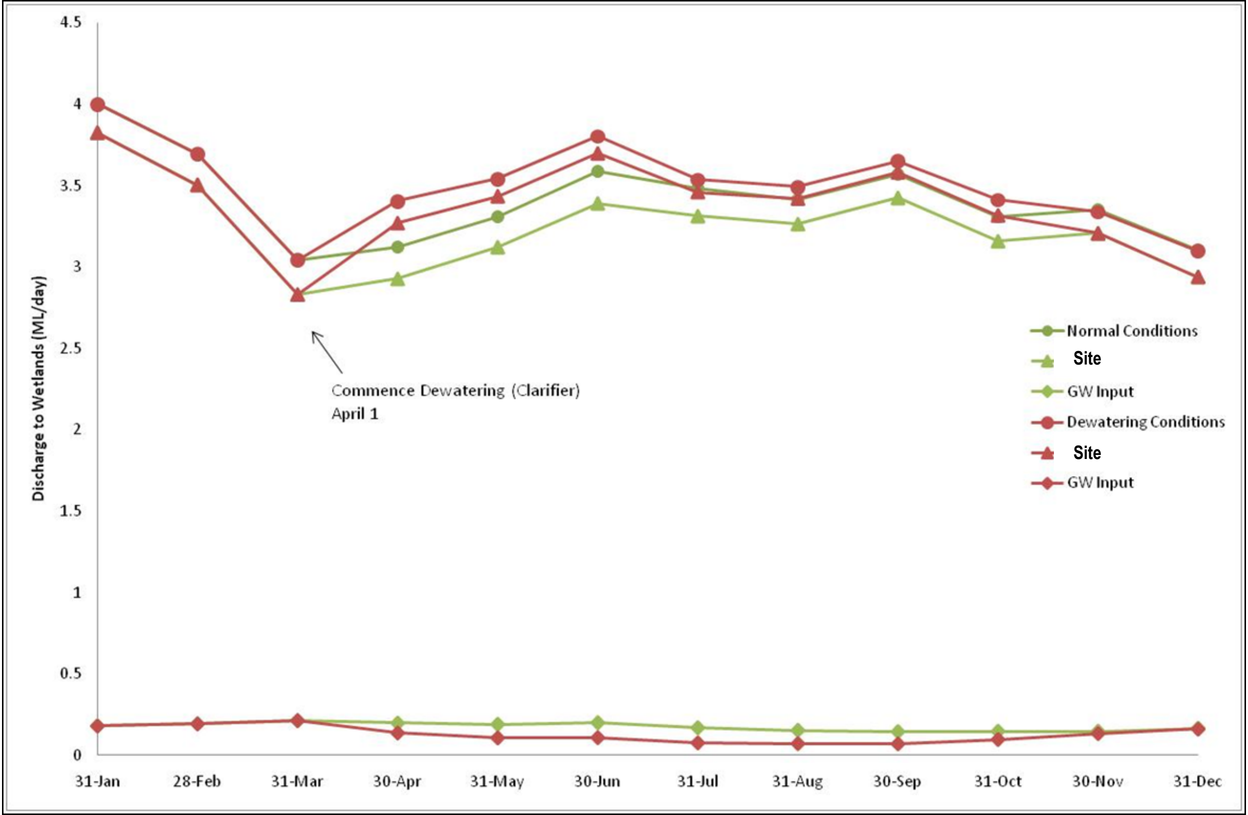

Figure 4 - Wetlands Mass Balance under Normal and Dewatering Conditions

Conclusions

The model results indicated that water table drawdown reached a maximum of 400 mm in those areas of obligate or obligate/facultative GDEs, with the average drawdown in these areas being 200 to 300 mm. The maximum drawdown radius of influence was predicted to occur at the end of dewatering for the clarifier construction (100 days). The drawdown results at 210 days indicated water levels in GDE areas returned to normal levels within ten days of stopping dewatering activities.

Based on the model results, proposed dewatering volumes and ground-truth ecological survey it was concluded that there would be no significant increase in the depth to groundwater below the obligate and obligate/facultative GDEs identified from this study (i.e. average 200-300 mm). Therefore, volume and length of dewatering was not expected to impose a significant impact on GDEs in the study area in the medium to long-term.

Based on these findings a licence was granted by DWE under Part 5 of the Water Act to undertake dewatering activities.

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Discrete interval sampling and pressure measurements in uncased boreholes using a zone-of-interest groundwater sampler (ZOIGS)

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Abstract

An improved method of sampling groundwater and measuring pressures from discrete intervals or zones-of-interest within uncased 96-123 mm (HQ-PQ) boreholes has been developed at ANSTO's Institute for Environmental Research. This technique avoids the ambiguous results usually associated with samples that are collected from an uncased borehole, where unknown inflows and loss zones will contribute to a mixed sample. ANSTO's zone-of-interest groundwater sampler (ZOIGS) is able to collect isolated samples from depths to 300 m, typically delivering samples and purge volumes of 10 L per cycle. The ZOIGS equipment has been used at sites within the Southern Coalfields of the Sydney Basin to investigate fracture zones, aquitards and porous zones. Standard chemistry, stable isotopes and tritium have been used to characterise intervals. The results have been used to infer groundwater flow paths and surface-groundwater relationships.

Before deployment, a five or ten metre zone-of-interest (ZOI) is selected for investigation from drill core or other logged data. Typically, the ZOI is a fractured, porous or altered layer of the strata with an expected high hydraulic conductivity. The ZOIGS is lowered into position, the ZOI isolated using inflatable straddle packers, and pumped using any suitable high purity inert gas (e.g. N_2 or He) from a standard gas cylinder. The interval is repeatedly purged and then allowed to refill and recover pressure, until constant chemical parameters are measured over a number of cycles, before taking samples and field measurements. Pressures are measured at four points throughout the process using vibrating wire pressure transducers (i) above, (ii) within and (iii) below the ZOI; and also (iv) within the pump chamber. Knowing the borehole and ZOI interval dimensions and recording the pressure recovery curve allows calculation of effective hydraulic conductivity for the ZOI.

Keywords: Discrete interval, zone-of-interest, uncased borehole, straddle packer, hydraulic conductivity, groundwater sampler.

Introduction

To better understand groundwater flowpaths and interactions with surface water it is necessary to be able to characterise the groundwater and hydraulic conductivities of discrete vertical intervals or zones-of-interest (ZOI) within aquifers. In many situations uncased boreholes provide the only opportunity to access *in situ* groundwaters in the

Sydney Basin, for example 96mm (HQ) coal mining exploration boreholes. Such boreholes are principally drilled for core and other stratigraphic logging, and stakeholders are often not prepared to install permanent cased and screened wells in the borehole. In these and other circumstances there is a brief opportunity to take samples and measurements at a number of ZOI within a borehole before it is permanently resealed by grouting. Even if they do choose to install hydrogeological equipment, there is an opportunity through sampling and measurement to ensure ideal placement of permanent pumps or piezometers.

When a borehole is drilled through coherent strata that contain fracture zones or other layers with increased hydraulic conductivity, there is an opportunity to exploit such zones for measurements and sampling. However, collection of isolated discrete-interval groundwater samples from a single borehole has historically proven difficult (e.g. Jones & Lerner 1995). Representative samples are often inaccessible because the uncased boreholes themselves provide vertical connections between otherwise separated ZOI and often extend to depths beyond the capability of normal sampling pumps. The alternate approach is to drill multiple wells adjacent to each other, each with a discrete screen interval; or a single well with multiple sampling levels built into customised casing and sampling ports. Both approaches are expensive and are rarely deployed for more than 2–4 selected intervals. A specialised means of isolation, measurement and sampling from discrete ZOI is required to create semi-continuous vertical groundwater profiles. Equipment suited to larger diameter boreholes has been available for some time (e.g. Holloway & Waddell 2008), but there is a lack of similar systems suitable for boreholes of less than 150 mm diameter. To take advantage of this opportunity and collect meaningful results from such boreholes, portable field equipment is necessary.

Portable equipment utilising inflatable straddle packers has been developed at Institute for Environmental Research (IER), a division of the Australian Nuclear Science and Technology Organisation (ANSTO). A zone-of-interest groundwater sampler (ZOIGS) has been designed to isolate ZOI for sampling and measurement in boreholes with diameters of 96 – 123 mm and depths to 300 m.

Background

To create semi-continuous profiles of groundwater chemistry and isotopes, sample representation must be assured and sample mixing avoided. Stable isotopes of interest include carbon-13 in dissolved inorganic and organic carbon for inferring various environmental or inorganic pathways, and deuterium (^{2}H) and oxygen-18 for source and evaporation history of water. Radioisotopes of interest include tritium (^{3}H), carbon-14, sulphur-35 and radon-222 to infer time since groundwater was last in contact with the atmosphere as precipitation or surface water.

One major limitation to using the above isotopes in groundwater has been the difficulty associated with collecting representative samples from deep, uncased boreholes. IER is also involved in other borehole-related activities including prompt gamma neutron activation methods and the determination of high resolution hydraulic conductivity using salt injection. All of these methods require sampling or injection in an isolated zone-of-interest (ZOI) within a deep, uncased borehole; hence the development of the zone-of-interest groundwater sampler (ZOIGS).

The original sampling/injection system was constructed for ANSTO by Sigra Pty Ltd, QLD; capable of a 50 m maximum depth it was raised and lowered by hand. It had one vibrating wire pressure transducer (piezometer) for measuring pressure within the ZOI. It used a Grundfos MP1 pump to purge the isolated ZOI, but required a large air compressor to pump large volumes and inject saline solutions. This 50 m depth was insufficient to reach ZOI in the Sydney Basin in many cases. The electric Grundfos pump also caused electrical interference with the vibrating wire pressure transducers, so pressure could not be logged during pumping.

The original version was modified at ANSTO to a 100 m system that used the same Grundfos pumping system for purging. To overcome the head limitations of the pump, each sample in this 100 m system was captured at depth in reinforced PVC tubes, with a total capacity of 7 L. The system had to be removed from the borehole to retrieve the sample. This system was used with some success to collect samples and pressure data from five borehole locations in the Sydney Basin, including the B.Env.Sci. Hons thesis of Hammond (2007). The 100 m system, however, had limitations: at greater depths the empty sample tubes were crushed by the high differential pressures prior to sample capture, and at shallow depths there was often insufficient pressure head to fill the tubes beyond one or two litres.

Even though the 100 m system only had one pressure transducer, up to two pressures could sometimes be derived following isolation of the ZOI. If water collected above the ZOI, and the resultant standing water level (SWL) was possible to measure, then pressure head above could be also calculated, as in the example in Figure1. There was no means of measuring pressure responses below the ZOI using this system.

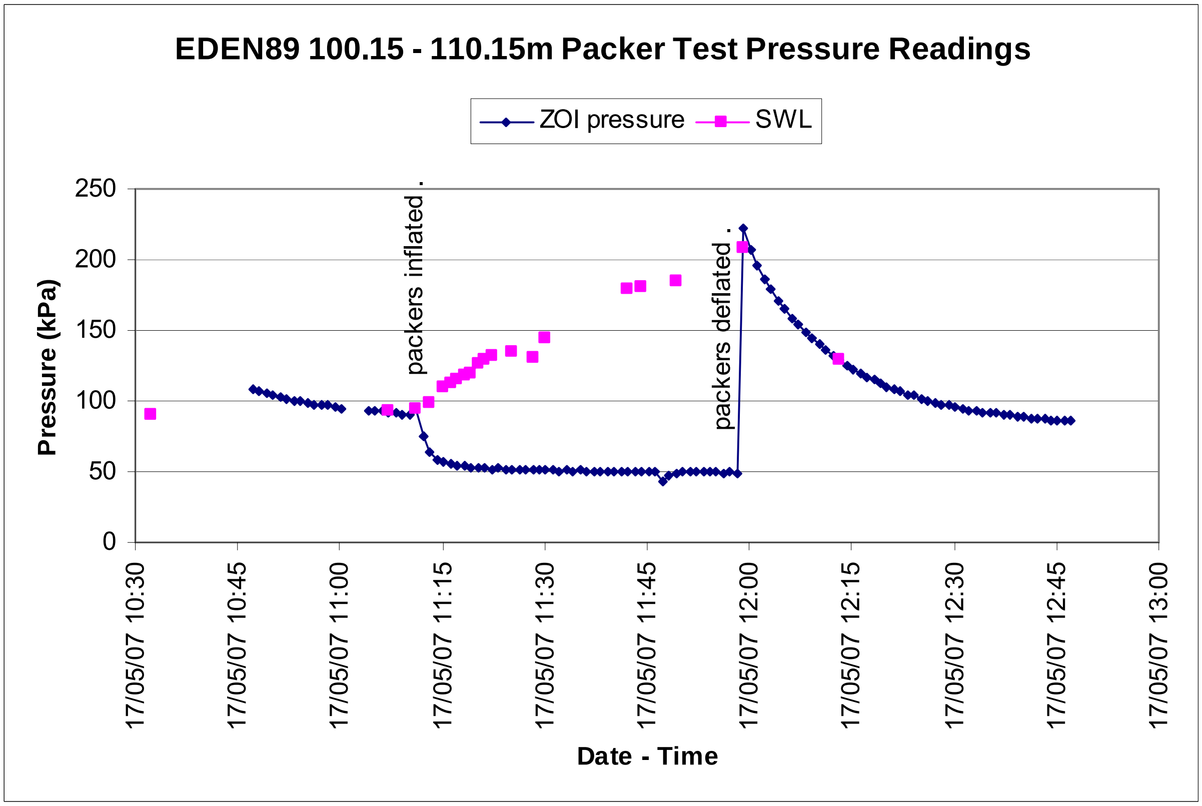

Figure 1. Pressure readings from the 100-110 m interval of borehole EDEN89, modified from Hammond (2007). This is an example of pressure data available from the earlier 100 m version of ZOIGS, used to isolate a fracture zone in Hawkesbury Sandstone. Note the drop in the ZOI pressure head and rise in overlying SWL following packer inflation, indicating a downward vertical gradient. When the packers are later deflated, a sudden increase and decay in pressure and SWL occurs as the overlying slug of water is released past the packers.

Zone-of-interest groundwater sampler (ZOIGS) design

The 100 m system was ultimately modified and extended to a 300 m zone-of-interest groundwater sampler (ZOIGS) at ANSTO. The pumping system was changed from electric to a custom built gas-drive double-valve pump utilising high purity nitrogen (or other inert bottled gas, e.g. argon or helium) to drive a 10 L purge volume or sample from greater depths to the surface. This system no longer requires removal of the sample chamber from the borehole to retrieve a sample. Four vibrating wire pressure transducers replaced the original one. Pressure is now measured above, within and below the ZOI, and within the pump itself.

ZOIGS has been designed to pump groundwater samples from uncased 96-123 mm diameter (size HQ – PQ) boreholes to depths of 300 m, with purge and sample volumes up to 10 L per cycle. The inflatable packers have a length to diameter ratio > 10, so satisfy the criterion usually applied for effectively sealing a borehole (e.g. Freeze & Cherry 1979; Sevee 1991). Current available ZOI interval lengths are 5 m and 10 m. The system is mounted on a 4WD truck (Fig. 2) to allow access to typically remote borehole locations.

Sampling, pumping and tracer injection tubes are 12.7 mm (9 mm ID) nylon pressure tubing, rated to 1.7 MPa. During sampling and purging the pumping gas is in contact with the top of the water column within the pumping tube and sample chamber for up to several minutes. It is therefore important to choose a gas with minimal impact on the sample chemistry. Up to three size G nitrogen cylinders (each of 50 L water capacity or 9 m^3 nitrogen) are normally carried on the vehicle. This is sufficient for several days work depending on the depths being investigated.

(a) **(b)**

Figure 2. (a) The inflatable packers and sample/pump chamber of the zone-of-interest groundwater sampler (ZOIGS). (b) Pressure readings are recorded on a laptop computer.

Pumping utilises the sample chamber as a large double-valve pump. The filling stage is via two check valves at the bottom of the sample chamber and sampling tube. The sample chamber check valve closes during the gas-drive stage of the pumping cycle, allowing the sample to be driven up the sampling tube to the surface. Gas pressure is then released, the pressure within the ZOI recovers according to the hydraulic conductivity of the ZOI and the sample chamber refills ready for the next pump cycle.

Pressure transducers are located at four points within the system: Above, within and below the zone-of-interest; and within the sample/pump chamber (Fig. 3). This allows continuous monitoring of pressure changes (Fig. 2(b)) in the isolated zone compared with those above and below, confirming that vertical sealing of the zone is effective. It also serves to establish the independence of the zone-of-interest from adjacent zones, ensuring no bypassing hydraulic connections exist throughout the testing. The pressure transducer within the pump likewise ensures the integrity of the sample chamber during pumping.

Collecting and interpreting pressure data

Pressure is currently recorded on a Sigra data logger using four 3000 kPa vibrating wire pressure transducers that incorporate thermistors for temperature correction. The logger is programmed to record data at regular intervals suitable for the activity. For example, during pumping or rapid refilling of the zone-of-interest, pressures may be recorded every 30 seconds or one minute. During slow refill stages, every hour may be sufficient. The data can be viewed on laptop computer as it is being recorded and/or simply downloaded after the event.

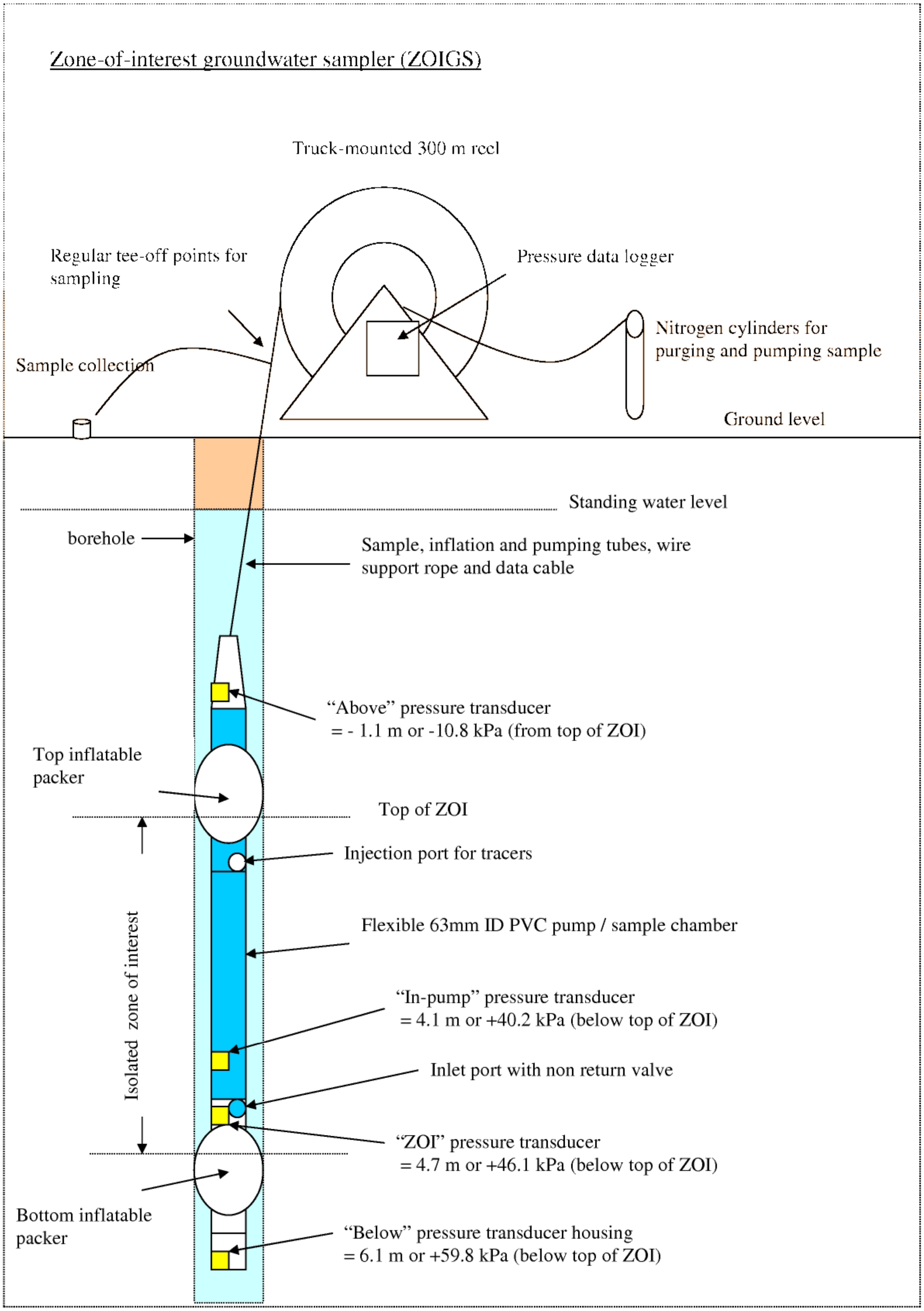
Zone-of-interest groundwater sampler (ZOIGS)
Truck-mounted 300 m reel
Regular tee-off points for sampling
Pressure data logger
Nitrogen cylinders for purging and pumping sample
Sample collection
Ground level
Standing water level
borehole
Sample, inflation and pumping tubes, wire support rope and data cable
"Above" pressure transducer = - 1.1 m or -10.8 kPa (from top of ZOI)
Top inflatable packer
Top of ZOI
Injection port for tracers
Flexible 63mm ID PVC pump / sample chamber
Isolated zone of interest
"In-pump" pressure transducer = 4.1 m or +40.2 kPa (below top of ZOI)
Inlet port with non return valve
"ZOI" pressure transducer = 4.7 m or +46.1 kPa (below top of ZOI)
Bottom inflatable packer
"Below" pressure transducer housing = 6.1 m or +59.8 kPa (below top of ZOI)

Figure 3. A simplified system overview of ZOIGS showing relative locations of the inflatable packers, pump/sample chamber and pressure transducers. Vertical distances and equivalent pressure differences for the 5 m interval setup are indicated for each transducer.

There are many different scenarios that may result depending on selection of the ZOI and its position relative to the SWL, inflow and outflow zones. The first case shown below (Fig. 4) resulted when the ZOI was above the SWL in the borehole. This minimises the amount of purging necessary, because the groundwater inflows drain directly down the borehole until the zone is isolated. Pressure recovery towards equilibrium within each zone occurs following isolation and/or purging. In this case the ZOI increased in pressure much faster than above the ZOI, indicating that there is faster net inflow in the 5 m ZOI interval than in the remaining ~36 m of the borehole above it.

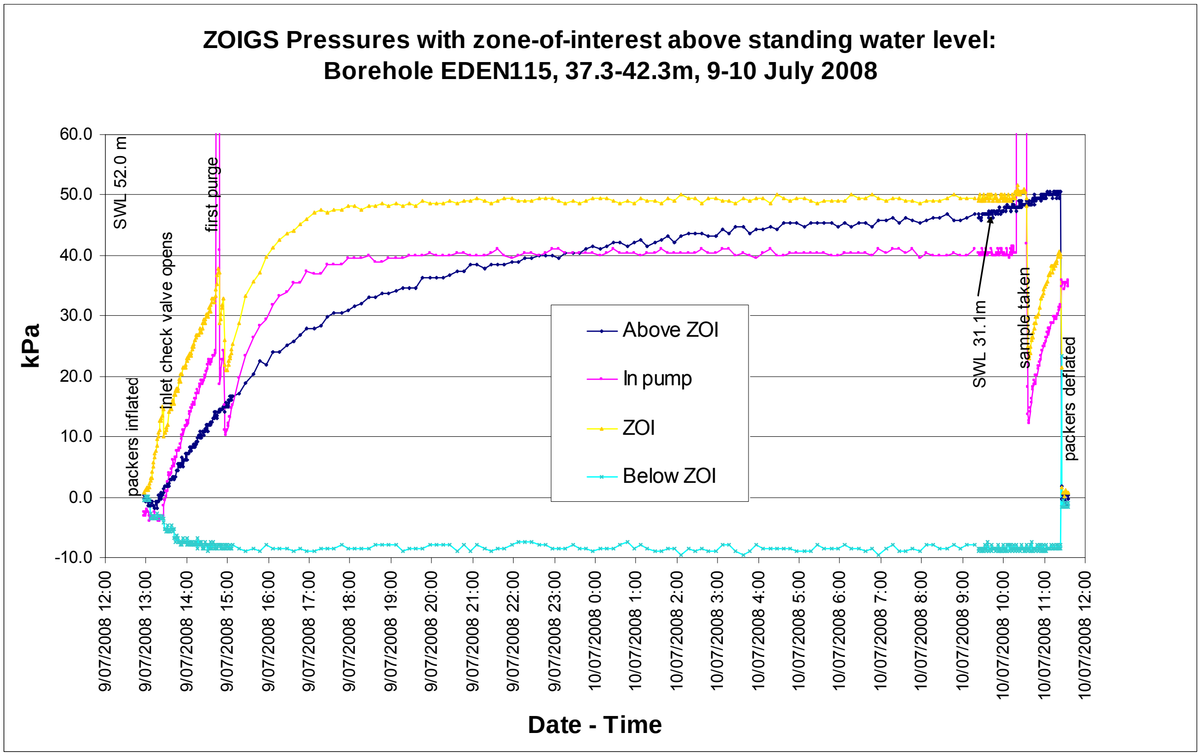

Figure 4. An example of isolating a zone-of-interest (ZOI) above the standing water level (SWL). Following isolation, pressure above the ZOI climbs steadily, indicating that the borehole was acting as a conduit to a lower pressure zone at depth. Note that the ZOI and pump pressures rise in parallel once the inlet check valve has opened. The 9 kPa difference is the combined effect of relative transducer elevation and check valve opening pressure. Below the ZOI pressure drops quickly to a steady negative value, indicating an outflow point below.

A more typical scenario is where the ZOI lies below the SWL in the borehole (Fig. 5). In this case when the ZOI is isolated, pressures start at some point above zero and stabilise towards the formation pressures. Figure 5 shows pressures within, above and below a logged fracture zone. In the ZOI and below, pressures drop quickly once the packers are inflated, while the SWL (Above ZOI) rises slowly and only slightly. Pressures within the ZOI end up substantially lower than those below it (even after allowing for transducer elevation differences), confirming that the fractured ZOI at 84-89 m is a lower pressure potential outflow zone, isolated from above and below by relative aquitards. The rapid recovery of pressure within the zone following each ~10 L purge, confirms high hydraulic conductivity in the ZOI.

The resulting recovery curves from most scenarios can be used to calculate effective hydraulic conductivities of the zones (e.g. Hvorslev 1951). Though this simple method is designed for porous media in a confined aquifer, it is valid if there is sufficiently dense fracture spacing to allow a continuum approach (Freeze & Cherry 1979). Comparisons of calculated values with packer tests carried out during drilling of the same boreholes (e.g. Hammond 2007) have given close results. Other methods that involve curve fitting may be more appropriate in some circumstances (Freeze & Cherry 1979).

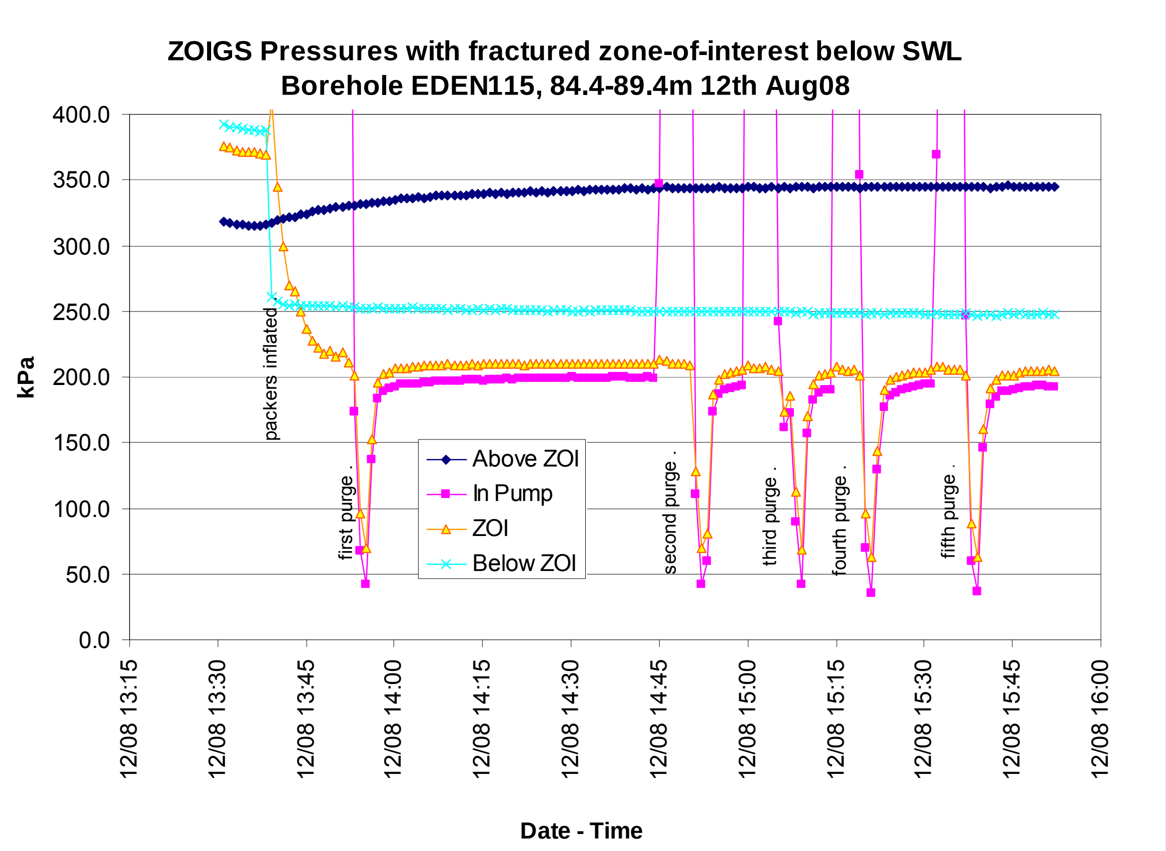

Figure 5. Pressures within and below a fracture zone drop dramatically once isolated, while the SWL above the zone rises slightly. Pressure within the ZOI is lower than that above and below it.

Purging and collecting samples

Once the ZOI has been confirmed as isolated, by independent pressures above and below the zone, purging and sampling rates are only limited by the recovery time of the zone. In the above examples, recovery times ranged from several minutes (Fig. 5) to several hours (Fig. 4). Boreholes that have been open for some time, with ZOI that exhibit relatively high hydraulic conductivity, may require a significant number of purges before constant field parameter measurements indicate that representative water is being delivered to the surface. The large volume (> 10 L) sample/pump chamber ensures that purging can be done using a minimum number of pump cycles. This also allows collection of tritium, carbon-14 (and other samples that require large volumes) from splits of one pump cycle.

The sample pump rate is controlled by the applied pressure of the drive gas, which is typically set at least 100 kPa above the equivalent water column lift required from the ZOI. Purging allows fine-tuning of the most appropriate pressure for collecting samples.

Example of results from a study of upland swamps

Samples collected from within a single borehole using ZOIGS have shown distinct characteristics from zone to zone. For example as part of an honours study (Mitry 2008) of the relationship between the geology, groundwaters and upland swamps on the Woronora Plateau, discrete samples were collected from ZOI in the borehole EDEN115. It was found that a zone of intermediate depth (63-68 m) was the end member in both chemical (Fig. 6) and tritium concentrations, with a nearby interval (52-57 m) plotting closest to swamp waters, and a deeper (84-89 m) zone having a signature between the two. Mitry (2008) used the results to infer the importance of extensive siltstone lenses within the Hawkesbury Sandstone as aquitards and fracture zones as aquifers in geologically controlled recharge of upland swamps.

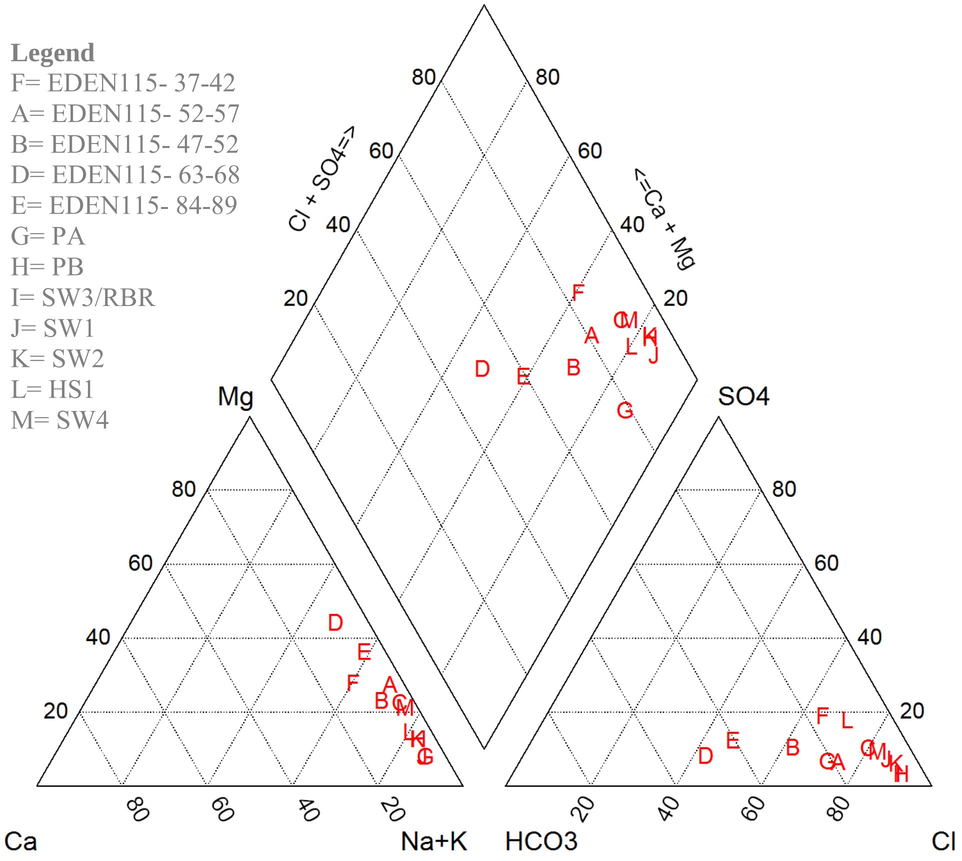

Figure 6. The zone-of-interest groundwater sampler (ZOIGS) was used to explore the relationship between zones in a borehole (EDEN115) and a nearby upland swamp. Swamp samples are prefixed as shallow piezometers (P), surface waters (SW) and hillslope water (HS). The Piper chart shows the

sample from 63-68 m (D) to be an end member, while the nearby 52-57 m interval plotted closest to the swamp results.

One consideration to be kept in mind during planning and analysis of results is the pumping method. Substantial fluctuations in pressure are imposed on the sample by the drive/vent cycle of the double valve pump, which may affect the analysis of volatiles or dissolved gases. Selection of the drive gas is also important, because there may be a small interface between the drive gas and the sample, e.g. nitrogen may be unsuitable for nitrate analysis.

Conclusion

ANSTO's zone-of-interest groundwater sampler (ZOIGS) is able to isolate discrete intervals of uncased 96-123 mm (HQ-PQ) boreholes for the purpose characterising hydraulic and chemical relationships with the surrounding strata. It can be used to create semi-continuous profiles of pressures, groundwater chemistry and isotopes within a single uncased borehole. Pressure data can be used to determine the effectiveness of isolation of a zone-of-interest and for calculating hydraulic conductivity from the recovery curves after purging. A case study using ZOIGS in the Sydney Basin at Woronora Plateau near Wollongong, NSW has shown that groundwater samples collected had distinct chemical and isotopic signatures and trends. ZOIGS is another tool to enhance the study of groundwater and its relationships with surface water and the environment.

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Keynote Paper

Developing Sandstone Groundwater Resources for Urban Water Supply across the Sydney Basin

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Abstract

Groundwater investigations for drought water supply for the Greater Sydney area were initiated in the Sydney Basin in late 2004 as part of the NSW Government's Metropolitan Water Plan (MWP) suite of initiatives. The importance of groundwater was described in the 2006 MWP after several priority areas were drilled and the prospectivity of the Hawkesbury Sandstone aquifers was confirmed at three locations in the Southern Highlands (1 location) and in Western Sydney (2 locations).

This keynote paper explores the many technical components of the investigation programs and emphasises that some of the critical pathways to building borefields are related to socio-economic issues as well as technical viability and environmental sustainability.

The groundwater targets were the porous and fractured rock aquifers in the Hawkesbury Sandstone in structurally deformed areas around the fringe of the Sydney urban area. The initial drilling and testing investigation programs were expanded at each of the three prospective sites as dam storage levels dropped and pressure grew to obtain planning approvals and to complete designs for emergency drought water supply borefields. Investigation and borefield development programs reached different levels of completion when the groundwater program was shelved in mid 2008. For example, the Kangaloon borefield program included substantial testing and proving programs, comprehensive environmental studies, and then long term pumping trials to improve knowledge and understanding of resource behaviour, and more importantly to confirm environmental impacts. The broad technical program was supported by the overlapping community consultation, planning approval, property acquisition, and engineering tender design work programs.

It was necessary to investigate and to prove the technical/environmental components (resource occurrence, availability, sustainability, and ecosystem linkages) to a high level of certainty before declaring a borefield development technically viable. Project viability was only confirmed after the completion of engineering, socio-economic, financial, economic and local community studies.

The staged approach that Sydney Catchment Authority (SCA) adopted was critical to the success of proving both the technical viability and the project viability for the Kangaloon borefield development. The same model was being used for the Leonay-Emu Plains and Wallacia borefield prospects but did not reach the same level of assessment because of the deferral of the project.

The SCA investigation approach (and the lessons learnt along the way) is important to document for the potential reactivation of these borefield developments in a future emergency, and also to inform others about the many steps that are required to establish borefields.

Keywords: groundwater, Hawkesbury Sandstone, drought water supply, strategic development

Introduction

Groundwater resource development, particularly the investigation and development of new potable water supply sources for a global city is a long and involved, and sometimes challenging task. There are many technical, environmental, and socio-economic aspects and consequences to deal with, and this paper explores the approach and methodology used over the last four years by Sydney Catchment Authority (SCA) to develop new drought groundwater supply sources for the greater Sydney area.

While the first new groundwater supply source for Sydney in more than 150 years has not yet been built, the substantial investigation programs completed since late 2004 together with the expected planning approvals for the first borefield at Kangaloon in the Southern Highlands have been important achievements.

It is useful to reflect on all the investigation and borefield development components required to deliver this new project and the learnings from the adopted approach. In hindsight the technical studies were the simpler work programs to complete with the community consultation, engineering designs and project approvals proving to be challenging and time consuming.

This paper provides a detailed outline of the staged approach to identifying and assessing the prospective groundwater targets, and evaluates the importance of other environmental and socio-economic studies. It also emphasises the depth of study required to prove new water sources to the satisfaction of all stakeholders, and highlights the necessity to initiate environmental studies and community consultation early in the project development. There were essentially three phases to arrive at the stage where this project can now be built, commissioned and operated with confidence – these can be broadly described as the technical viability, environmental sustainability, and project viability phases.

The Sydney Basin is not endowed with productive regional aquifers suitable for large scale development however locally there are important aquifers that can make a significant contribution during drought for a variety of consumptive uses. SCA has investigated seven high priority areas, identified three areas that are prospective and proved that they are technically viable, and taken one area through to project viability. While borefield development may not happen for years for the greater Sydney area, the approaches adopted since 2004 and the lessons learnt along the way, provide invaluable knowledge.

The knowledge obtained from this drought water supply investigation program is substantial – seven out of about 30 priority areas across the Sydney Basin area have now been investigated with 148 bores and wells constructed and tested, 17950 metres of drilling completed, a billion litres of groundwater pumped, and more than 150 technical reports written.

Background

Groundwater investigation and borefield development projects are part of the NSW Government's 2006 Metropolitan Water Plan (MWP) to secure Sydney's water needs for drought and the next 25 years (NSW Government, 2006). Groundwater investigations for drought water supply under the MWP were initiated by SCA in December 2004 at seven priority sites across the Sydney Basin. Essentially the groundwater (technical) program comprised initial investigations, pilot testing, extended pumping trial programs and borefield development studies.

Of the seven sites investigated under the main work program, three areas (Upper Nepean at Kangaloon, Western Sydney at Leonay-Emu Plains, and Western Sydney at Wallacia) were considered prospective for potential borefield development and progressed to pilot studies in 2005 and 2006. In view of the worsening drought conditions, pilot investigation programs were approved, initially at Kangaloon (August 2005) and then at Leonay (February 2006) and Wallacia (August 2006) to confirm resource potential. The only area that progressed to the initial borefield development stage was the Upper Nepean (Kangaloon) area (initiated in November 2006). Extended pumping programs were completed at Kangaloon and at Leonay-Emu Plains during 2007 and 2008.

On 18 June 2008, the NSW Government decided to halt development of the Kangaloon Borefield once the environmental and planning assessment process was concluded and land acquisition, tender design and project documentation were completed. Also at this time, it was formally announced that investigations at Leonay and Wallacia would be deferred once the initial pilot studies were completed.

Adopted Investigation Strategy

Severe drought was the driver for the groundwater investigations that commenced in late 2004. The 2004 and 2006 Metropolitan Water Plans (NSW Government, 2006) identified that diversification of water supply sources was required for the future and that the greater Sydney region should not be totally dependent on surface water supplies from Warragamba Dam and the smaller Metropolitan dams. While groundwater is also a rainfall dependent supply,

- it has the advantage of providing additional water during drought periods because groundwater storage is usually very large in regional aquifer systems
- yields are mostly unaffected by drought provided individual aquifers within the same resource are reasonably well connected
- it can be extracted quickly in high permeability areas, and
- aquifers can be recharged during intervening wet periods.

Groundwater also provides distinct advantages in that it is not subject to large evaporation or transpiration losses, it moves reasonably slowly through the sub-surface, and large groundwater storages are mostly insulated from contamination and water quality issues.

The adopted approach in the MWP was to target those groundwater sources that were close to the existing water supply system or close to the water filtration plants so that groundwater could augment supplies quickly and reduce the rate of depletion of stored surface water. Prior to the 2002 to 2007 drought, daily demand across Sydney was around 1600 ML/day, although with drought restrictions and other demand management measures, consumption reduced to around 1250 ML/day during this period. Groundwater was only ever considered a drought supply for two to three years. It was never contemplated that groundwater could supply more than about 30% of the greater Sydney area requirements (equivalent to about 500 ML/day) even if all possible sources were developed and fully operational (PB, 2003).

With the water supply dams and catchments located south west of Sydney, along the Woronora and Illawarra plateaus and in the Shoalhaven, it was logical that the groundwater targets for the required drought supplies had to be the porous and fractured sandstones of the Sydney Basin. The primary resource targets were the mid Triassic Hawkesbury Sandstone that is exposed over a very large area of the southern, western and northern Sydney Basin, and the underlying Narrabeen Group sandstones that are also exposed further west and north.

There was enough information from private bores constructed around the fringe of the Sydney Basin (and particularly in the Southern Highlands) to suggest that large yields of low salinity groundwater suitable as a raw water supply source for potable supply are available from the Hawkesbury Sandstone. Yields from the Narrabeen Group rocks are more problematical. However detailed knowledge and understanding was poor as bores into the Hawkesbury Sandstone were rarely fully penetrating, some areas had never been drilled, and long term rates of extraction had never been assessed.

Numerous areas were evaluated in an earlier desktop study (PB, 2003) and the seven most prospective of these 30 priority areas that were located close to existing water supply infrastructure were chosen for investigation.

Given there had not been a major water supply investigation on this scale for more than 70 years (the development of the Tomago Sandbeds in the 1930s for Newcastle water supply is probably the most comparable example) and there had never been development of porous and fractured aquifers on this scale across NSW, the resource investigation program was staged and results carefully evaluated.

Four assessment stages were devised (initial assessment, pilot testing, pumping trials and borefield development) and for each area there had to be success at the completion of each stage to progress to the next stage. The successful completion of the first three stages ensured that an area (and any associated borefield development) was technically viable, however it was only with the completion of additional numerical modelling, planning approvals, engineering designs and resolution of important property and water access issues that full project viability could be considered achieved.

Environmental sustainability was equally important in deciding whether borefield development across an area was viable. Comprehensive studies were completed for the Upper Nepean (Kangaloon) area and preliminary environmental studies completed for the two western Sydney areas. Current natural environments (and the quantity and quality impacts of resource development) were considered in detail and included headwater springs, stream baseflows, upland swamps, terrestrial vegetation, aquatic fauna, and aboriginal and cultural heritage.

In addition important socio-economic consequences were considered including visual amenity, traffic disruption, noise/dust, property/road impacts, and loss of water for other consumptive uses. Land and water access and the acquisition of two strategic properties have also been completed.

The status of all investigations outlining the technical work completed, planning approvals, engineering designs, land and water matters, and the additional studies required, has been fully documented should the borefield development program be reactivated in the future.

Investigation Approaches

One of the first tasks in late 2004 was to confirm the seven priority areas for investigation. Deep fractured and porous sandstone aquifers were the targets at every site, although the Hawkesbury Sandstone was the main target at only five of the seven selected areas. The areas chosen are shown in Fig. 1 and were:

- Area 1 – Avon/Nepean Dams (Hawkesbury Sandstone)
- Area 2 – Upper Canal (near Appin) (Hawkesbury Sandstone)
- Area 3 – Upper Nepean catchment (near Kangaloon) (Hawkesbury Sandstone)
- Area 4 – Megalong Valley (Berry Formation/Megalong Conglomerate)
- Area 5 – Western Sydney (Leonay) (Hawkesbury Sandstone and potentially the Banks Wall Sandstone)
- Area 6 – Illawarra (Kembla Grange) (Budgong Sandstone)
- Area 7 – Warragamba – Wallacia (Hawkesbury Sandstone and potentially the Banks Wall Sandstone)

The primary criteria adopted to select the seven priority areas for the initial investigation program were:

- Potential (high) bore yields
- Suitable (low salinity) water quality
- Proximity to existing water supply infrastructure (SCA water storages or Sydney Water Corporation water filtration plants)
- Potential pumping interference (minimal private bore development)
- Potential environmental impacts (minimal groundwater dependence)
- Acceptable lead time/development obstacles (minimal property, land and services access constraints)

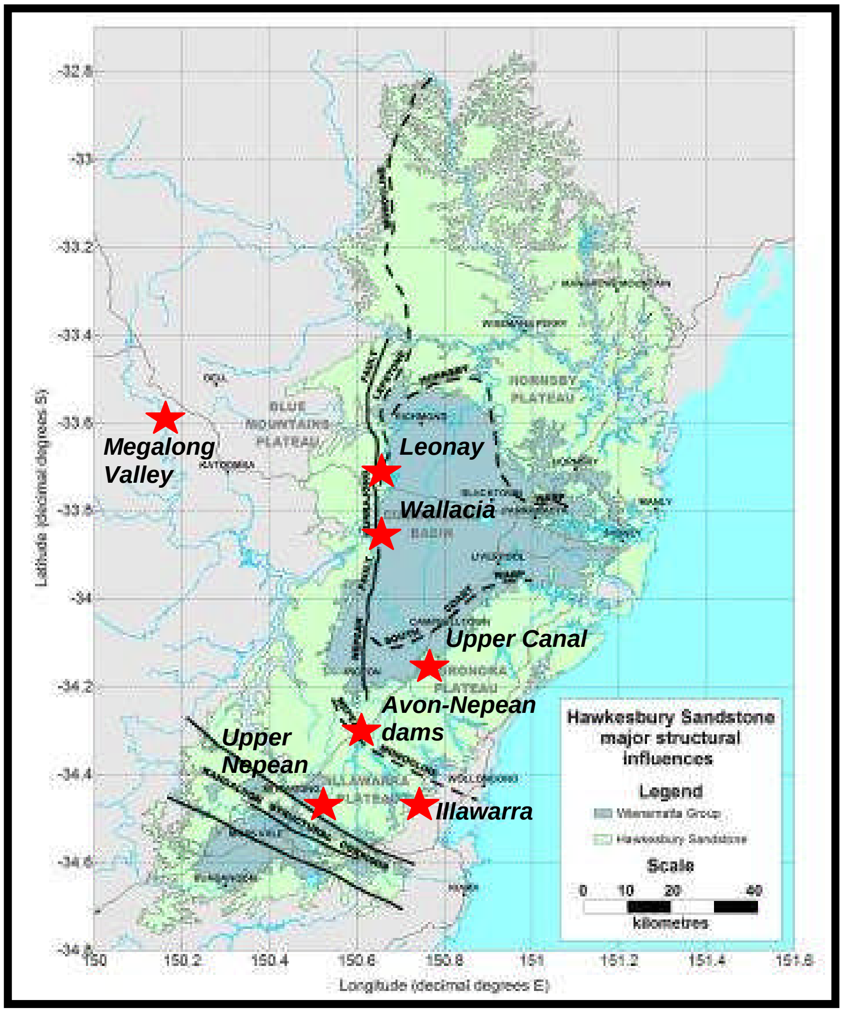

Figure 1 Location of the seven priority investigation areas (geology after Russell, 2007)

Those investigation areas that were the most successful were located on major structural features across the basin – in the south the Mittagong Horst-Graben Zone (Lee, 2000) and in west the Lapstone Structural Complex (PB, 2008d). These are equivalent to the Nepean Fault – Kurrajong fault – Lapstone Monocline and Kangaloon Structural Corridor as shown in Fig. 1 (Russell, 2007). Early in the investigation program it was evident that the more structurally deformed areas where fault and monoclinal features extended over a large area, were the more likely to provide the best prospects for emergency groundwater supply sources.

The three areas that were prospective after the initial investigations were the Upper Nepean (Kangaloon), Leonay, and Wallacia sites. Generally there was a 10-fold increase in yield at those drill sites where the sandstone was more fractured and faulted compared to other areas where there was little apparent deformation. At each of these three locations, high bore yields (up to 80 litres per second (L/s) in airlift and 30 L/s in pumping tests) and low salinity groundwater ranging from 50 to 500 µS/cm in the best aquifers was encountered. The subsequent evolution of the technical investigations for each of the three areas is shown in Fig. 2.

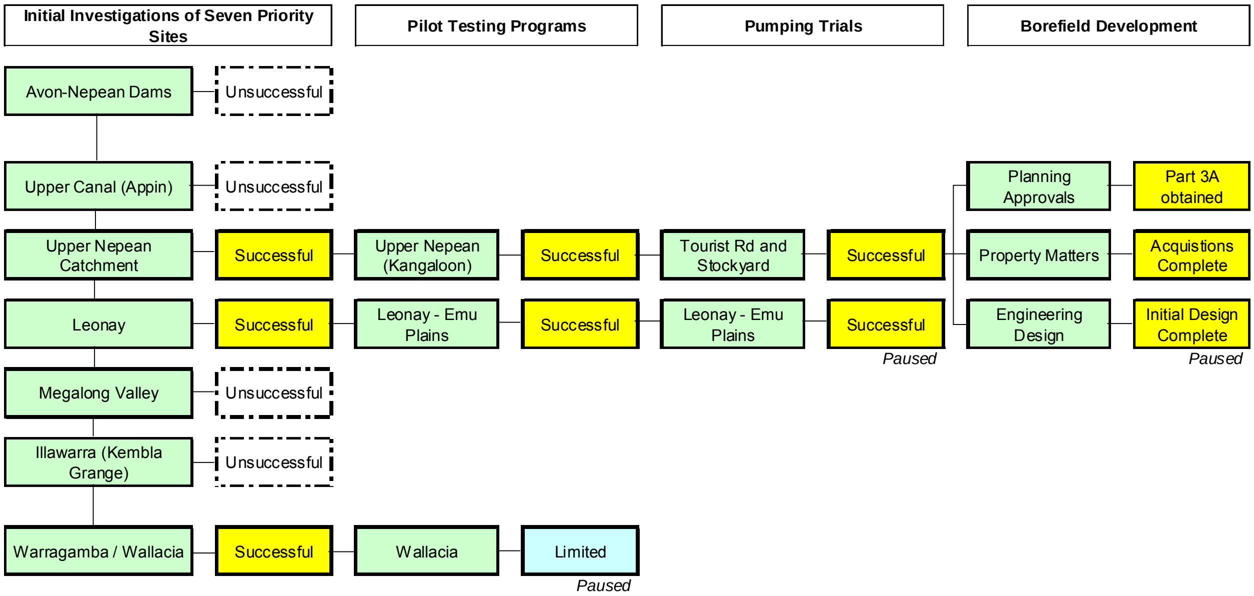

Figure 2 Assessment stages for each of the seven priority areas and three prospective sites

The investigation programs for each of the prospective areas were comprehensive to justify borefield development over many tens of kilometres. Even though drilling at the initial investigation sites within each area in 2005/2006 had been very encouraging, it was suspected that yields and water quality may not be consistent across each area hence more comprehensive drilling and testing programs were needed. Substantially more drilling and testing was completed in 2005, 2006, 2007 and 2008 to characterise each area.

The initial Kangaloon drilling and testing program involved seven bores and 867m of drilling across three investigation sites. The expanded (pilot) drilling and testing program involved 31 new bores / wells and 2842m of drilling across 11 investigation sites. This program involved the construction of the first four production bores for long term testing. The later pumping trial, research program and infill drilling programs involved 60 new bores and 5439m of drilling mostly in the eastern borefield areas 2 and 3. This program involved the construction of another eight production bores for long term testing.

The initial Leonay drilling and testing program involved 960m of drilling across four bore sites. The expanded (pilot) drilling and testing program involved 2825m of drilling across 18 bore sites.

The initial Warragamba-Wallacia drilling and testing program involved 742m of drilling across three bore sites at Wallacia and 534m of drilling across two bore sites at Warragamba. The expanded (pilot) drilling and testing program involved 2049m of drilling across 14 bore sites.

Additional specialist technical studies were completed during the pilot testing and pumping trial stages at each site, and baseline monitoring programs were commissioned for each area. More studies were completed at Kangaloon than at the other sites with the range of additional studies including hydrochemistry and environmental isotopes, aerial and surface geophysics, ecosystem studies, flora and fauna surveys (including stygofauna), surface water-groundwater connectivity, aboriginal heritage and numerical modelling.

The pumping trials were the most complex of the technical studies completed as both resource and environmental sustainability questions needed to be addressed for project approvals and to allay community concerns. Two substantial pumping trials were completed at Kangaloon along Tourist Rd (close to Butlers Swamp) for a period of four months (URS, 2007) and at Stockyard Swamp for a period of three months (URS, 2008). In addition there was a two-month pumping trial at Leonay-Emu Plains (PB, 2008c). Summary details are shown in Table 1.

Table 7 Summary of pumping trial results

Area and Trial	Length of Test (days)	No. of Test Production Bores	Volumes Pumped (ML)	Recovery Period (days)
Kangaloon – Tourist Rd (Butlers Swamp)	114	7	458	Various 5 to 150 days
Kangaloon – Stockyard Swamp	92	3	169	Various 30 to 120 days
Leonay – Emu Plains	57	4	381	Various 7 to 160+ days

By February 2006, the Upper Nepean (Kangaloon) prospect was preferred as the initial borefield development because of its setting and being mostly located on SCA lands within the protected Metropolitan Special Area. Pumped groundwater could be supplied by run-of-river to both Nepean and Avon Dams and to the closest water filtration plants at Nepean Dam (for the Picton/Bargo supply zone) and at Kembla Grange (for the Illawarra supply zone). Raw water could also be supplied into the Upper Canal to supply the Sydney metropolitan area through the Macarthur and Prospect water filtration plants.

Environmental Necessities

Once the initial drilling and testing programs were completed in 2005/2006, and when the pilot investigations were well advanced in 2006/2007 it was evident that there were broader environmental issues to resolve if borefield developments were to be constructed and operated successfully. The borefields had to be sustainable from both a water resource perspective and an environmental perspective.

For the Kangaloon aquifer, long term aquifer depletion and potential loss of water from permanent streams and perched water tables that were supplying upland swamps and potentially terrestrial vegetation were important issues to resolve.

As early as autumn 2006, ecosystem surveys were under way to determine the biodiversity and health of the local ecosystems, particularly the swamp ecosystems and the aquatic ecosystems. Baseline water level monitoring of perched water bearing zones near swamps, shallow sandstone and deep sandstone commenced at the same time. There is now more than three years of baseline monitoring data across both drought and wetter seasons that shows the natural variability of the groundwater resource and the ecosystems of this catchment.

In addition:

- Specialist studies on environmental isotopes (PB, 2006; PB, 2007; PB, 2008a; PB, 2008b) have provided important conclusions on recharge, discharge and flow processes and groundwater residence times.

- A large research project on surface water-groundwater connectivity (PB, 2009) has provided new insights into stream interaction and fracture flow in coastal catchments.
- Pumping trials have proven that shallow perched water is hydraulically disconnected from the deeper regional aquifers in the sandstone (URS, 2007; Woolley, 2007; URS, 2008; Woolley, 2008).

For the western Sydney borefield prospects only preliminary environmental studies have been completed to provide an overview of the natural and built environments, and the important environmental issues that need to be further assessed.

The ultimate investigation goal for a new project is the integrated environmental assessment of the proposed development and subsequent planning approval. For the Kangaloon borefield, two important documents have been completed – the environmental assessment (EA) for concept and project approval of the final development (KBR, 2008) and a supplementary preferred project report (PPR) (SCA, 2008). These documents have succinctly combined all the technical studies, together with the current environmental knowledge and the assessed impact of the proposed development.

Community Consultation

One of the most critical components of this investigation and borefield development program was community consultation. Groundwater systems are complex and the recharge, discharge, flow and pumping impacts can be difficult to comprehend for non technical people. SCA's strategy was to provide early advice by having a dedicated team and engaging the community in parallel with the more detailed site investigations. Technical information was supplied to the community well in advance of lodging project applications for developing borefield proposals. A number of methods were used to provide information and opportunities for comment on the borefield proposals (public exhibitions, media releases, web information, a dedicated community information phone number and email address, newsletters, stakeholder briefings and a Community Reference Group (CRG) for the Upper Nepean source).

The first release of information (apart from what was published in NSW Government, 2006) was aimed at explaining the initial investigation program, the groundwater targets, and early results from the prospective sites at Upper Nepean (Kangaloon) and at Leonay. Later initiatives in late 2006, 2007 and 2008 mainly focused on providing technical, environmental and design information on the Kangaloon borefield prospect.

The first major release of information was in mid 2006 when a non-statutory public exhibition of groundwater studies (SCA, 2006a and SCA, 2006b) was held from 3 July 2006 to 18 September 2006. More than 70 responses were received on the studies released, most of them from the Southern Highlands and most of them against the use of groundwater. Later communication included media releases, interviews, stakeholder meetings and four newsletters to all households in the Southern Highlands and one newsletter to all households in the Penrith area regarding Leonay-Emu Plains.

Peer review was another important aspect of ensuring that the technical work completed was credible and that subsequent work programs and conclusions were justified. SCA engaged an eminent hydrogeologist to assist with this independent review and many reports were prepared (including Woolley, 2006; Woolley, 2007; Woolley, 2008). SCA also funded a separate peer review commissioned by the CRG (McKibbin, 2006). These peer review reports were supplied to the CRG and made available to the wider community.

One of the best initiatives was a groundwater survey of all properties within 2km of the expected Kangaloon borefield corridor to identify existing springs, bogs, dams, perennial creeks, bores and wells and to record their yield/flow, depth, water level and water quality status during the drought. The free survey reports that were subsequently provided to landowners were well received. The benefit for SCA was that all local water sources were identified and a baseline of local use during severe drought was established.

The Community Reference Group (CRG) was tasked with disseminating information to the local community and their respective interest groups over a period of almost two years. A constant flow of information was provided with minutes posted to SCA's website after each meeting.

Later in the consultation process after the project application was lodged with the Department of Planning (DoP) and during the preparation of the EA, information was provided on borefield layout, power, pipeline and water treatment designs. Similarly information on property acquisitions and likely easements was supplied during the consultation period. The CRG provided useful feedback on designs, visual amenity, the local environment and community acceptance.

The exhibition of the Kangaloon Borefield EA (KBR, 2008) in April 2008 was the culmination of all the technical, environmental and socio-economic studies. The SCA received a total 147 submissions during the consultation period. Thirty one (31) submissions were from groups (or government) and 116 submissions were from individuals. Issues raised in the submissions (in order of the number of mentions) were environment (1650); planning and governance (681), monitoring and operations (484), socio-economic consequences (479); borefield design (277); and management issues (220).

Important learnings from the consultation program included

- provide relevant information early
- provide it in a form that is easily understood
- use multiple forms of information dissemination
- be transparent with the latest project information and results
- encourage questions and support independent peer reviews
- be available quickly for questions and group discussions
- concentrate on stakeholder groups
- listen to and document all comments and concerns
- engage the community by meeting locally and showcasing investigations.

Borefield Development Essentials

The only area that has progressed to the borefield development stage is the Upper Nepean (Kangaloon) source area. The borefield proposal is to extract 10 to 15 billion litres per year of water in drought periods. The period of operation will depend on the length and severity of drought and the number of significant rainfall recharge events. Operations will cease when dam storage levels increase above the operational trigger level which is currently 40% of full supply levels under the 2006 MWP.

The borefield concept evolved as the pilot investigation program reached its conclusion and layouts were finalised after the pumping trials and widespread community consultation. It was possible to propose a borefield layout that maximised access to the sandstone resource and minimised the environmental impact. The engineering footprint was restricted to already disturbed areas and spread out over a lateral distance of 50km. The final adopted borefield layout is shown in Fig.3.

The eastern areas 2 and 3 were identified for initial borefield development because of generally higher yields, lower salinity and expected better recharge characteristics. The following infrastructure was confirmed for the borefield:

- 75 production bores (cased and screened, and equipped with submersible pumps) ranging from 90 to 180 metres deep, positioned between 500 and 750 metres apart
- a buried water transfer system, with pipes ranging in diameter from 100 to 300 millimetres enabling the water to be transferred to the Nepean River system.
- two water quality treatment facilities to adjust temperature and oxygen levels, and to reduce iron concentrations
- two river discharge locations – one on the Nepean River and one on Maguires Creek – from where the water will flow to the Nepean Dam
- an 11 kilovolt (kV) power network (combination of overhead and buried power lines) supplying electricity to transformers that will power the submersible pumps and water treatment facilities
- an outdoor switchboard at each bore which will house the power and control switchgear to each bore pump
- fibre optic cabling from each bore to a central location for control and communications
- a preventative maintenance system at each bore location to prevent iron scaling and iron bacteria blooms
- a network of monitoring bores and gauging stations to monitor resource behaviour and manage borefield performance and impact.

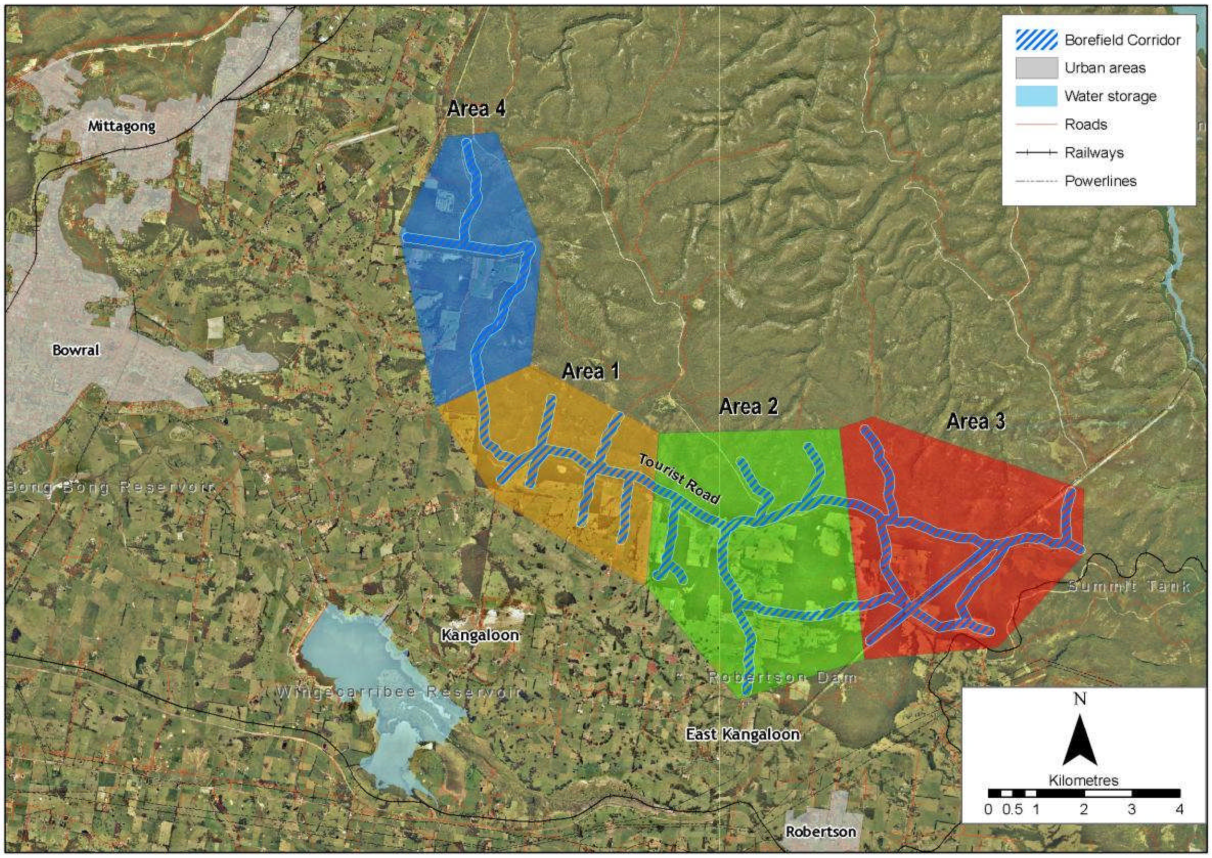

Figure 3 Kangaloon borefield showing development corridor and Areas 1 to 4

Apart from community consultation, the most important work packages to prove project viability related to the planning approvals, engineering design, and land and water matters. Numerical groundwater modelling using an impact assessment numerical model was used to demonstrate the expected resource and environmental sustainability.

Several stages of modelling are usually required to describe likely resource impacts under pumping. For Kangaloon, two modelling projects were completed with the last model upgrade involving transient modelling of several borefield extraction scenarios under different climatic conditions (Coffey Geotechnics, 2008).

Numerical Modelling

For the natural resource agencies in particular, it was the numerical modelling predictions of the borefield impact at Kangaloon that provided increased certainty of the extent and depth of drawdowns across the sandstone aquifer under full pumping conditions. The conceptual model of groundwater recharge, discharge and flow and the earlier steady state modelling was substantially updated for the final assessment of the project. Details are included in the PPR but essentially the modelling confirms that borefield capacities in excess of 35 to 40ML/day can be sustained for the first 12 months of borefield operation, however rates decline as areas dewater. By locating bores on high permeability features and optimising bore spacings, modelling suggests that the attainable borefield pumping rate might be up to 35ML/day (or around 13,000 ML/year) at the end of an extended pumping event.

Planning Approvals

The SCA lodged its development application with the NSW Department of Planning (DoP) for the Kangaloon Borefield and lodged its project referral with the Commonwealth Department of Environment, Water Heritage and the Arts (DEWHA) in December 2006. The Department of Planning assessed the project under Part 3A of the *NSW Environmental Planning & Assessment Act 1979 (EP&A Act)*. The Minister for Planning declared the development a project under Part 3A and further declared the project 'critical infrastructure' because of its significance at the time. The Director-General of the DoP issued his requirements for the environmental assessment of the project on 21 January 2007. A supplement to these requirements was issued on 6 August 2007.

The project was also declared a controlled action under the *Commonwealth Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act)* in July 2007. A bilateral agreement exists between the Commonwealth Government and the NSW Government for projects assessed under Part 3A of the EP&A Act. Therefore the project is subject to a single environmental assessment, public exhibition and reporting process as prescribed in the bilateral agreement.

The SCA's environmental assessment (EA) for the project was lodged with the DoP for public exhibition in March 2008. The public exhibition was from 2 April to 5 May 2008 and was extended to the 16 May 2008 to allow for late submissions. The submissions report and changes to the design of the borefield resulting from submissions and new engineering designs were detailed in the preferred project report (PPR) lodged with DoP in January 2009.

The DoP has assessed the project, and the Minister for Planning is currently considering project approval. The Commonwealth Minister for the Environment, Heritage and the Arts also has to approve the project under the EPBC Act.

The planning approvals process for this project has taken more than 2½ years. Some of the time involved extra technical studies that were required by DEWHA but much of the time has related to preparing the required documentation, the public exhibition period and engaging in stakeholder discussion. The learnings from the planning approval process included

- lodge the project application and ensure that the EA is commissioned early once the decision is to build the development
- decide whether concept approval or project approval is the desired outcome
- closely manage the transition if the planning focus changes (either the type of approval or the scheme itself)
- closely manage communications and any additional studies required where there are joint NSW-Commonwealth approvals
- engage stakeholder groups early so that project information is communicated

Engineering Design

The final engineering design for the borefield did change slightly to what was exhibited in April 2008. The final layout (which is within the corridor identified in Fig.3) further minimised the impact along some roads with sensitive fringing vegetation, and maximised the use of SCA fire trails and recently acquired properties. Architectural drawings were also provided for screening the water treatment plant and collection pond areas. The services layout was slightly adjusted to maximise the use of public roads and existing power lines.

Infrastructure is buried in important visual amenity areas (all pipelines and some power) and in other areas such as the production bore compounds and around the water treatment plants, extra vegetation screening is proposed. The geotechnical investigation, power line designs, hydraulic design work, determination of pipeline sizes, bore pump sizes and individual power requirements took substantial time to complete. For Kangaloon, much of this design work will need to be checked again once the final production sites and individual bore yields are confirmed. In addition road/bridge dilapidation studies are required in advance of any construction program. The learnings from the engineering design phase included:

- Develop the engineering feasibility and the best pump and delivery concepts early
- Commission drilling programs (investigation, production and monitoring bores) separate to civil contracts so as to complete programs sequentially
- Drill all the production bore sites (and have their design characteristics completed) in advance of the detailed conceptual designs
- Bundle all civil components together as one tender managed by a head contractor unless particular components need to be fast-tracked
- Power designs are probably the most difficult of the civil engineering components and again concepts should be developed early
- Leave detailed design for pipes, power, pumps and minor buildings to the construction phase and award work as a D&C contract (this includes the power master plan approvals from power wholesalers)
- Water treatment plant design should essentially be a performance specification based on a standard water quality discharge volume and quality
- Manage very carefully if time is critical and some programs have to overlap (eg the drilling and civils program) or be separated (eg the power master planning and construction from the civils program)

Land and Water Matters

Land and water access also needed to be confirmed to ensure that the project was viable. Two critical parcels of land were purchased to ensure that the production bore locations, and the location of the main water treatment plant and pipeline routes could be optimised. The final Kangaloon borefield layout has the advantage that more than 97% of the proposed production bore locations are sited on SCA land (or easements), all the pipeline routes are either on SCA land or Council road reserves, and more than 80% of the new and upgraded power line requirements are also on SCA land. This final outcome will make it relatively easy to reactivate the project if required.

Access to the groundwater resource is also essential for project viability. Negotiations are under way with the Department of Water and Energy (DWE) regarding allocation, operational triggers, and appropriate monitoring / management responses. A compensatory commitment is also in place should the scheme adversely impact private water bores and landowners access to water from the sandstone aquifers.

Again these land and water aspects take time to initiate and resolve, and proponents should allow 1 to 2 years to resolve access issues. Important learnings from the land and water access program included:

- Resolve property and access issues early so that designs do not change substantially
- If property has to be acquired, advise community of reasons and purchase early so as to maintain certainty
- Finalise easements early in the borefield development/construction phase for both construction and long term access to bores, pumps, power and pipelines
- Ensure all water and pollution licences are current

Conclusions

Developing any large groundwater proposal, particularly new water supply schemes, requires substantial effort. Hydrogeological studies are important to confirm whether a project area is technically viable from a resource perspective, however it is the other environmental, community consultation, planning approval, access and engineering design studies that determine the final project viability.

The staged approach that SCA adopted for these MWP groundwater investigations was critical to the success of proving both the technical viability and the project viability for the Kangaloon borefield development, and determining the technical viability of the two western Sydney sources. When starting and little is known about the resource potential of a prospective area, it is important that drilling and testing programs be staged, the results aggregated and the conceptual model progressively refined. Work scopes and results should be peer reviewed, and data gaps plugged so that rework is minimised and all work is scientifically defensible. Several stages of numerical modelling are equally important in confirming the resource and environmental sustainability.

The community should be engaged early, and investigation programs and results distilled so that information can be easily communicated to different audiences. Continuous dialogue, and respectful and trusting relationships will ensure a good understanding of the final project.

The SCA experience was that the community consultation together with the planning approval, land and water access, and engineering design work was equally as time consuming and demanding as most of the technical and environmental studies.

Initial hydrogeological studies are essential to confirm prospectively, however once this is confirmed then the proving studies need to be closely managed in parallel with the equally as important community, planning, access and engineering design studies.

Acknowledgement

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Hydrogeology of Upland Swamps in the Nepean River Catchment
Southern Highlands New South Wales

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Abstract

One of the most significant ecosystems that occur on the sandstone landscapes of the Woronora and Illawarra Plateaus are the upland swamps. These ecosystems contain threatened species and are classified as threatened ecological communities under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (the EPBC Act).

The connectivity of rainfall, shallow perched water and deeper regional groundwater sources and the dependence of ecosystems on these water sources is an area of increasing interest given the longwall mining and proposed water resource developments across the area.

Sydney Catchment Authority (SCA) as part of its substantial investigation program for the Kangaloon borefield development, completed several field investigations where the regional aquifers in the Hawkesbury Sandstone were pumped for extended periods and water levels in the adjacent upland swamps were monitored. Results of drilling investigations, pumping trials and hydrochemistry studies are presented to explain the hydrogeology of these swamps.

Two long pumping trials at Butlers Swamp and Stockyard Swamp in the Nepean River catchment have confirmed that the perched water bearing zones and regional sandstone aquifers are disconnected. The ephemeral perched water that supports the upland swamps is solely derived from rainfall and is very responsive to all rainfall events while the deeper groundwater in the fractured sandstone aquifers beneath these swamps has a lagged response to rainfall. Pumping the deeper groundwater for several months created drawdown in the regional aquifer under both swamps however there was no evidence of drainage or drawdown in the shallow perched groundwater zones.

It is concluded that groundwater in the regional sandstone aquifers is not hydraulically connected to the shallow perched water bearing zones, and hence there will be no resource impacts due to borefield development and pumping.

Keywords: hydrogeology, groundwater, perched water, upland swamps, ecosystem dependence

Introduction

The swamps on the sandstone rocks of the Woronora and Illawarra Plateaux south of Sydney are important ecosystems containing a diversity of flora and fauna species. The ecology of these swamps has been studied by many (Young, 1982; SMEC, 2006, 2007a, 2007b and 2008; PB, 2007b) however the hydrology and hydrogeology of these swamps is poorly known. They were suspected by some to be groundwater dependent ecosystems (Hatton and Evans, 1998). Recent studies by the Sydney Catchment Authority (SCA) in the Southern Highlands at Kangaloon have provided valuable information on the hydrogeology of these swamps, particularly the underlying groundwater systems and the temporal changes when stressed (under both drought and intensive groundwater pumping conditions).

These studies were part of the environmental suite of studies completed under the Metropolitan Water Plan (MWP) groundwater investigation program to prove the viability of borefield development in the Kangaloon area for drought water supply, and to demonstrate the sustainability of both resource development and natural ecosystems.

The work was required to support the borefield project applications under Part 3A of the NSW EP&A Act and the Commonwealth EPBC Act. The upland swamps contain threatened species listed under the NSW Threatened Species Conservation Act and the vegetation community is listed under the EPBC Act as a Threatened Ecological Community (known as Temperate Highland Peat Swamps on Sandstone). Butlers Swamp, North Pole Swamp and Stockyard Swamps are named as endangered swamps under this listing.

Background

There are seventeen (17) upland swamps within the Kangaloon borefield area (PB, 2007b) and most are shown on Fig. 1.

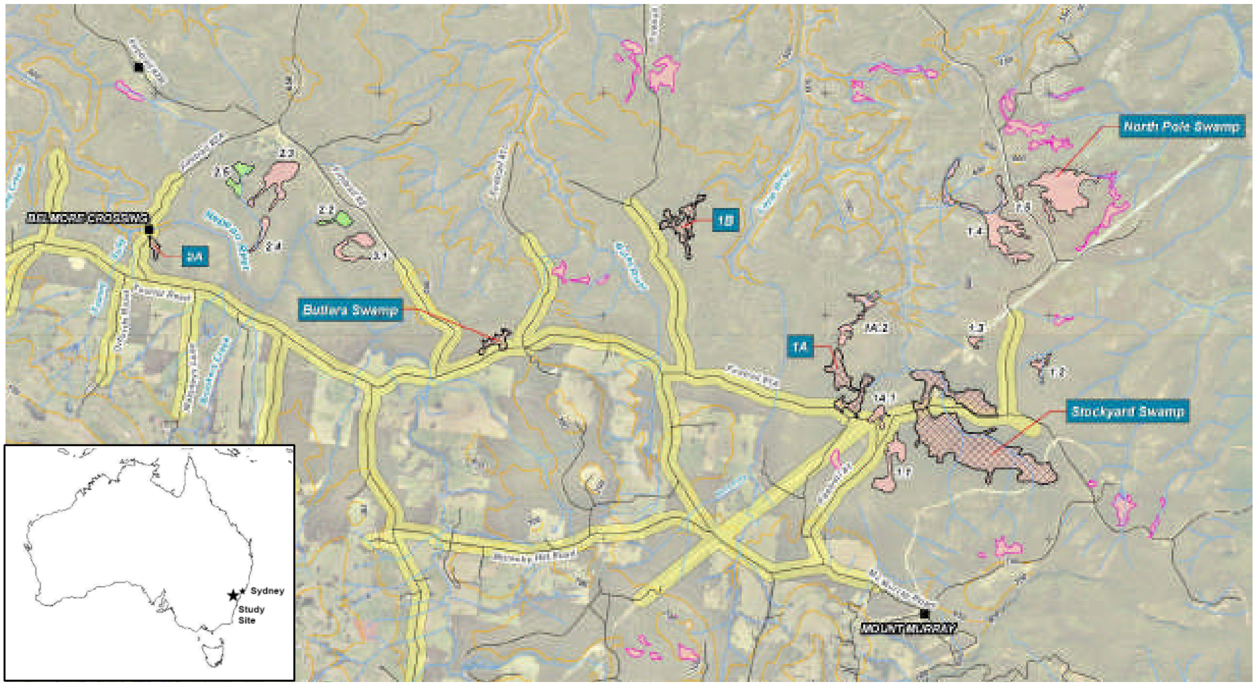

Figure 14 Important upland swamps in the vicinity of the Kangaloon Borefield corridor

Rainfall

Most of the swamps occur within 10-15kms of the Illawarra Escarpment or the Mittagong Ranges in the wetter areas of the respective plateau areas. Rainfall in these areas is mostly above 1000 mm per annum and high rainfall periods above 50mm are regular events even during drought periods.

Topographic Setting

Upland swamps on the Hawkesbury Sandstone terrain of the Woronora and Illawarra Plateaux are either headwater/drainage divide or valley fill swamps (Tomkins and Humphreys, 2006). In the borefield area, there are 16 swamps in total that occur from RL 640 mAHD in the south to around RL 580 mAHD in the north. All of the swamps in the investigation area, except for part of the Stockyard Swamp complex, are headwater/drainage divide swamps that occur mostly on the sides of valleys close to the top of dominant ridges in areas where there are slight depressions in the landscape. Stockyard Swamp (at 55ha) has many different components and is mostly a valley fill swamp. It is the only known swamp in a valley setting with a permanent creek flow at the outlet. This outflow is the start of Dudewaugh Creek which is a major tributary of the Nepean River.

Geology and soils

Upland swamps typically formed during the Late Pleistocene – Holocene period and are filled with sandy sediments tending to peat during conditions of high water tables and low sediment supply (Tomkins and Humphreys, 2006). Most swamps are less than 10ha in area with the thickness of colluvium rarely exceeding 1.5m. Beneath some swamps a thin clayey or silty sediment layer occurs directly over the Hawkesbury Sandstone bedrock (URS, 2007). These low permeability horizons are thought to have been deposited in areas where there is nearby Ashfield Shale or Mittagong Formation that has eroded from the ridgelines to be deposited in these silt traps.

Groundwater hydrology

The groundwater systems beneath the swamps were conceptualised as a perched water bearing zone occurring in the colluvial sediments with regional (fractured and porous rock) aquifers occurring in the deeper Hawkesbury Sandstone. The water levels and the respective interaction between these zones were not known at the outset of investigations but by the end of the investigation program, it was clearly evident that systems were hydraulically disconnected.

The groundwater hydrology of these features is shown schematically in Fig. 2. Rainfall accumulates in the perched water zone (from direct rainfall and runoff from small local catchments) and over the coming months this water sustains local vegetation. There are no known contributions from spring zones. Overland flow and permanent standing water within the swamps is rarely seen (again with the exception of Stockyard Swamp) because of their limited catchment area and high “valley side” setting. A proportion of water that accumulates in these swamps is lost to evaporation and infiltration.

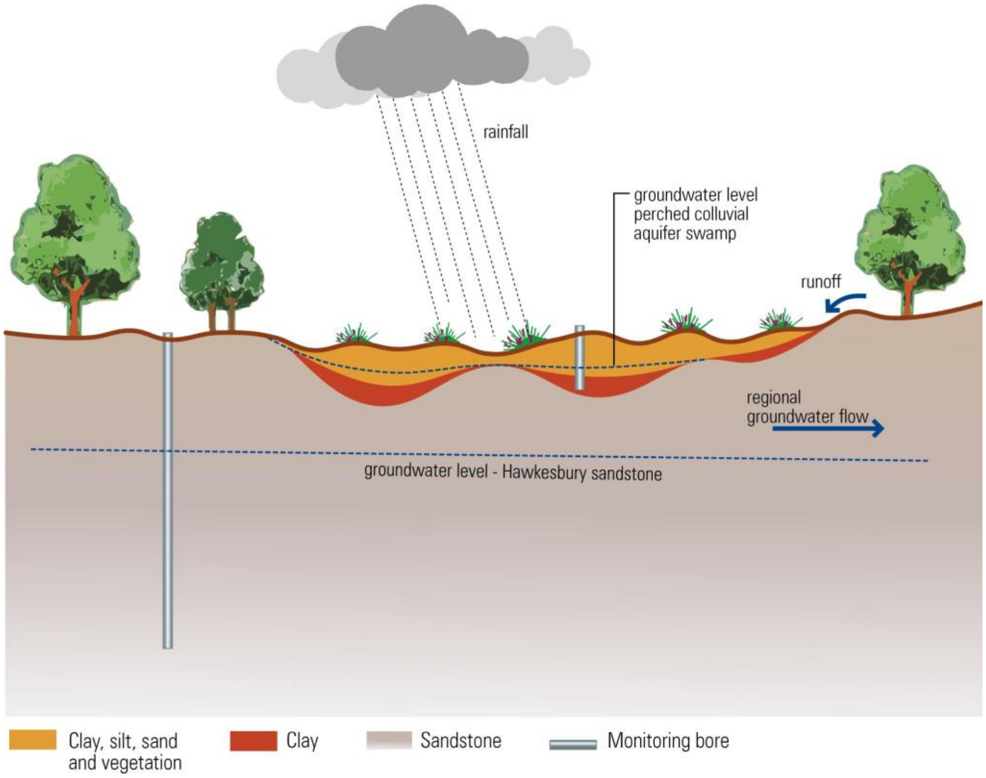

Figure 15 Schematic showing disconnected perched water bearing zone and regional sandstone aquifers

Upland swamps of the Upper Nepean catchment

As part of the suite of investigations, an inventory of swamps and their known or likely attributes was compiled (PB, 2007b). This information is summarised in Table 1. Of these 17 swamps, detailed ecological surveys were conducted across five of the swamps (Swamp 2A, Butlers Swamp, Swamp 1B, Swamp 1A, and Stockyard Swamp) and shallow wells were drilled in three of the swamps (Butlers Swamp, Stockyard Swamp and Swamp 1A). Beside Butlers Swamp, Stockyard Swamp, and Swamp 2A, nested monitoring bores into the Hawkesbury Sandstone aquifers were constructed (generally to around 25m and 50m depth) and deeper test bores / production bores were completed for resource investigation purposes.

Table 8 Swamp Characteristics in the Kangaloon Borefield area

Swamp	Size (Ha)	Altitude (mAHD)	Depth to Perched Water Table (mbgl) *	Av. Depth to Sandstone Water Table (mbgl) **
Monitored				
Butlers	3.4	637	1 to 1.4	10
Stockyard	54.9	586	1 to 1.3	4
2A	4.0	599	none present	17
1B	6.0	579	unknown	23
1A	8.0	583	0.5	5.3
Others				

1.1	8.3	589	unknown	at surface
1.2	1.9	583	unknown	24
1.3	1.2	597	unknown	18
1.4	17.8	581	unknown	unknown
1.5	0.9	615	unknown	unknown
1A.1	2.4	582	unknown	3
1A.2	5.3	581	unknown	3
2.1	6.1	616	unknown	est 15 to 25
2.3	10	638	unknown	33.5
2.4	2.4	634	unknown	est 15 to 20
2D	2.9	525	unknown	est 15 to 25
North Pole	22.1	592	unknown	est 20 to 30

Key * - late 2007 levels after a dry period – these rise to surface after wet periods; ** - as measured in nearby bores

The main drivers for the swamp studies were to confirm the conceptual model for the hydrology of the swamps, to determine the hydraulic connectivity (if any) with the regional sandstone aquifers across the area, and to determine the diversity and health of the species living within and adjacent to the main swamps.

Discussion of Water Levels

Water levels from nested (sandstone) monitoring bores located beside both Butlers Swamp and Stockyard Swamp indicate that water levels in the uppermost fractured aquifers are slightly higher than the deeper fractured aquifers. The water levels in the overlying perched water bearing zone are significantly higher at Butlers Swamp (by about 6 to 8m) and marginally higher at Stockyard Swamp (by about 1 to 3m). There is potential for vertical flow through the fractured sandstone from upper sandstone aquifers to lower sandstone aquifers, although lateral flow predominates (PB, 2009). Vertical flow would be more pronounced during (or immediately after) long groundwater pumping periods. There are no data to suggest infiltration losses from perched water tables to sandstone aquifers (although some minor infiltration is suspected).

The main work program completed to determine the connectivity between perched water and regional sandstone aquifers involved two pumping trials at each of Butlers Swamp (over a 4 month period) and Stockyard Swamp (over a 3 month period). Details for each pumping trial are provided in Table 2.

Table 2 Pumping Trial Details

Pumping Trial and Production Bores	Individual Pumping Rates (L/s)	Static Water Levels at Start (mbgl)	Maximum Drawdown Levels (mbgl)	Volumes pumped for each Trial (ML)
Tourist Rd Trial (Butlers Swamp) – 4 months				
Eastern bores (2F, 2C, 2L, and 2G) near swamp	3.8 to 20	4.4 (2F) 9.6 (2C) 18.2 (2L) 19.4 (2G)	60.0 (2F) 50.2 (2C) 77.4 (2L) 83.0 (2G)	314
Perched well 2m1p		surface	surface	
Western bores (2E, 2D, 2M)	3.5 to 10	2.4 (2E) 15.9 (2D) 1.6 (2M)	76.6 (2E) 79.5 (2D) 73.3 (2M)	144
Stockyard Swamp Trial – 3 months				
Bores (3Z, 9B, 3H)	3 to 15	6.3 (3Z) 3.5 (9B)	49.3 (3Z) 70.7 (9B)	169

	6.1 (3H)	74.1 (3H)
Perched well 9m1p	0.75	0.5

It was the pumping trials and hydrographs of before, during and after water levels at each of the sites that were the most conclusive for proving no connectivity. Hydrographs from selected nested bores and perched wells are shown in Fig. 3a for Butlers Swamp and Fig. 3b for Stockyard Swamp. Water levels were drawn down to a maximum of 77 mbgl (RL 563mAHD) at nearby production bore 2L at the Butlers Swamp site and to a maximum 74 mbgl (RL 509mAHD) at production bore 3H beside the Stockyard Swamp site. Drawdown from upper sandstone aquifer zones due to the production bore extractions is evident in the hydrographs presented in Fig. 3 however there was no change in water levels at any of the perched water table locations within the adjacent swamps. Perched water levels do oscillate during the pumping trials but these changes are clearly the result of rainfall recharge or evapo-transpiration during drier periods. These water level trends are supported by other monitoring bores and wells that were closely monitored during the pumping trials and respective recovery periods.

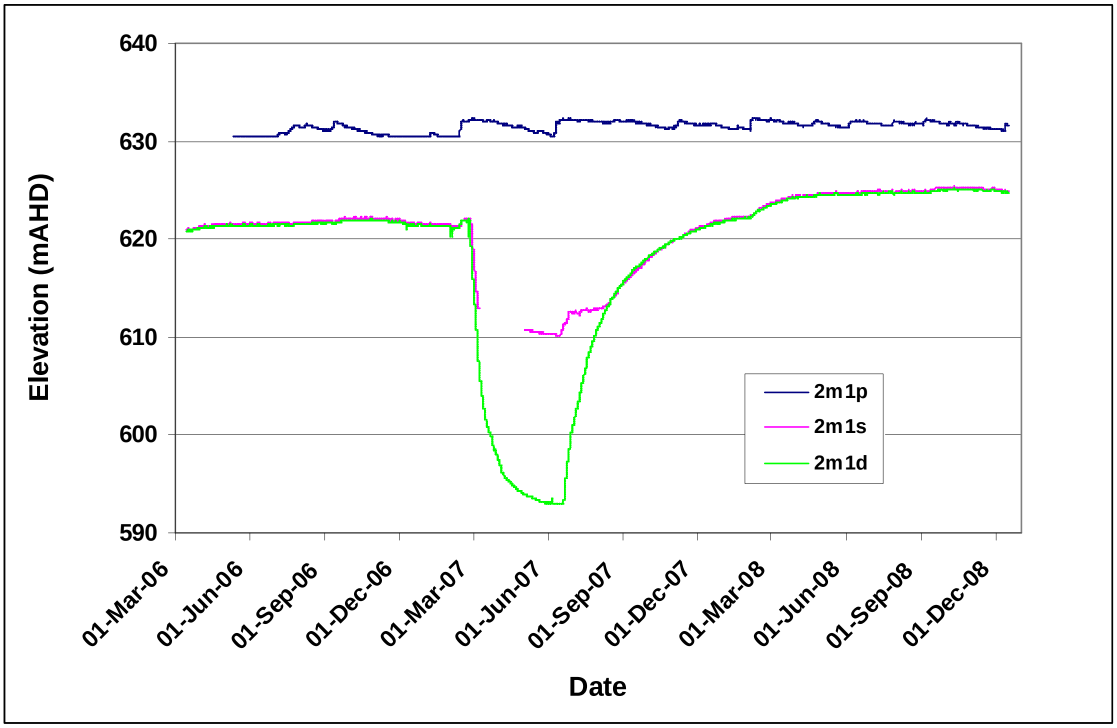

Figure 3a Groundwater level trends at Butlers Swamp

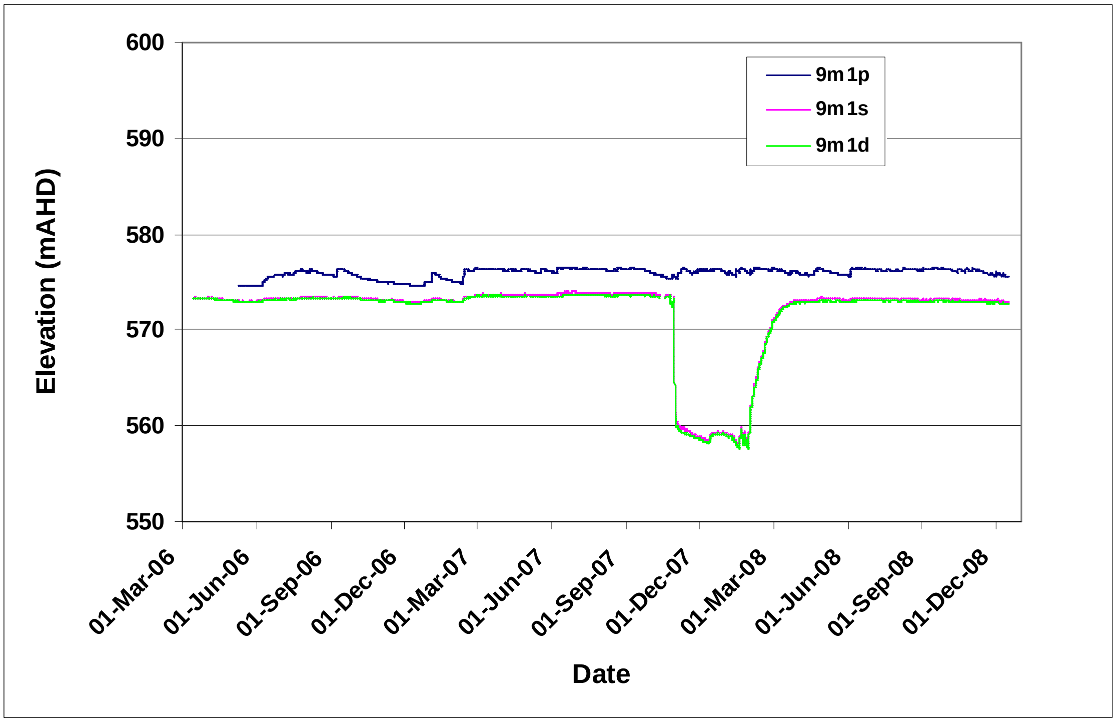

Figure 3b Groundwater level trends at Stockyard Swamp

Discussion of Hydrochemistry

Chemical characterisation of the water and determining the age of groundwater using environmental and radioisotopes were used pre-pumping (PB, 2006 and PB, 2007a) and then during the pumping trials for both the Butlers Swamp site (PB, 2008a) and the Stockyard Swamp site (PB, 2008b). Hydrochemistry provides an independent verification method for determining the origin of waters and assessing the degree of interaction between different aquifer zones and between perched zones and deeper aquifer zones.

The origin of all groundwater in the Kangaloon area is rainfall so it is not generally possible via simple chemistry to differentiate the groundwater in perched water bearing zones from the groundwater in the sandstone aquifers. Both waters are generally Na-HCO_3-Cl /Na-Cl- HCO_3 dominant (although sandstone waters can have higher Ca/Mg content due to the dissolution of minerals from the sandstone matrix). Also the sandstone groundwaters usually have slightly higher conductivities due to their longer residence time and higher dissolved iron and manganese concentrations.

Radioisotope techniques, particularly C_{14} and tritium methods, were useful in aging waters at each site (PB, 2008a, and PB, 2008b). Pumping and post pumping trial data is summarised in Table 4.

Table 4 Pumping and post-pumping water chemistry and isotope results from selected bores / wells

Bore Location (pumping/post-pumping)	Conductivity (µs/cm)	Water Type	Carbon 14 (Average corrected age) (years)	Tritium age (years)
Tourist Rd Trial (Butlers Swamp)				
2F (1.6.07/31.7.07)	59/63	Both Na-Cl- HCO_3	Modern/Modern	26/17
2C (1.6.07/31.7.07)	51/52	Both NaCl	Modern/368	23/20
2G (1.6.07/31.7.07)	100/98	Both Na-Mg-HCO_3-Cl	3104/1714	old/younger
2m4p (31.7.07) *	65	Na- HCO_3-Cl	Modern	7
Stockyard Swamp Trial				
9B (3.12.07/28.2.08)	129/58	Na-Mg-Cl- HCO_3 / Na-Mg- HCO_3-Cl	3330/3860	old/younger
3H (3.12.07/28.2.08)	132/44	Na-Mg-Cl- HCO_3 / Na-Ca- HCO_3-Cl	1890/850	old/younger
9m4p (14.11.07) *	125	Na-Mg-Cl	Modern	8
9m9p (14.11.07) *	142	Na-Cl- HCO_3	Modern	8

Key * - perched water bearing zone in each swamp (pre-pumping samples for 9m4p and 9m9p)

Conclusions

Studies have concluded that those swamps intensively studied in the Upper Nepean catchment (which are considered typical of all those across the whole plateau area) are not dependent on the regional sandstone aquifer system as a water source. Instead they are reliant on regular rainfall recharge and ephemeral perched water tables for their maintenance and survival.

Given this hydraulic disconnection, production bores can be sited with confidence around the many upland swamps. Pumping will not drain these important features and will not impact shallow water that sustains these ecosystems.

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Water Level Trends in Fractured Hawkesbury Sandstone Aquifers in the Kangaloon Area, Southern Highlands, New South Wales

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Abstract

Groundwater investigations for drought water supply for the Greater Sydney area were initiated in the Sydney Basin in late 2004 as part of the NSW Government's Metropolitan Water Plan (MWP) suite of initiatives. The prospectivity of the Hawkesbury Sandstone aquifers was confirmed at three locations in the Southern Highlands (Kangaloon) and in Western Sydney (Leonay and Wallacia).

Groundwater monitoring networks and subsequent data collection and analysis have been important studies in assessing resource variability, sustainability, and recharge and discharge trends. A large network of shallow, intermediate and fully penetrating test bores has been installed across the primary resource area at Kangaloon and monitoring has been under way for more than three years.

Data collected since early 2006 covers the last 12 months of the 2002 to 2007 severe drought period and the slightly below average rainfall periods of 2007 and 2008. The data and analysis has provided important information on:

- Regional recharge patterns
- Local and regional discharge patterns
- Groundwater flow
- Connectivity between perched water and the fractured sandstone aquifers

These data sets were essential for steady state and transient numerical modelling and were equally important in assessing the recharge potential of these aquifers after extending pumping trials. Important conclusions drawn from the data to date are:

- The Hawkesbury Sandstone aquifer in the Kangaloon area responds rapidly to rainfall
- Aquifer recharge following rain events greater than 50 mm is estimated at between 2 and 16%, with the most likely range between 3 and 10%
- Steep hydraulic gradients generate and maintain high water levels and artesian pressures at some locations
- General groundwater flow is from the primary recharge area south of the borefield area to the north
- Uplands swamps behave as separate hydraulic systems from the underlying regional sandstone aquifer

Keywords: water level trends, fractured aquifers

Introduction

Recent studies by the Sydney Catchment Authority (SCA) in the Southern Highlands at Kangaloon have identified a substantial regional aquifer in the Hawkesbury Sandstone strata that would be suitable for drought water supply. The borefield development program has progressed to planning approval, land acquisition and tender designs. The monitoring network comprises 104 bores and wells drilled and constructed at a range of depths to monitor the full profile of the Hawkesbury Sandstone aquifer, intermediate and shallow Hawkesbury Sandstone horizons, perched water tables in three upland swamps and under thickly forested areas, and shallow Nepean River alluvium sites. Baseline monitoring is critical to understand natural variations and fluctuations around swamps and permanent streams. In addition to the bores and wells, there are a number of spring and surface water sites monitored. All these sites provide data along the main alignment of the proposed borefield and at sites distant from it (mostly downgradient).

The distribution of the bores in the Kangaloon area is presented in Fig. 1, which also presents composite water level contours at May 2009.

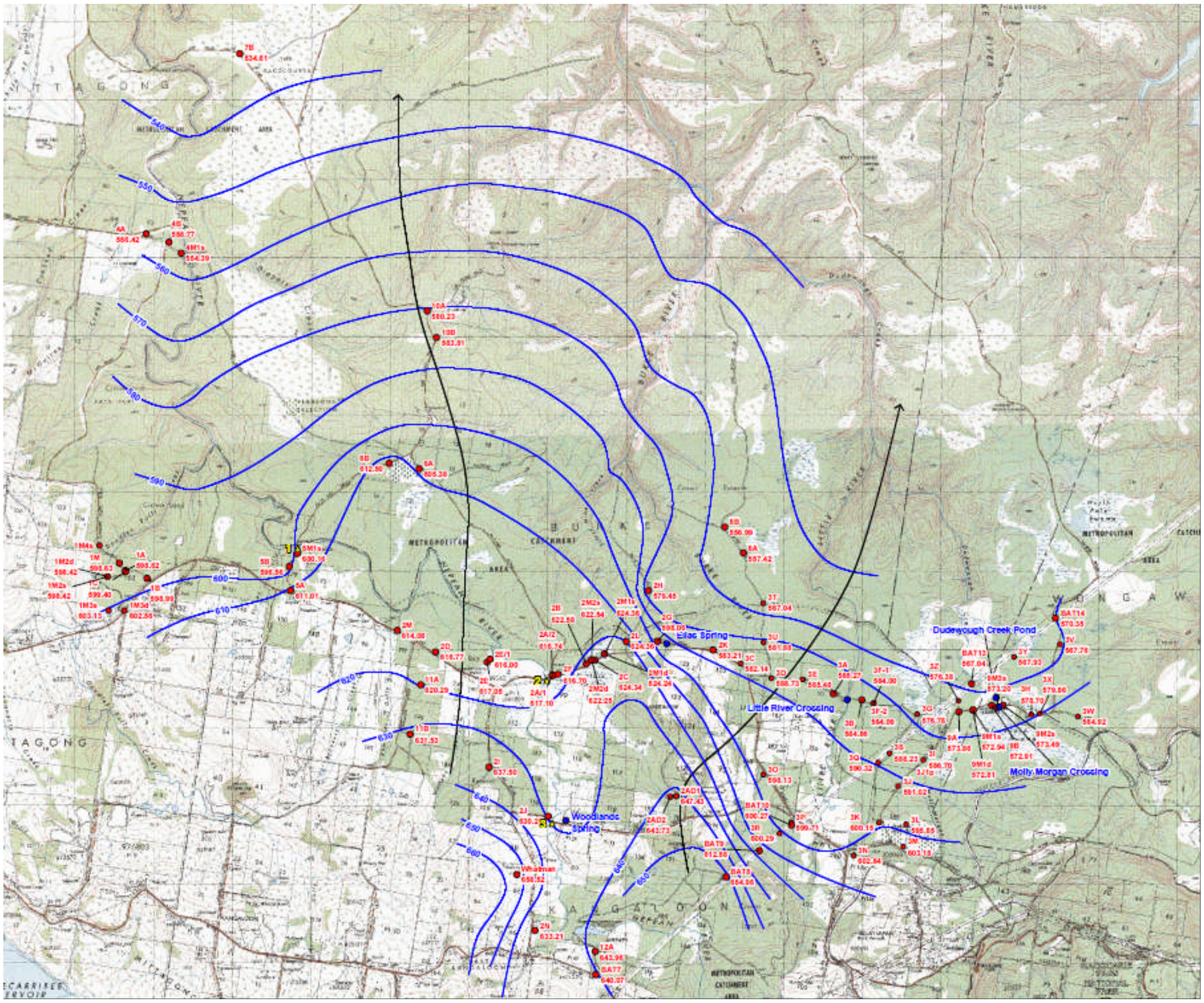

Figure 16 Kangaloon monitoring network and latest water level contours

Water level monitoring has been performed by manual measurements (all sites) and by automatic dataloggers installed in 42 bores/wells and at 4 surface sites.

The Kangaloon area receives an average of 1675 mm of rainfall per year, almost evenly distributed over the 12 months. Intense storm periods can produce up to 500 mm of rain in one week. One such event was experienced in June 2007, at the end of the 4-month Tourist Rd pumping trial (URS, 2007a).

Regional Recharge Patterns

The duration of the project, the wide areal distribution of the monitoring points, the daily rainfall records and the high quality of the daily data collected have confirmed recharge areas and patterns, and allowed estimates of the rainfall recharge over the area to be carried out.

The Bureau of Meteorology annual rainfall data from the Caalong Street station in Robertson is provided in Table 1. The long term average for the station is 1675 mm/year.

Table 9 Annual rainfall statistics for BoM Station at Caalong St Robertson

Year	Annual Rainfall (mm)	Comments
July 2008 to May 2009	998.2	Data is for 10 months only
July 2007 to June 2008	1376.9	
July 2006 to June 2007	1825.0	1456mm in the 8 months January to August 2007
July 2005 to June 2006	1148.8	

Water level responses are fastest in the shallow alluvial bores and perched water table wells because of high permeability sediments and shallow water tables. Recharge to these shallow zones also appears to be substantially greater than the recharge to the deeper regional water table in the sandstone strata. An example of a shallow water table response is provided in Fig. 2 for alluvial bore 2A/1.

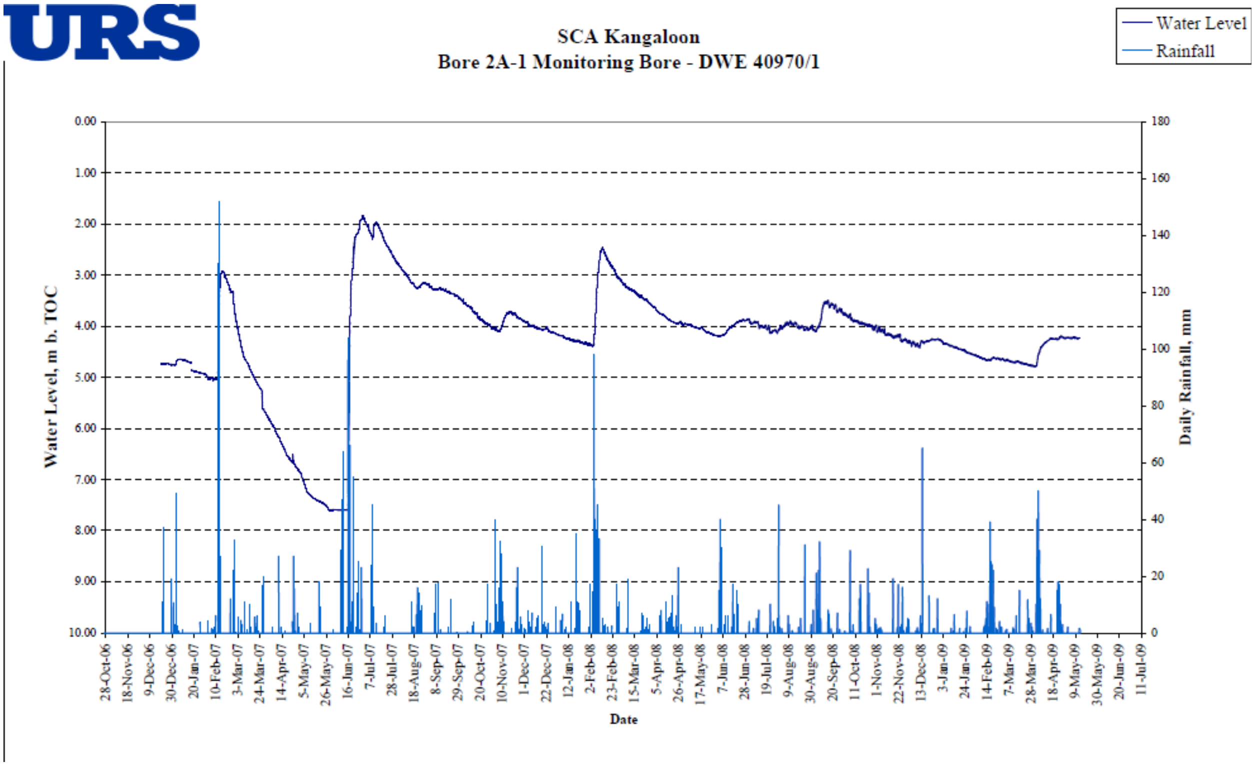

Figure 2 Bore Hydrograph for bore location 2A/1

The majority of the sandstone bores respond to rainfall events with a short time lag varying from hours for the shallow and intermediate bores, to a few days for the deep bores. Water level responses are generally faster in shallow water table areas compared to the deeper water table areas to the north (for example Fig. 3 for bore 10A is typical of a slow and lagged response).

However there are other factors that also influence groundwater recharge rates and responses. These include proximity to structural features, the degree and depth of fracturing, primary porosity, topography, soil profile and the intensity and duration of rainfall.

Recharge estimates were carried out using the high rainfall events during 2007, the measured rise in the water table during the period, and estimates of porosity for the fractured sandstone aquifer of 3%, 5% and 10 % (URS, 2007b). These parameters provided recharge rates ranging between 2 and 16 % of incident rainfall, with the more realistic range considered to be between 3 and 10 %. The data also indicated that localised higher rates of recharge were possible, as indicated by the hydrographs of some bores where the water table has continued to rise throughout the monitoring period (for example Bore 2J, Fig. 4).

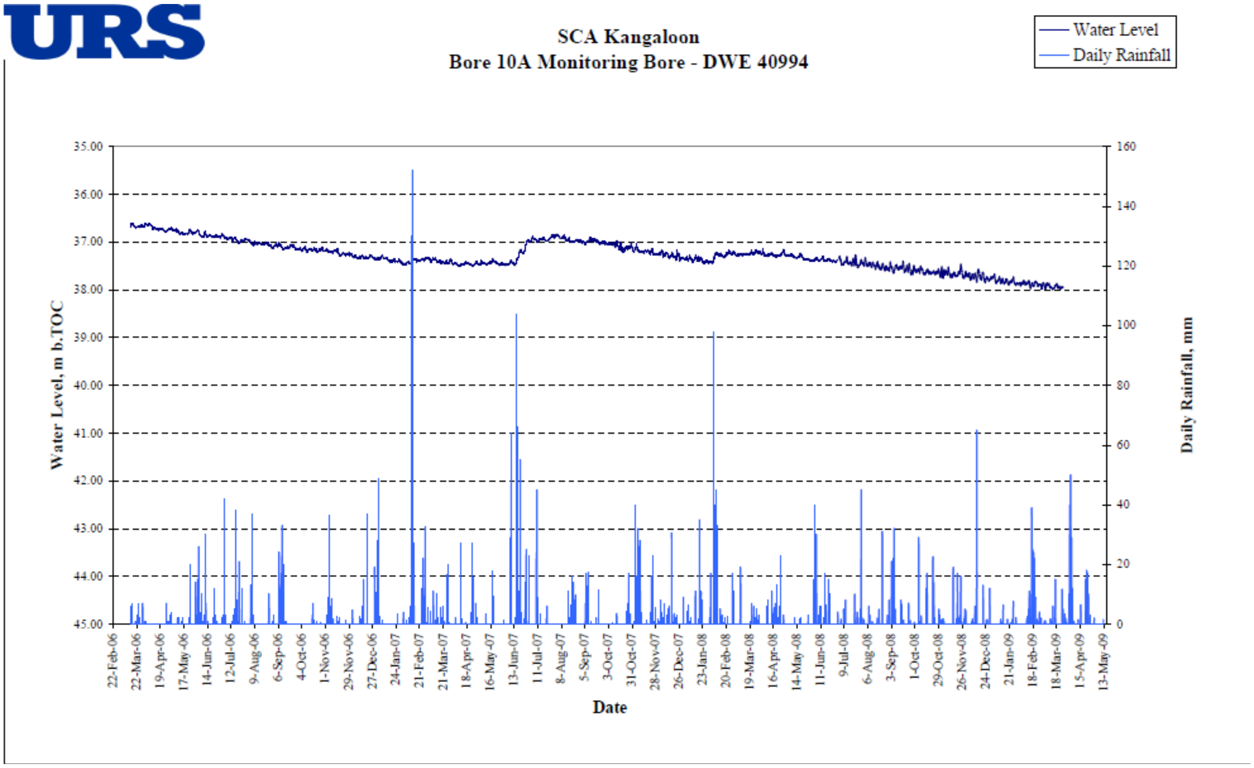

Figure 3 Bore Hydrograph for bore location 10A

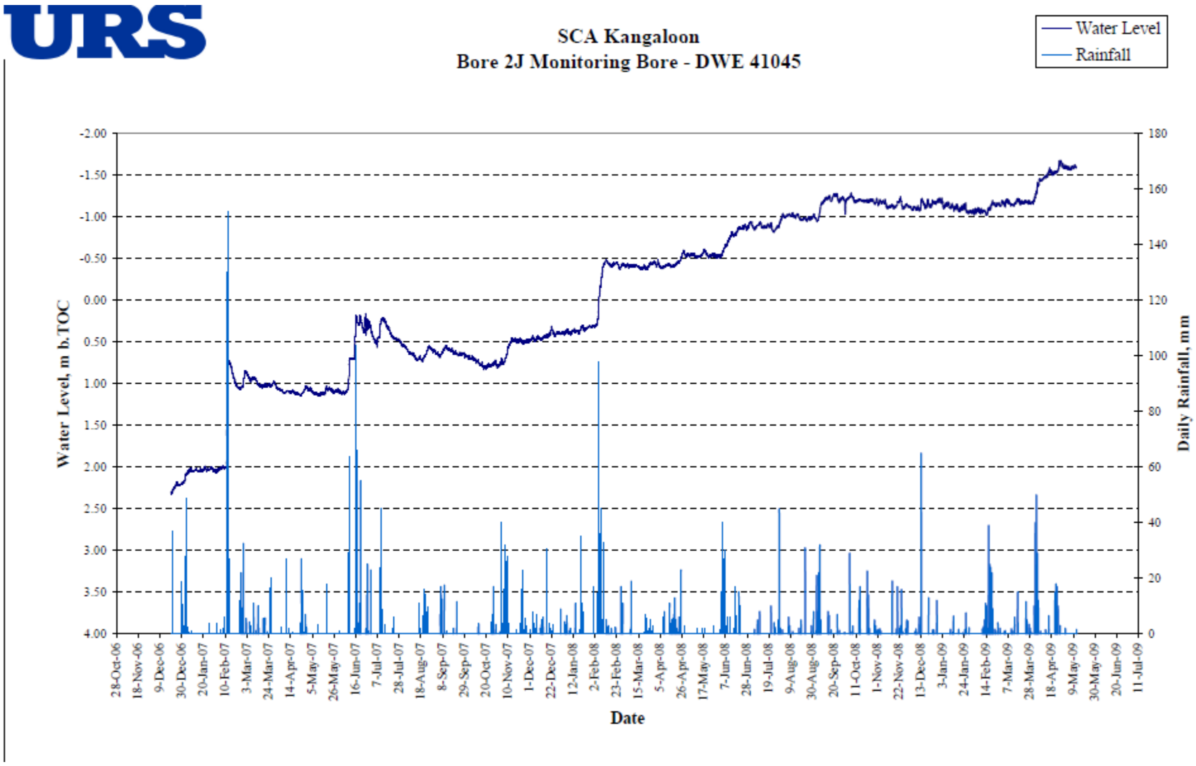

Figure 4 Bore Hydrograph for bore location 2J

Trends observed in the water level monitoring data set for 2008-2009 suggest that similar recharge rates apply even though the slightly lower year rainfall has generated fewer recharge events and lower volumes of annual recharge.

Local and Regional Discharge patterns

Fig. 1 presents the combined water level contours for the intermediate and deep monitoring bores in the Hawkesbury Sandstone. Data is poor in some areas but the interpretation is considered reasonable for the semi-confined/confined portion of the regional sandstone aquifer.

The contours present the same general pattern recorded over the three years monitoring period, i.e., they show a high water table zone in the area south of Moresby Hill Road and Kangaloon Road, which has been identified as the primary recharge zone (PB, 2006), a central lower gradient area along Tourist Road and a downgradient area with regional flow towards the gorges and incised permanent streams north of Tourist Road.

The contours indicate that the overall groundwater flow direction is towards the north and generally follows the topography and the dip of the sandstone strata.

Local groundwater discharge occurs where there is fractured sandstone at surface and along some of the slightly incised watercourses (SCA, 2006) which generally run from south to north and are often associated with structural features and patterns.

Other groundwater discharge is possible through the high pressure zones where there is impeded lateral flow in the aquifer due to geological and structural constraints. Examples of such sites include Bore 2J (Fig. 4) which is artesian and above the Nepean River level, and bore 2I under the thickly forested area within the eastern portion of the investigated area.

Water level data for most of the deep bores intersecting the full thickness of the Hawkesbury Sandstone aquifer suggests that sub-artesian conditions exist for the majority of the deeper aquifers, and that at most sites the natural hydraulic gradients are downwards from the shallowest fractured aquifers to the deepest zones.

Connectivity between Perched Zones and Fractured Sandstone Aquifers

Perched water bearing zones associated with the upland swamps (particularly Butler Swamp and Stockyard Swamp which are located along the main alignment of the proposed borefield) have been shown during two long pumping trials to be unaffected by drawdown in the deeper sandstone aquifers (URS, 2007a and URS, 2008a). The combined hydrographs of shallow sandstone bores and perched water table wells from the Stockyard Swamp pumping trial (Fig. 5) in late 2007/early 2008 illustrates this independence of water levels (URS, 2008b). Similar conditions were observed in the four month pumping test in the Butlers Swamp area in early to mid 2007 (URS, 2007a).

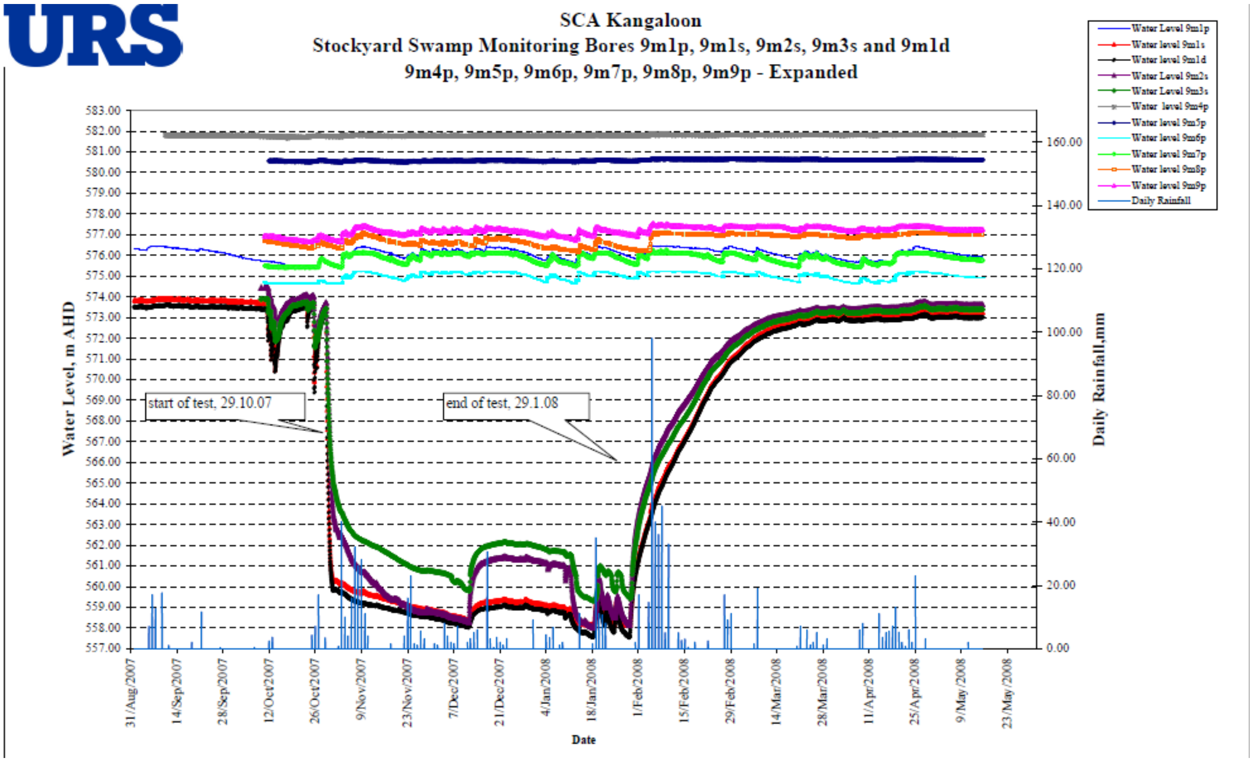

Figure 5 Bore hydrographs for bores and wells at Stockyard Swamp

Of significance is the very quick recovery of water levels at the cessation of short and long term pumping tests. This is clearly shown by the hydrograph of Bore 11A (Fig. 6), which shows the recovery/recharge after the Tourist Rd pumping trial. This aquifer behaviour has been observed in all the bores monitored during the two long term pumping trials (URS, 2007c and URS, 2008b). In most cases the water level at the completion of the tests was higher than that at the start of the tests because of large rainfall recharge events at the end of each pumping trial.

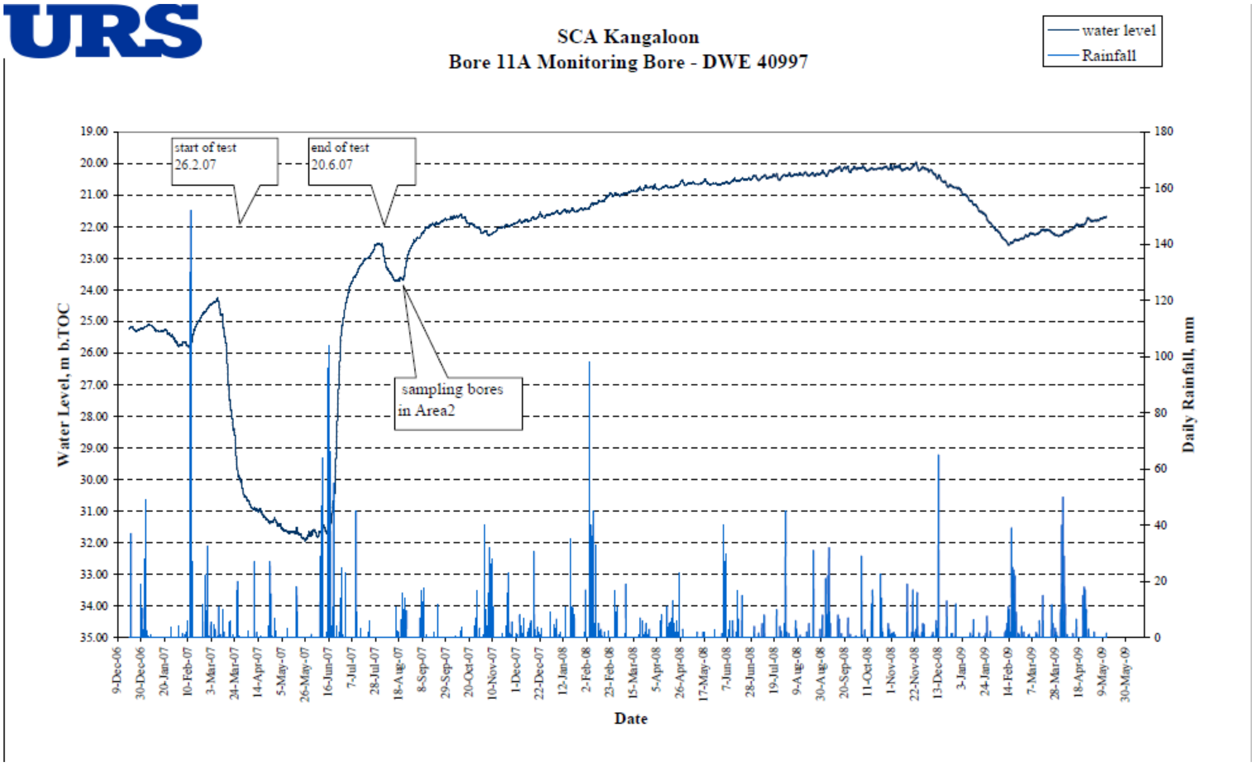

Figure 6 Bore hydrograph for bore location 11A

Conclusions

Important conclusions drawn from the analysis of the water level data to date are:

- The Hawkesbury Sandstone aquifer in the Kangaloon area responds rapidly to rainfall
- Aquifer recharge following rain events greater than 50 mm is estimated at between 2 and 16%, with the most likely range between 3 and 10%
- Steep hydraulic gradients generate and maintain high water levels and artesian pressures at some locations
- General groundwater flow is from the primary recharge area south of the borefield area to the north
- Uplands swamps behave as separate hydraulic systems from the underlying regional sandstone aquifer

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A Groundwater Resource Assessment of the Triassic Rocks of the Sydney Basin

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Abstract

Water bore completion records archived in the State Government's Groundwater Data System include information on geology and water bearing zones as well as the rudimentary groundwater characteristics of yield and salinity. That database has been widely used to guide exploratory drilling and collectively represents the most comprehensive collation of information that directly relates to the hydrogeology of Triassic strata in the Sydney Basin. This paper considers various studies undertaken to date that have utilised the data, and provides an overview of the broad scale character of groundwater in those strata without attempting to volumetrically quantify the resource or discuss management approaches.

Analysis of information from the water bore records database indicates that the pervasive sandstone strata (Hawkesbury Sandstone and Narrabeen Group), regionally significant aquifers within the basin, contain a groundwater resource of variable quality (less than 500 to in excess of 3,000 milligrams per litre total dissolved solids) and permeability. Reported and calculated permeability estimates for the sandstone strata range between 2×10^{-9} and 1.7×10^{-5} metres per second; the lower values relating to massive units and the upper bound corresponding to fractured porous layers. A discussion of recharge dynamics in the sandstone units is included that provides an interpretation, based on graphical analysis, of water level measurements from the State Government's monitoring bore network.

Triassic age shale units (Wianamatta Group), regionally significant aquitards, exhibit permeability ranges orders of magnitude broader than the sandstone strata, typically 1×10^{-12} to 2×10^{-5} metres per second, the former representing highly impermeable massive layers and the latter corresponding to more permeable fractured horizons. The shale units also contain groundwater of considerably higher salinity than the sandstone strata (less than 3,000 to in excess of 5,000 milligrams per litre total dissolved solids).

Keywords: Triassic, groundwater, Sydney Basin, water bores

Introduction

Data considerations

Licensed water bore drilling contractors (drillers), as part of their licensing obligations with the NSW Department of Water and Energy (DWE), are required to provide completion details of any groundwater work to the State Government for inclusion on the water bore information database (Groundwater Data System; GDS). The information provided by drillers relates to all aspects of the physical construction of the installation, including the strata encountered and the components used. The value of the reported data is entirely dependent on the skill of the operator in identifying strata and the diligence of the driller in completing the report in sufficient detail to render the information useful. Nevertheless, despite these obvious limitations, the data set archived by DWE is the best information available that directly relates to the hydrogeology of the area. The discussion of groundwater characteristics presented in this paper is based on interpretation and, despite the likelihood that erroneous data is the main cause of anomalous results; these have been retained so as not to introduce further subjective bias.

Information from that archive does not fully describe the sandstone units, as most bores only partially penetrate the strata. Drilling results indicate that bores installed into the deeper parts of the Hawkesbury Sandstone, in particular, progressively increase in yield with depth at some locations. In such cases, fully penetrating bores might intersect higher yields than those recorded in the archive, although this is not guaranteed.

Automatic water level recording data from DWE monitoring bores is archived as time series information into a separate database (HYDSYS), from which hydrographs of groundwater elevations can be generated. This information relates to discrete points irregularly distributed across those areas of the Triassic sandstone units with a history of groundwater use and management. Therefore, given the variability of the groundwater characteristics of the sandstone aquifers, the conclusions drawn are specific to those locations and broader generalisations presented in this paper are inferences only.

Previous work

The data archived within the database have been previously used as the basis for significant studies and major investigations within the basin, including:

- A description of the chronological development and locality characteristics of the Triassic sandstone units around Sydney (McKibbin & Smith 2000).
- The desktop assessment of potential groundwater drilling targets for further investigation as part of the staged Sydney Catchment Authority (SCA) investigations into contingency drought relief measures for Sydney (Parsons Brinckerhoff 2003).
- The quantification of groundwater resources leading to the placement of embargoes in parts of the Southern Highlands (Pritchard, *et. al.* 2004) and also parts of the Blue Mountains.
- The generation of an overview of the groundwater attributes of the Hawkesbury Sandstone (Russell 2007).

This paper updates the previous work with the broad findings of recent studies to provide an overview of groundwater characteristics within the Triassic strata.

Physical setting

The sedimentary rocks deposited in the Sydney Basin range in age from about 290 million years to 230 million years (mid-Permian to mid-Triassic) and are up to 5,000 m thick. The Triassic strata occupy a large, centrally situated area of the Sydney Basin (Fig. 1), and form a sedimentary sequence up to almost 1,200 m in thickness. Only the upper 250 m of the consolidated Triassic deposits, comprising sandstone, shale, siltstone, claystone, and minor conglomerate, are the subject of this paper.

The stratigraphic units recognised as part of the late Permian to middle Triassic depositional episodes comprise, in order of decreasing age: Narrabeen Group (marine and non-marine sediments including lithic sandstone, quartz sandstone, claystone, siltstone and conglomerate), Hawkesbury Sandstone (non-marine quartz-rich sandstone with minor interbedded shale), and Wianamatta Group (marine shale with minor interbedded sandstone). The older sandstone-dominated facies exhibit similarities with regard to groundwater occurrence and movement, and they have therefore been considered as a single hydrogeological unit for the remainder of this paper.

Uplift of the deposits during the middle of the Triassic resulted in a broad expanse of gently dipping units that then underwent sediment consolidation and later erosion. Regional scale deformation created a topographic low (the downwarped Cumberland Basin) and surrounding elevated plateaux (Blue Mountains, Hornsby, Woronora and Illawarra Plateaux). Several significant regional scale features, such as the Lapstone Structural Complex (Fergusson, 2006), a major north trending association of monoclines and faults forming the frontal ridge of the Blue Mountains Plateau, and the Hornsby and South Coast Warps, delineate the main area of displacement.

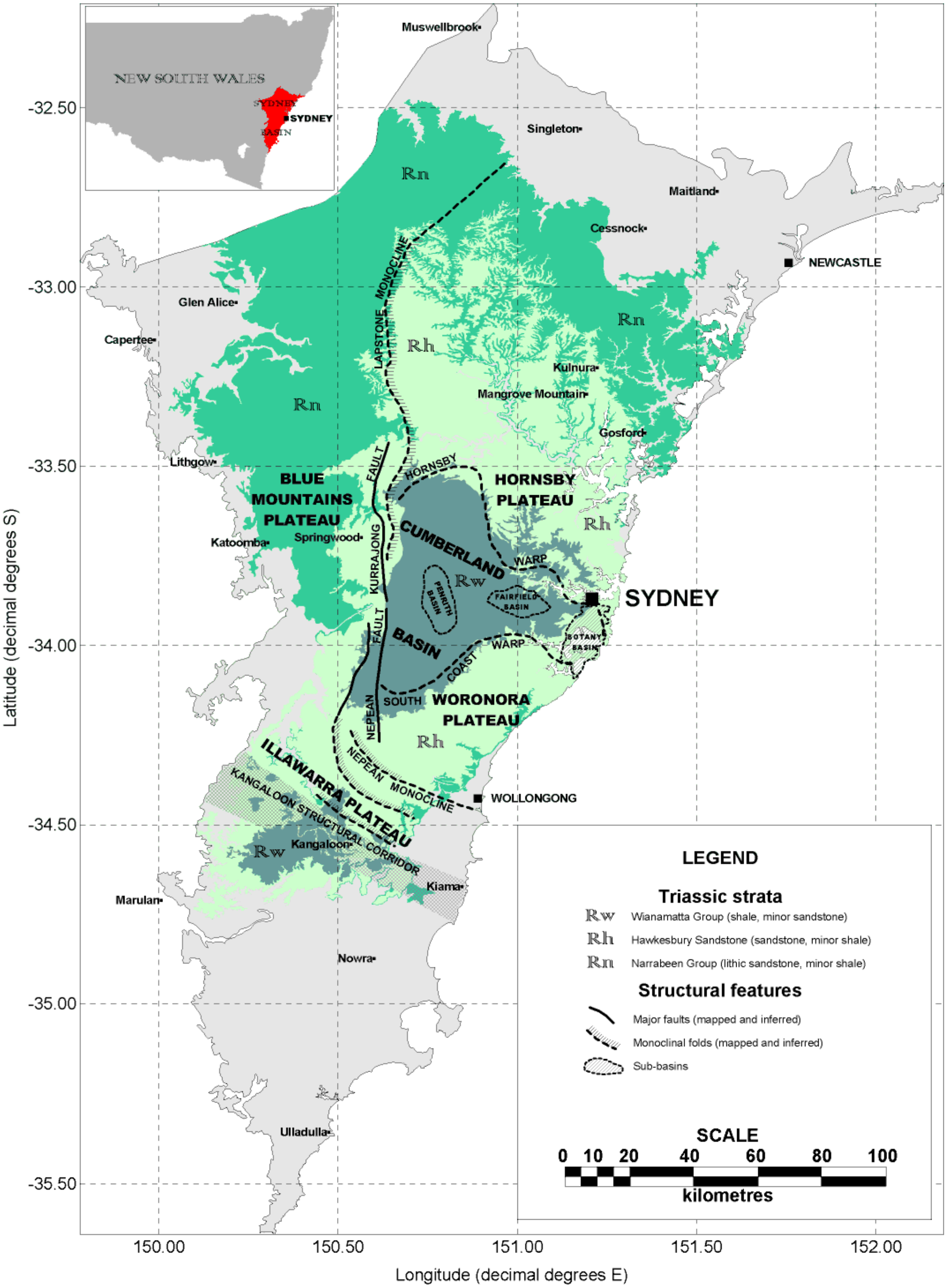


Figure 17 Distribution of the Triassic sandstone units (Hawkesbury Sandstone - Rh and Narrabeen Group - Rn) and Wianamatta Group (Rw) in the Sydney Basin

Groundwater ages and recharge dynamics

The porous sandstone strata form regionally significant aquifers within the basin, whereas the generally impermeable shale strata are regionally significant aquitards. The sandstone strata extend across a large proportion of the basin and provide a source of water supply to many areas lacking reticulated mains water. In contrast, the shale strata constrain the development of water supply, mainly in the western Sydney area, due to the typically impermeable nature of the unit, or, in the unusual instances where a water bearing zone is encountered, contributing high salinity groundwater to bores. Studies of recharge and the age of groundwater are therefore limited to the widespread sandstone strata, and very detailed investigations have been undertaken in the Kulnura Mangrove Mountain and Southern Highlands areas.

Groundwater ages

Work in progress on the Kulnura Mangrove Mountain Water Source continues under a memorandum of understanding between DWE and the Australian Nuclear Science and Technology Organisation (ANSTO). Both groundwater and drill chip samples from the DWE monitoring bore network have been collected and analysed for several naturally occurring radioactive isotopes in order to provide indicative age profiling of the groundwater resource. Initial results indicate an age layering with depth having three distinctive phases. These are (i) a shallow aquifer (<50 m depth) reflecting the local groundwater system with groundwater recharge occurring after an extended period of above average rainfall observed in the late 1980s to early 1990s; (ii) an intermediate zone (<100 m depth) where groundwater ages are up to several thousand years; and (iii) the deep regional groundwater system (>100 m depth) where the indicative ages are in excess of 3,000 years.

Elsewhere in the Sydney Basin, SCA has undertaken isotopic studies of sandstone groundwater for the Upper Nepean catchment as part of the Kangaloon groundwater investigations. That agency found that groundwater is mostly of modern origin (less than 50 years old) across the investigation area, although localities with strata of inherently low permeability and sites downgradient to the north of the highlands exhibit groundwater ages up to the order of 8,000 years (J. Ross, SCA, *pers. comm.*). Water in high permeability fracture zones is considerably younger than groundwater held within the porous parts of the Triassic sandstone units. In addition, other studies by SCA in the western Sydney region have demonstrated groundwater ages of up to the order of 20,000 years within the confined sandstone beneath Wianamatta Group shale strata.

Recharge dynamics

Recharge to the sandstone units is more strongly linked to prevailing long-term climatic conditions (wet and dry periods) than to the short-term rainfall pattern. The residual rainfall mass (RRM) curve is shown as the blue line in Figs. 2-4 and it is used here to represent the long-term climatic conditions. The RRM curve is the cumulative mean deviation from monthly rainfall plotted against time. A positive slope in the RRM curve indicates a continuous period of above average rainfall conditions whilst a negative slope indicates a continuous period of below average rainfall conditions.

Whilst some apparent recharge events identified on groundwater hydrographs (Figs. 2-4) can be correlated with large individual rain storms, a greater degree of correlation is readily apparent in the comparison of the RRM curve and hydrographic plots. The correlation comparison can be depicted by the use of scatter plots and the R^2 (co-efficient of determination) value which can range from 0 to 1, whereby a value of 1 indicates a perfect correlation. Figures 2c, 3c and 4c plot monthly groundwater level against monthly rainfall total, with a line of best fit and R^2 value inserted. Figures 2d, 3d and 4d plot the same groundwater level but this time against the residual rainfall mass. A vast improvement in the correlation of groundwater levels with residual rainfall mass is evident by the distribution of points around the line of best fit and the R^2 value.

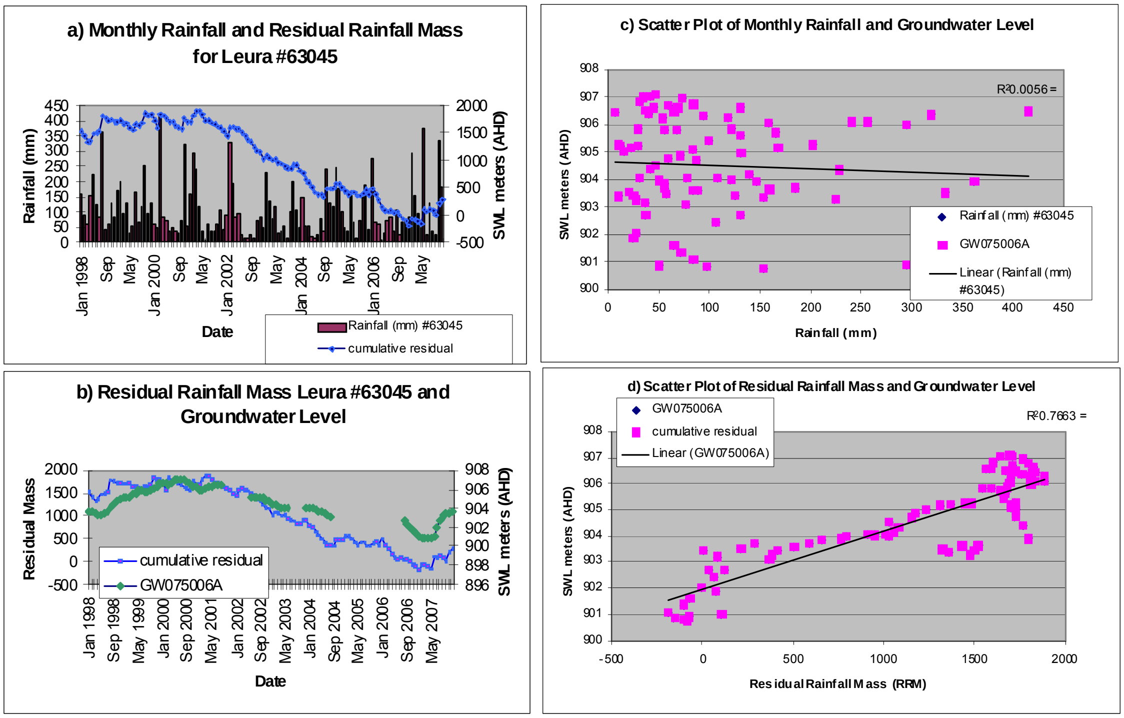


Figure 18 Correlation between monthly rainfall, residual mass curves and groundwater hydrographs for DWE monitoring bore in the Blue Mountains: (a) monthly rainfall and groundwater hydrograph; (b) residual mass and groundwater hydrograph; (c) scatter plot illustrating correlation of monthly rainfall and groundwater level; (d) scatter plot illustrating correlation of residual mass and groundwater level.

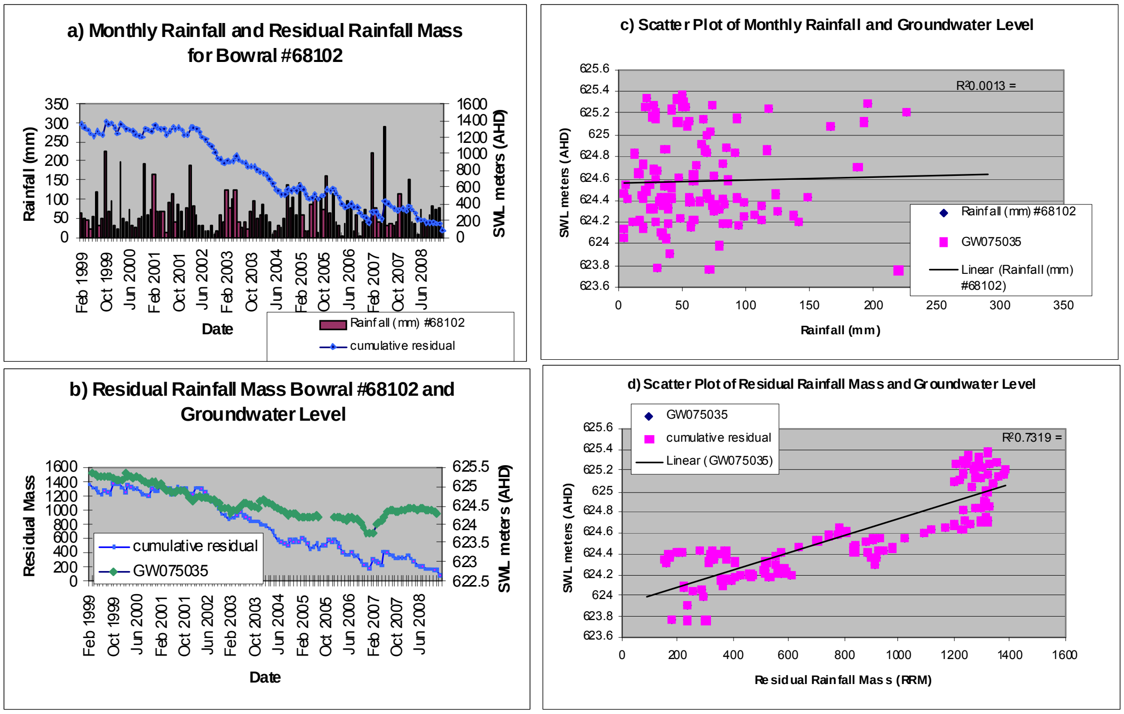


Figure 19 Correlation between monthly rainfall, residual mass curves and groundwater hydrographs for DWE monitoring bore in the Southern Highlands: (a) monthly rainfall and groundwater hydrograph; (b) residual mass and groundwater hydrograph; (c) scatter plot illustrating correlation of monthly rainfall and groundwater level; (d) scatter plot illustrating correlation of residual mass and groundwater level.

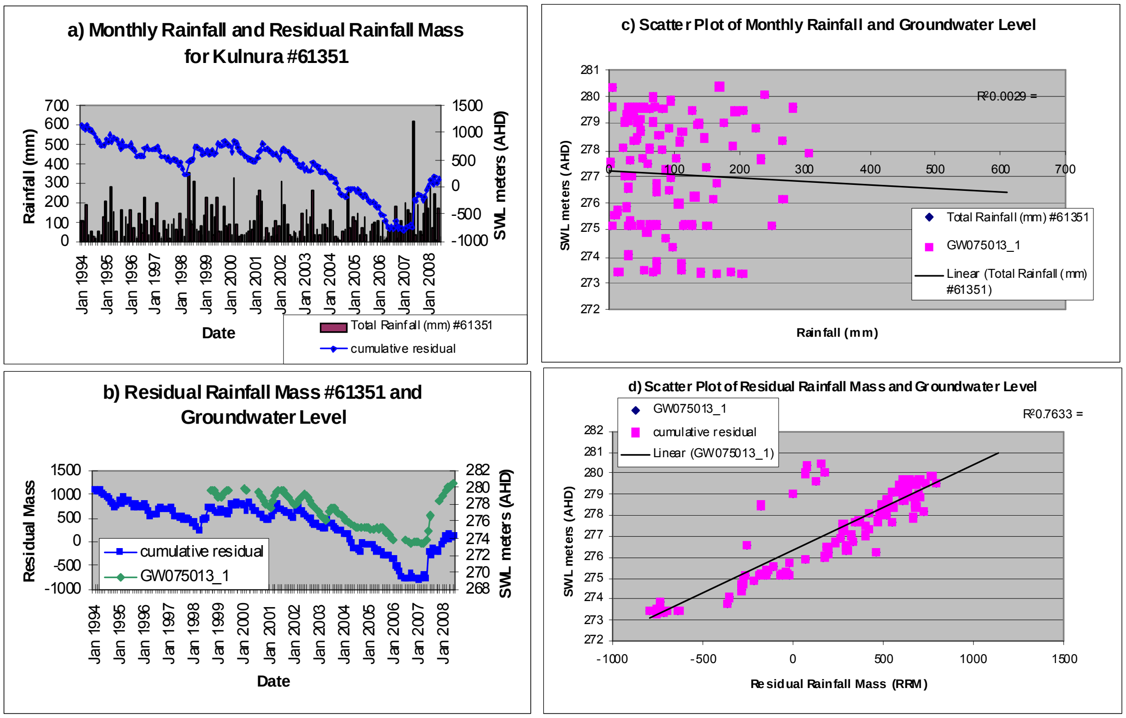


Figure 20 Correlation between monthly rainfall, residual mass curves and groundwater hydrographs for DWE monitoring bore on the Kulnura plateau: (a) monthly rainfall and groundwater

hydrograph; (b) residual mass and groundwater hydrograph; (c) scatter plot illustrating correlation of monthly rainfall and groundwater level; (d) scatter plot illustrating correlation of residual mass and groundwater level.

The isotopic work undertaken on groundwater in the sandstone units to date (discussed in the preceding section) indicates that groundwater stored within the shallow aquifer represents a mixing of water with different ages. Larger volumes of recharge occur when the above average rainfall climatic conditions (upwardly trending residual rainfall mass curves) predominate, as observed in the short section of the plot for the period during the late 1990s. As much of the sandstone exposure occurs as elevated plateaux, with deeply incised valleys and relatively rapid dispersion of surface water runoff, the mixing processes are not readily apparent. It is likely that recharge to shallow layers is a more gradual process, where weathered friable sandstone forms an unconfined aquifer that absorbs a significant component of the influent water. This weathered zone acts to temporarily store water during periods of a positive slope on the RRM curve, but it is also subject to depletion and drying out during periods of negative slope on the RRM curve. Water that is stored in this weathered zone can then gradually recharge to the deeper semi-confined aquifers over a longer period of weeks to months. This may in part explain the one- to three-month time lag between a rise in groundwater level and a change in the RRM curve from a flat or negative slope to a positive slope.

Sandstone strata characteristics

The generally horizontally layered Triassic sandstone strata exhibits specific characteristics related to local scale stress relief effects and broader scale deformation features. The sandstone strata are dual porosity aquifers (McKibbin & Smith 2000), with primary pore space porosity that is overprinted by secondary fracture or solution porosity.

On local scales, fracturing and bedding plane shearing occurs in association with the stress relief effect of valley bulging. In valleys incised into horizontally layered rocks, the removal of the confining rock mass through erosion allows upward vertical movement of the floor and shearing of the walls. Such local scale parting and fracturing is significant in improving the permeability of the porous sandstone units, as evidenced by drilling fluid losses and substantial inflows into excavations in valley locations (McNally, 1980).

Drilling by the SCA, in response to the recent severe drought, has identified areas highly prospective for groundwater of yields and quality suitable for raw water to contribute to the water supply for Sydney. Whilst deep seated regional deformation generated much of the disturbed terrain in the area of the drilling investigations, much of the resultant faulting occurs on more intermediate scales (Lee, 2000). These, together with radial displacement fracturing generated by intrusive bodies have made this area an attractive target for the SCA investigative water supply drilling in the Southern Highlands within what is proposed to be called the Kangaloon Structural Corridor (T. Mount, DWE, *pers. comm.*). The overprinting by fractures and jointing in this area introduces a complexity that can enhance recharge and improve bore yields from less than 5 litres per second (L/s) in areas where groundwater is sourced solely from porous sandstone, to up to 40 L/s where dual porosity conditions exist.

The effect of secondary influences on the permeability of the Triassic sandstone strata (demonstrating the effects of dual porosity conditions) is apparent when published information is considered (Table 1). Massive units typically exhibit permeabilities two orders of magnitude less than the same fractured strata. Detailed investigations in the Upper Nepean catchment identified similar ranges (i.e. two orders of magnitude) in the permeability of sandstone strata, where values were found to be generally between 5.7 x 10^{-7} to 1.7 x 10^{-5} metres per second (m/s). Such permeability estimates have been derived from transmissivity values at localities where porous and fractured strata (typically 5 to 150 m^2 per day; m^2/d) were obtained from the analysed results of controlled pumping tests. An assumed aquifer saturated thickness of 100 m was used (J. Ross, SCA, *pers. comm.*). Highly fractured target areas exhibit transmissivity values in the upper part of this range (50 to 150 m^2/d), equivalent to 5.8 x 10^{-6} to 1.7 x 10^{-5} m/s.

Table 10 Reported permeability values for Triassic sandstone strata in the Sydney region

Strata	Characteristic	Location	Permeability (m/s)	Reference source
Hawkesbury Sandstone	Fractured	Wolli Creek	7.5 x 10^{-6}	Hatley (2004)
Hawkesbury Sandstone	Massive	Lane Cove area	2 x 10^{-8}	Tammetta & Hewitt (2004)
Narrabeen Group sandstone	Massive	Not indicated	2 x 10^{-9} to 3.9 x 10^{-7}	Beavis (1985)

The characteristics of the Triassic sandstone units dominate this discussion, as they form the main target aquifers of that age in the Sydney Basin, and consequently are the focus of monitoring and hydrogeological studies. Groundwater within these units is sourced from vertically discrete horizontally oriented layers. Typically three or four such water bearing zones are intersected during the drilling of water supply bores at depths ranging from around 20 or 30 m below ground level (bgl), to 150 or 180 m bgl. Few bores are drilled to depths beyond 200 m due mainly to the expense involved. Estimated bore yields for the Triassic sandstone units vary significantly from less than 0.3 L/s, to more than 40 L/s. The bore yield distribution (Fig. 5) exhibits a correlation with major structural features and also reflects the confining effects of significant masses of overburden, particularly in the western Sydney area.

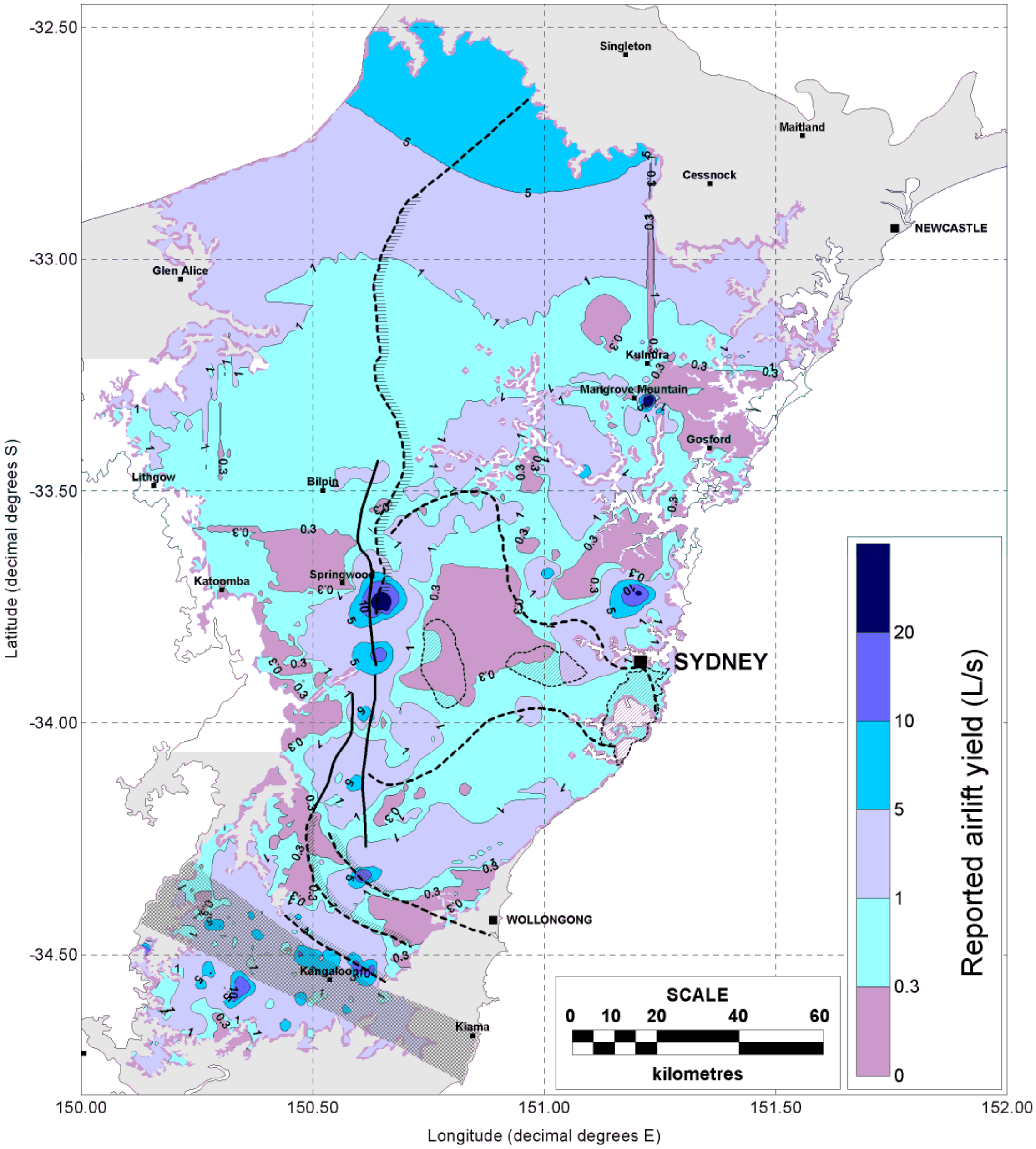


Figure 21 Estimated bore yield distribution for the Triassic sandstone units of the Sydney Basin (structural features as for Figure 1)

The groundwater salinity distribution (Fig. 6) from the sandstone units illustrates the presence of a centrally-located accumulation of saline water existing beneath the Cumberland Basin. This corresponds to a conceptual model where groundwater flows radially inward from elevated recharge areas around the fringes of the downwarped region and then is constrained by a limited number of discharge locations. Such constraint reduces the opportunity for flushing of accumulated salts to occur, and, coupled with increasing residence times and possible contributions from the overlying shale unit, results in elevated salinities (exceeding 3,000 milligrams per litre, mg/L, within the downwarped region) generally in the groundwater within the sandstone. There is limited evidence on which to conclude where discharge locations may occur, however it is inferred that some outflow from the sandstone must occur due to the head pressures observed throughout suburban Sydney.

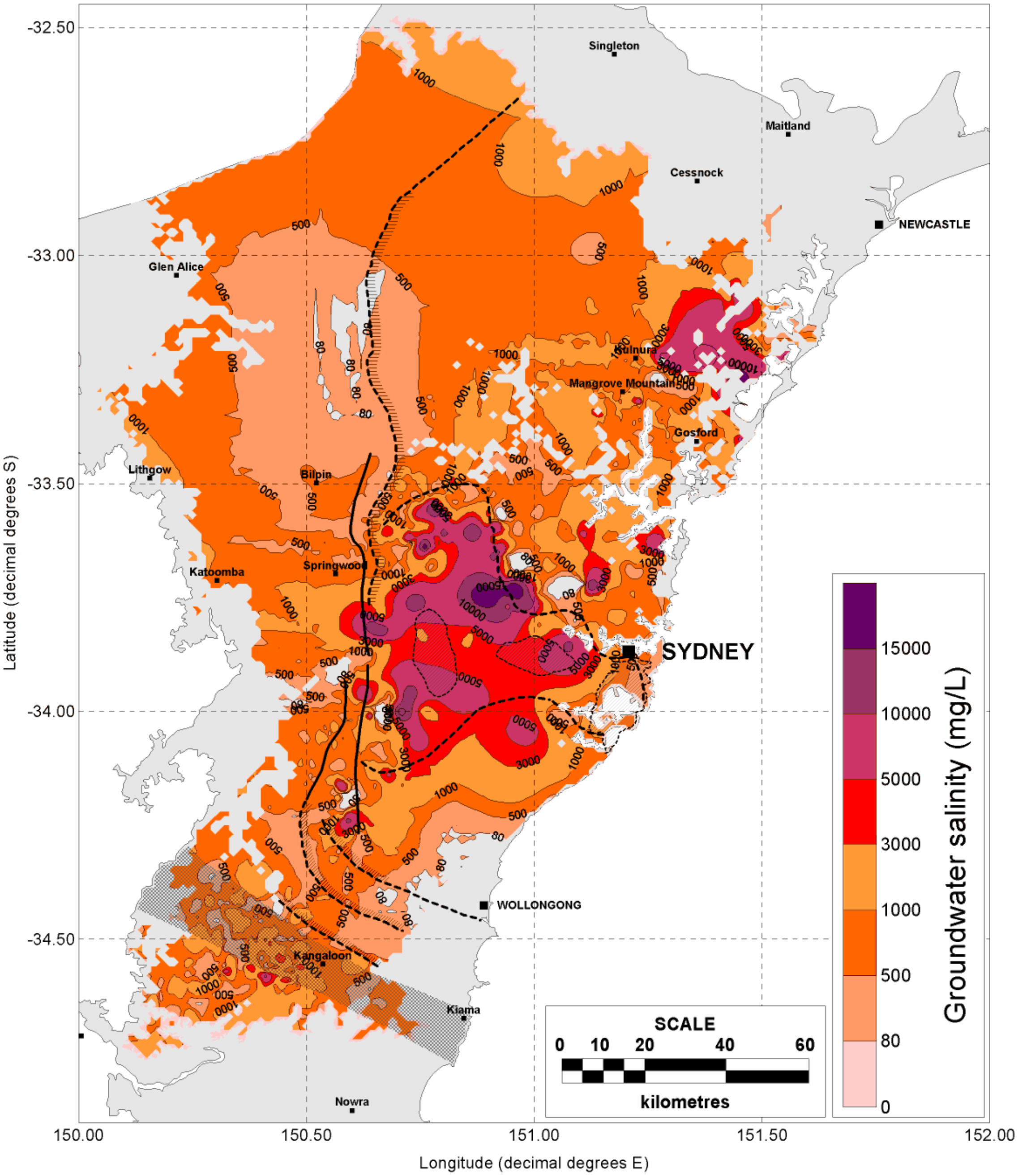


Figure 22 Groundwater salinity measurement distribution for the Triassic sandstone units of the Sydney Basin (structural features as for Figure 1)

Many of the bores installed through the Wianamatta Group shale strata and into the underlying sandstone exhibit pressure heads that commonly rise to within 20 or 30 m of the ground level. Were there to be no discharge from the underlying sandstone strata external to the landward part of the basin, it is to be expected that artesian flow conditions would rapidly be generated and be commonly observed. In fact, the existence of artesian groundwater conditions within the sandstone units is only known by the authors to occur at a few favourable locations, predominantly at the base of significant topographic relief. For example, recent drilling by DWE (described elsewhere in this volume by Green, *et. al*.) at the base of the Lapstone Structural Complex at Emu Heights resulted in the installation of an artesian bore with a pressure head approximately 3 m above ground level. It is therefore postulated that some outflow from the deeper confined sandstone strata must occur, however the location of the discharge locations has not yet been identified.

It is apparent from the mapping presented above that the Triassic sandstone strata of the Sydney Basin are significant target aquifers throughout most of the region. The groundwater is generally of good quality, apart from the central downwarped part, and may be suitable for most purposes. However, yields tend to be variable and may not be sufficient for a particular intended purpose. Areas of enhanced bore yields (permeability) have been generally identified, and, where the interest in groundwater as an alternative supply has accelerated, such as in the Southern Highlands, embargoes have been established to manage the demand. Also, due to the dependence of many environmental features on groundwater discharge, particularly in National Parks and areas of World Heritage significance, controls have been established to limit further growth in development and prevent adverse ecosystem impacts. Elsewhere, these units remain a potential water supply option and are often worthy of more detailed investigation.

Shale strata characteristics

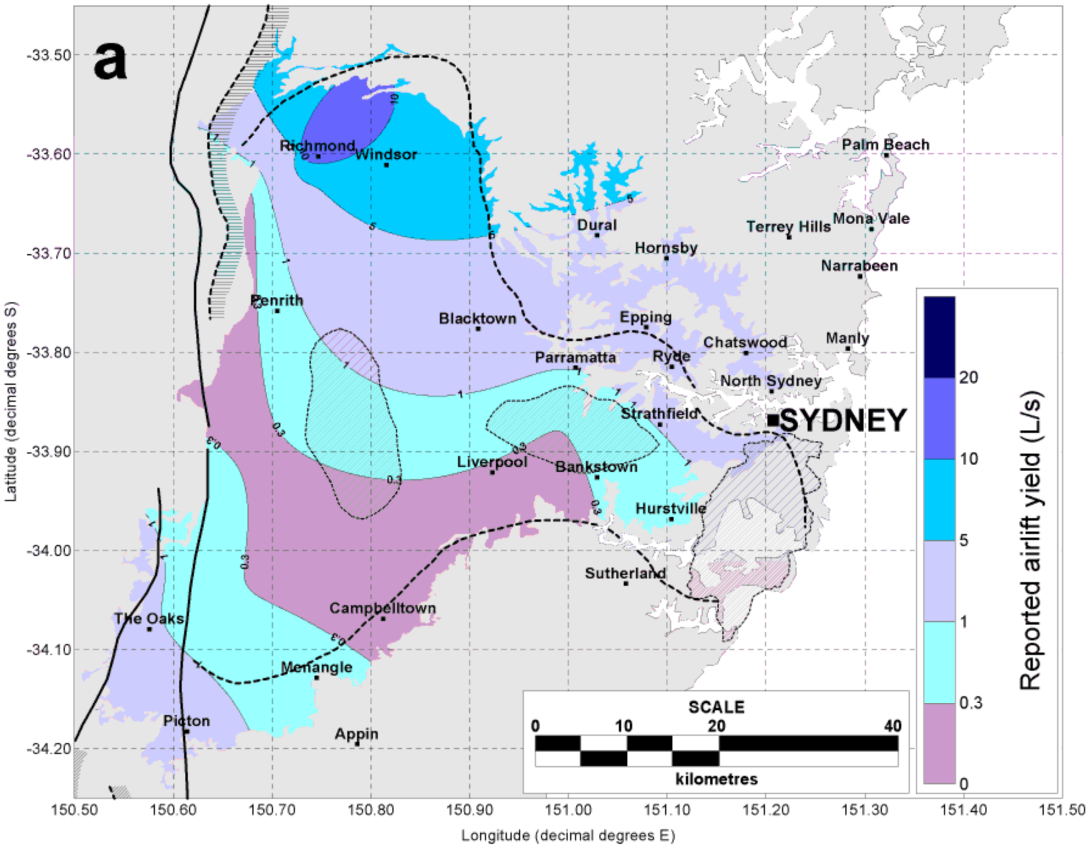
The dearth of data for the Wianamatta Group shale unit is a reflection of the generally poor groundwater availability and quality within this aquitard. Most of the information on the Groundwater Data System relating to bores intersecting only the shale units predates the 1980s, before advances in drilling technology allowed deeper investigations. As such, most yield and salinity data is descriptive, rather than measured, and has had to be interpreted in order to allow mapping to occur.

The shale units have had little investigative work conducted into the recharge and permeability of the strata as a whole, with only limited studies having been undertaken into the near-surface parts exposed in brick pits and quarries, mostly in the western Sydney area. In contrast to the sandstone strata, reported permeability values for the shale units (Table 2) indicate a considerably greater range (up to seven orders of magnitude) that is inferred to result from the variability in both bedding plane parting and secondary fracturing. The aforementioned drilling by DWE, this time at Glenmore Park (near Penrith), encountered dry conditions within the shale strata in two of three holes, and intersected moderate volumes of saline groundwater in the third.

Table 11 Reported permeability values for Triassic shale strata in the Sydney region

Strata	Characteristic	Location	Permeability (m/s)	Reference source
Wianamatta Group shale	Fractured	Merrylands	1 x 10^{-8} to 1 x 10^{-6}	McNally & Branagan (1998)
Wianamatta Group shale	Massive	Not indicated	1 x 10^{-12} to 2 x 10^{-5}	McNally (2004)

The estimated bore yield distribution (Fig. 7) for the Wianamatta Group in the western Sydney and Southern Highlands areas respectively, demonstrate local to intermediate scale enhancement of permeability in isolated parts. These areas of enhanced yield are likely to represent localities where fracturing of the shale is more pronounced. However, due to the limited data available on which to base any specific conclusions, in particular for the western Sydney exposure, these could be artefacts of poorly completed bore records or erroneous entries into the database.



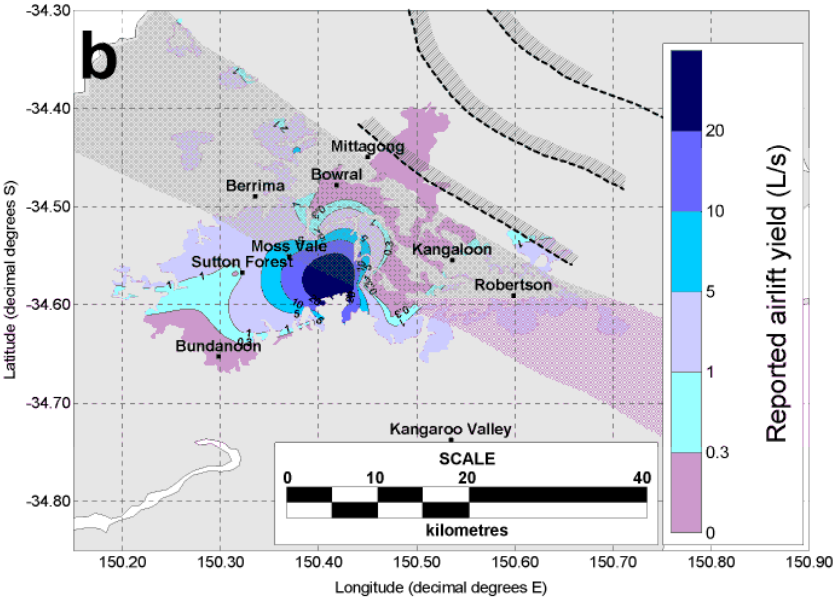


Figure 23 Estimated bore yield distribution for the Triassic shale strata in (a) western Sydney and (b) Southern Highlands (structural features as for Figure 1)

Notable differences exist between groundwater salinity distributions for the Wianamatta Group strata in the western Sydney area and in the Southern Highlands (Fig. 8). In particular, the salinity of groundwater in the Southern Highlands is generally considerably less (typically <3,000 mg/L) than that in the western Sydney area (mainly >5,000 mg/L). This is presumed to be related to the topographic elevation of the former due to regional and intermediate deformation and uplift leading to the subsequent flushing of accumulated salts from the rock matrix. It is worth noting that the only other attempt to broadly define groundwater salinity within the shale strata of western Sydney (Old, 1942) identified values up to 24,000 mg/L (1,700 grains per gallon equivalent), however that author's study included samples taken from shallow wells and creek ponds that may have been influenced by evaporative concentration.

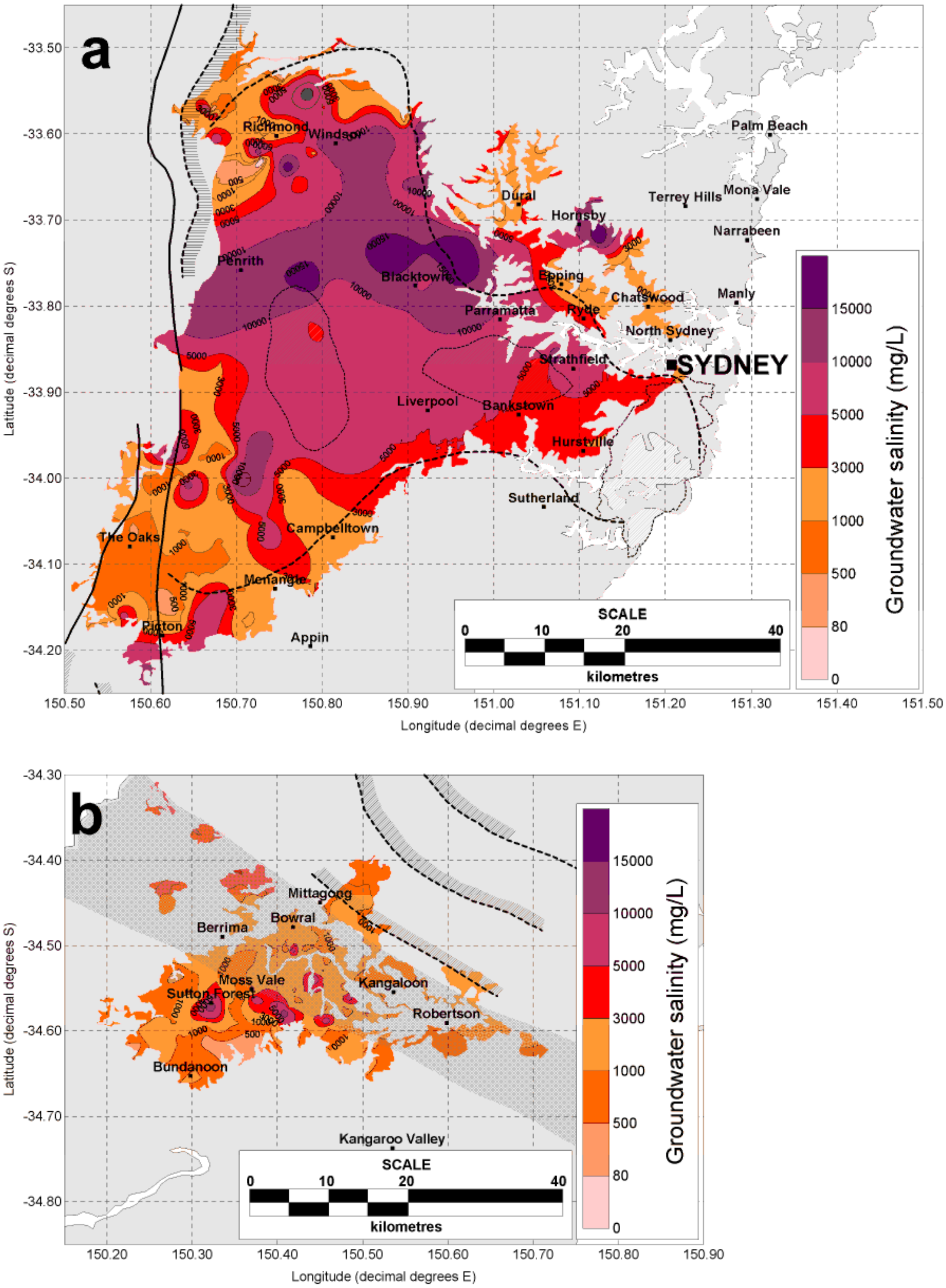


Figure 24 Inferred groundwater salinity distribution for the Triassic shale strata in (a) western Sydney and (b) Southern Highlands (structural features as for Figure 1)

The Triassic shale strata of the Sydney Basin do not typically represent targets for water supply, due to the lack of water bearing zones in many cases or, when encountered during drilling, the generally very low yields and highly saline groundwater. As a result, the units have very low potential as a water supply and the high cost of drilling investigations required to prove up a resource is not generally considered cost effective, particularly when a more reliable sandstone target may exist at deeper levels or in adjacent areas. In fact there is an overriding requirement on holes drilled through the shale sequence into the underlying sandstone units to construct the bore with a design that prevents inflow of saline water thus protecting the deeper groundwater resources. This is only successfully achieved through the application of pressure cementing techniques that isolate the hole from the shale strata.

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Use of Isotopic and Chemical Tracers to Determine Water Flow Pathways in a Small Agricultural Catchment during a Rain Event

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Abstract

Isotopic and chemical tracers were used to understand flow pathways in a small agricultural catchment at the headwaters of, Kellys Ck in the Southern Highlands of NSW, Australia. Sampling was conducted prior to and during a rain event in June 2008. Stream, rain, shallow groundwater, spring and dam waters were collected and analysed. Dissolved organic carbon, ^{222}Rn, δ^2H, δ^{18}O, nutrients and major ions were measured for use in hydrograph separations and for hydrogeochemical analysis.

Both two component and three component hydrograph separations, using δ^2H, δ^{18}O and Cl^-, were conducted to identify the sources of storm flow. Although the hydrograph separations differ slightly in terms of which component contributes the majority of flow, it was found that a significant proportion of the stormflow was event water, sourced from precipitation runoff. Three component hydrograph separations also identified farm dams as important contributors to stormflow during the event. Pre-event or shallow groundwater was found to have a lower contribution to stormflow, but was dominant during the first flush and gradually increased post event. Low deuterium excess was a useful tool to distinguish evaporated pre-event waters (e.g. dam or stream water) from event waters.

Keywords: Hydrograph separation, stable isotopes, deuterium, oxygen-18, water flowpaths

Introduction

Hydrograph separation techniques are used to identify the components of stream flow during and after a rain event. These techniques involve solving isotopic and/or chemical tracer mass balance equations for a catchment's storm water runoff (event water) and water already within the catchment, in soils or groundwater (pre-event water) (Burns *et al*, 2001). These components are often referred to as end members (Brown *et al*, 1999). Several assumptions are required for this technique when using isotopic tracers; that there is a significant difference between isotopic content of event and pre-event components; the isotope signature of event and pre-event components is constant in time and space or variations are otherwise accounted for; contributions from the vadose zone are negligible, or isotope content of soil water is similar to groundwater; and contributions from surface storages are negligible (Buttle, 1994; Genereux and Hooper, 1998).

Hydrograph separations have been undertaken in many studies of small to medium sized, and mostly forested catchments (Buttle, 1994; Genereux and Hooper, 1998), the majority indicating that pre-event water supplies at least 50% of streamflow at peak discharge (Buttle, 1994). Much lower pre-event water contributions have been found for studies in Mediterranean agricultural catchments (Ribolzi *et al*, 2000, Marc *et al*, 2001). There is no agreement as to how pre-event water is exported from drainage basins in storm events (Buttle, 1994). The mechanisms by which catchments store water and rapidly release during rain events are still not well understood.

This study aimed to determine the contribution of event and pre-event waters to the streamflow in a small agricultural catchment and, more specifically, the contribution of shallow subsurface flow (through the soil), overland flow (runoff) and groundwater discharge as potential pathways for the transport of water and contaminants into the creek. The role of farm dams, which store both runoff and spring water, in the generation of stormflow in the catchment, was investigated. The use of farm dams as an end-member in a hydrograph separation was attempted even though standard hydrograph separations assume no surface storage.

Study Area

The study was conducted in a 128 ha agricultural catchment at the headwaters of Kellys Creek at Avoca in the New South Wales Southern Highlands, 100 km south west of Sydney, Australia. The site location and selected sampling sites are shown in Fig. 1. The catchment is a cattle grazing area with clay soils overlying shale and basalt. Farm dams intercept approximately 59% of the catchment. Springs occur throughout the catchment and in some cases dams are spring fed and their overflow contributes to baseflow even during dry periods. Kellys Creek is a tributary of the Wingecarribee River which flows into Warragamba Dam, the main water supply for Sydney. Nutrients are a critical factor in water quality in the Warragamba Dam catchment and high nutrient loadings in streams and rivers have previously led to toxic algal blooms in the dam.

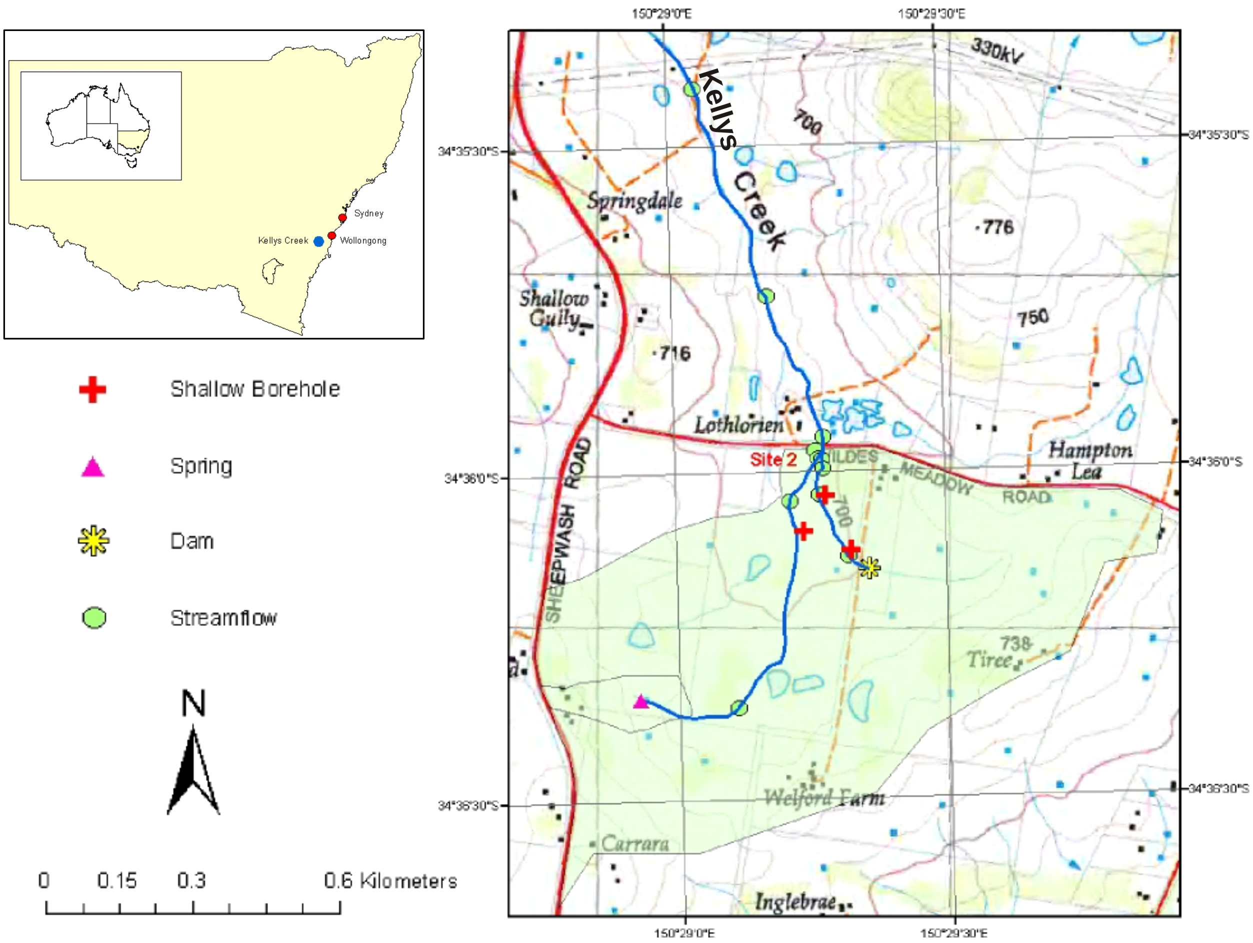

Figure 1 Location of Kellys Creek study site and selected sampling locations, NSW, Australia.

Methods

Rainfall, stream, shallow groundwater, spring and dam samples were collected during baseflow (pre-event), flow event and post event periods around a four day rainfall event in June 2008. All samples were analysed for δ^2H and $\delta^{18}O$, and terrestrial (non-rainfall) samples were also analysed for ^{222}Rn, dissolved organic carbon (DOC), nutrients (total nitrogen and phosphorus) and major ions.

Rainfall amount was measured using a tipping bucket and manual rain gauges. Rainfall was collected in a composite vessel for four months prior to the focal rain event, with collection occurring after rain events. Stream discharge was determined at the base of the catchment where a gauging site with pressure sensor and rating curve (Site 2, Fig. 1) had previously been established as part of an overarching nutrient study.

Hydrograph separations were conducted to examine the contribution of event water (precipitation in the catchment), stored dam water and other pre-event water (shallow groundwater or stream water) to streamflow for a nine day period encompassing the rain event. Two and three component hydrograph separations were completed using mass balance equations (Hinton *et al*, 1994) to identify the sources of storm flow. Mixing diagrams (Inamder and Mitchell, 2006) were used to identify suitable tracers for the hydrograph separations and to ensure there was sufficient difference in tracer concentrations between the components of streamflow (end members).

Results and Discussion

Baseflow and end member definition

During baseflow conditions the flow rate was ~0.01 m^3/s. Two weeks prior to the rain event ^{222}Rn was elevated in one of two main tributaries in the catchment suggesting a zone of groundwater input. Shallow groundwater ^{222}Rn was ~55 kBq/m^3 pre and post-event. Pre-event groundwater and streamwater had very similar stable water isotope values with mean±SD of δ^2H=-29.10±0.81 ‰ and $\delta^{18}O$=-5.46±0.09 ‰ (stream water n=7) and δ^2H=-29.48±1.35 ‰ and $\delta^{18}O$=-5.43±0.28 ‰ (groundwater n=3) (Fig. 2), suggesting that pre-event stream flow (baseflow) is primarily sourced from shallow groundwater. Spring waters were more depleted in both δ^2H and $\delta^{18}O$ than streamflow and were quite variable. Two dams sampled in the catchment showed an evaporated isotopic signature with low deuterium excess ($d=\delta^2H-8\delta^{18}O$) and the spring source of Dam 1 water is clearly reflected in the stable isotope data. The pre-event average rainfall (p=248 mm) isotope value for the region for four months prior to the event was δ^2H=-31.6 ‰ and $\delta^{18}O$=-5.94 ‰, slightly more depleted than the pre-event waters.

Major ion chemistry indicates that waters in the Kelly's Creek catchment are of Na-Cl type. Pre-event stream waters and groundwater had average chloride values of 16 mg/L (n=2) and 15 mg/L (n=2) respectively. Pre-event dam chloride was estimated using data collected during dry periods before and after the event, to average 22 mg/L (n=8), largely due to elevated levels in some spring-fed dams. Dissolved organic carbon (DOC) in pre-event streamflow, groundwater and dam water ranged from 2-4 mg/L.

Event waters

The precipitation and stream flow and δ^2H hydrographs are shown in Fig. 3. Rainfall during this period totalled 97 mm and occurred in a number of pulses over a 4 day period. Following an initial wetting up period (❶ in Fig. 3) where little runoff was observed, stormflow generally increased quickly in response to rainfall, indicating a fast response time in the catchment. The ratio of discharge to rainfall increased throughout the period as indicated by an increase in the peak discharge with respect to rainfall intensity from ❷ to ❹ (Fig. 3). These observations suggest that surface runoff is a dominant factor in the hydrology of the area. The increase in catchment response to new rainfall as the period progresses indicates that soil and dam storage, which initially formed a buffer to store rainfall and runoff, gradually fill up and those parts of the catchment begin to contribute to discharge. As an example, the peak flow on the June 6 (❹), which had a larger runoff ratio than the previous peaks, can be explained by the filling and subsequent discharge from largest dam in the catchment (Dam 2 shown in Fig. 1).

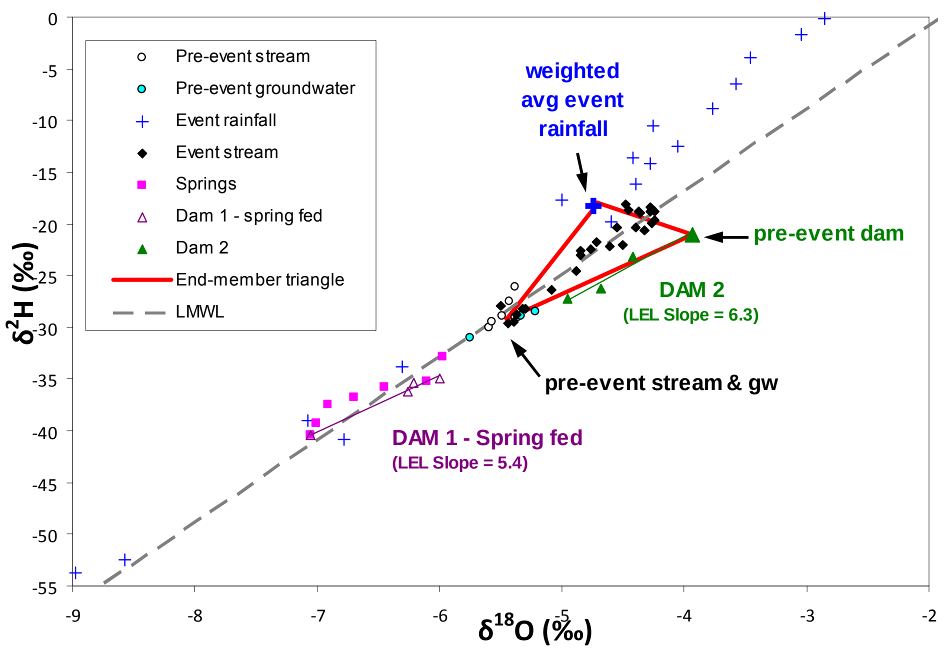

Figure 2 Stable water isotope values (δ^{18}O‰ and δ^2H‰) in event water, pre-event water and potential end members for Kellys Creek catchment. In the absence of a long time series for rainfall in the southern highlands, the local meteoric water line (LMWL) is estimated as $\delta^2H=8\delta^{18}O+15.24$‰ adopting the global meteoric water line slope of 8 and using the average d-excess of the springs and groundwater, which are the best available 'records' of longer term precipitation, as the intercept.

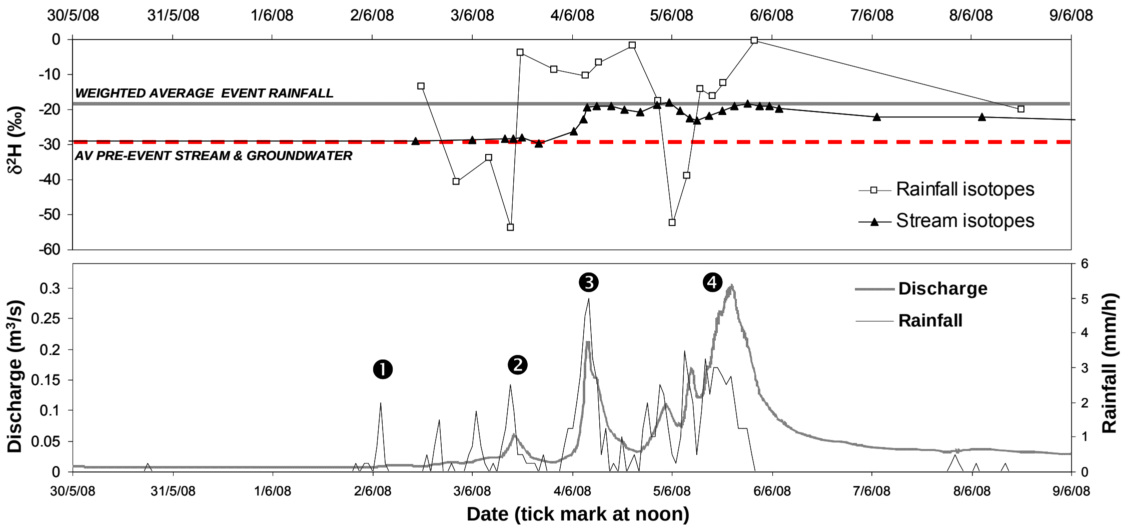

Figure 3 Streamflow, rainfall intensity and stable isotope hydrograph for Kellys Ck Site 2, 30/5/08 to 9/6/08.

Stable isotope values for June 2008 rainfall were highly variable, ranging from -0.21 ‰ to -53.71 ‰ for δ^2H, and from -2.85 ‰ to -8.98 ‰ for δ^{18}O, with a weighted average of $\delta^2H=-18.0$ ‰ and $\delta^{18}O=-4.81$ ‰ (n=17)(Figs 1 & 2). This variability is not uncommon, especially in storm events that have large rain amounts and long event periods (Genereux and Hooper, 1998). Event stream isotope values ranged from

-18.05 ‰ to -29.57 ‰ for δ^2H, and from -4.24 ‰ to -5.50 ‰ (n=30), varying within the range bounded by the pre-event water and the weighted average event rainfall (Fig. 3). Event chloride data was lower than pre-event values averaging ~17 mg/L (n=26) for streamflow and ranging from 1-2 mg/L for rainfall (n=4). DOC was not measured in rainfall, however, event stream DOC ranged from 4-12 mg/L (n=28). Stream nutrient concentrations ranged from 0.08-0.8 mg/L for total N and 0.005-0.08 mg/L for total P (n=19). Groundwater and dam water were not sampled during the event.

Hydrograph separation

Stable isotopes δ^2H and δ^{18}O, chloride, DOC and ^{222}Rn were considered as potential tracers in the hydrograph separation. Although DOC has been used successfully as a tracer in hydrograph separations (Ladouche *et al*, 2001, and Inamder and Mitchell, 2006), in this study event water DOC was higher than any measured source term indicating that the source term (potentially the streambed or shallow soilwater) was not identified, therefore it could not be used in the hydrograph separation. Although measured, ^{222}Rn was also not used in the hydrograph separation because of the difficulty of accounting for degassing, decay, and exchange in the hyporheic zone. Therefore δ^2H, δ^{18}O and chloride were found to be most suitable for use in a hydrograph separation for the June 2008 rain event at Kellys Creek. In this study a two component hydrograph separation using δ^2H found that event water contributed 84% of stormflow discharge. However, as the dam δ^2H signature was similar to that of the rainwater this value would include dam water, therefore an additional tracer was required to separate the dam contribution in a three component hydrograph separation.

Mixing diagrams were used to determine the viability of using any combination of δ^{18}O, δ^2H and chloride as tracers in a three component separation, by assessing whether the formed ‘end member’ triangle (e.g. Fig. 2) encloses the stream samples (Inamder and Mitchell, 2006). For both δ^{18}O/Cl^- and δ^{18}O/δ^2H the majority of stream samples are enclosed, although several samples are outside and these may introduce error to the mass balance. δ^2H/Cl^- was not suitable as too many samples were outside the triangle.

Due to the high variability of the rainfall isotopic signature throughout the rain event cumulative weighted mean values, using volume or intensity of rain fallen (McDonnell *et al*, 1990) were compared. Minimal difference was found between the two methods so results in this paper are for volume weighted means.

Three component hydrograph separations using δ^{18}O/δ^2H (Fig. 4a) and δ^{18}O/Cl^- (Fig. 4b) were conducted. The δ^{18}O/δ^2H hydrograph separation found event water was the primary contributor (51.1 %) to stormflow, followed by the dam component (37.3 %), with pre-event water contributing the lowest percentage (11.6 %). Alternatively, the δ^{18}O/Cl^- hydrograph separation, found a lower event water contribution (31.7 %), with the almost half the discharge being sourced from dams (48.1 %), followed by pre-event water (20.2 %).

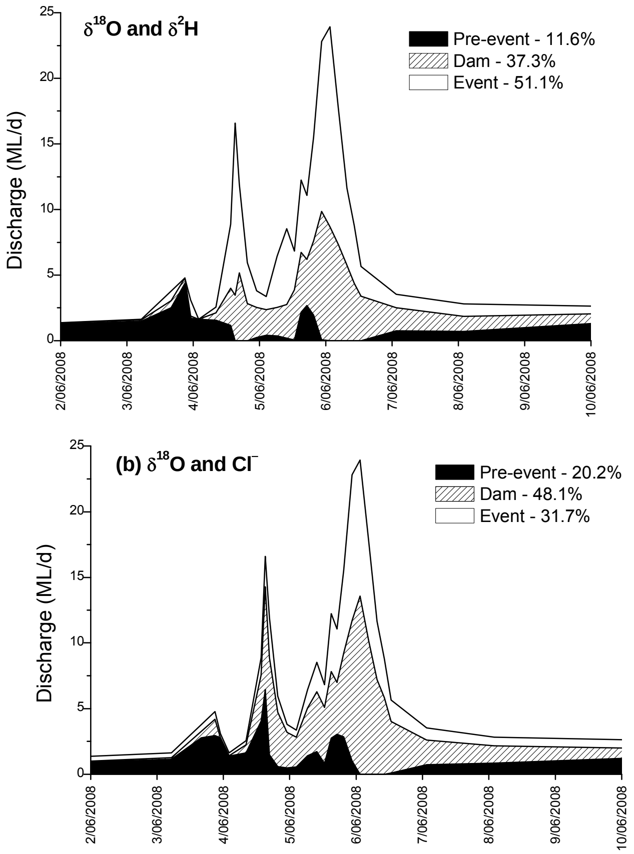

Figure 4 Three component hydrograph separation using (a) δ^{18}O and δ^{2}H; and (b) δ^{18}O and chloride. Percent contributions of each end-member to streamflow are given in the legend.

Both hydrograph separations show the largest contributions of event water at the peak event flow (Peak❹, Fig. 3) and the largest contribution from pre-event water at Peak❷, (Fig. 3) for both separations. Minimal contribution by pre-event water occurred throughout the event, with a gradual increase in the contribution, approaching pre-event levels, following the event (Fig. 4). Substantial contributions from the dam component were found for both separations, with differences of ~10%.

Soil water was not sampled in this study, and may potentially have a similar evaporated signature to the dam water, rendering uncertainty as to whether soil water was a significant contributor to storm flow. This could explain 'dam' contributions at the start of the event, prior to any likely dam discharge into the stream. Dam leakage may also explain this finding.

As the Kellys Creek catchment is an agricultural catchment with compacted soils, less vegetation than forested catchments and fewer root channels in the soil, it was expected that less subsurface flow would take place with a higher event water contribution to stormflow. This was confirmed in this study.

The highest concentrations of nutrients (TP and TN) were found at the beginning of the event, indicating a first flush response in the catchment. Following the first flush, nutrient levels were found to increase with discharge during the event, decreasing to original concentrations after approximately two weeks. No clear correlation between discharge and nutrients was found. As the shallow ground water appears to be the main contributor to baseflow (based on stable isotope data), where nutrient concentrations are low, it may be speculated that the major source of exported nutrients is via the event water flow pathway, i.e., along the catchment's surface, or through the shallow subsurface.

Conclusions

Two and three component hydrograph separations have been conducted, using several tracers (δ^2H, δ^{18}O, and chloride), that incorporate surface and subsurface waters and highly variable isotopic rainfall signatures. Although the hydrograph separations differ slightly in terms of which component contributes the majority of flow, it was found that a significant amount of the stormflow was event water, sourced from runoff of event precipitation. Three component hydrograph separations also identified farm dams as important contributors to stormflow during the event. Whilst shallow groundwater, the main contributor to baseflow, was found to have minimal contribution to stormflow, it was dominant during the first flush and gradually increased post event. Low deuterium excess was a useful tool to distinguish stored pre-event waters (i.e. dam or soil water) from event waters.

Nutrient (TP and TN) analysis indicated a first flush response in the Kellys Creek catchment with no strong correlation between discharge and nutrients. It may be speculated that the major source of exported nutrients is via the event water flow pathway, i.e., along the catchment's surface, as baseflow and shallow groundwater have low nutrient concentrations.

Further modelling of the Kellys Creek data is to be undertaken, including transit time distribution modelling, to improve the handling of the highly variable rainfall isotope input.

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Studies of near-surface hydrology and hydrogeology of the Woronora Plateau

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Abstract

At the southern margin of the Sydney Basin, the Woronora Plateau includes 8% of Sydney's water catchment area in productive near-coastal catchments of man-made Lakes Woronora, Cataract, Cordeaux, Avon and Nepean. The terrain is almost exclusively Triassic Hawkesbury Sandstone, exhibiting similar topography throughout and vegetation types from common upland swamps to dry sclerophyll forest on slopes with pockets of rainforest in gorges. Hydrographic monitoring and hydrologic modelling of two sub-catchments suggested that the Plateau hydrology is significantly influenced by widespread hillslope aquifers storing a surprising amount of water. Conceptual modelling suggested a typical mean unconfined storativity around 0.05 and horizontal hydraulic conductivity in the $10^{-7} – 10^{-6}$ m/s range. A comprehensive review of long term 36-year dam hydrographic records for the Cataract, Cordeaux, Avon and Nepean catchments and published papers on hydrographic records of other regional coastal catchments outcropped by Triassic and Permian sandstones was made. Statistical ranges for annual evapotranspiration (ET) for all catchments were then compared with predictions for each made with a widely-used algorithm for predicting annual ET of catchments (with no significant loss to deep storage) from annual precipitation and major catchment vegetation type distribution. That comparison strongly suggested a significant fraction of Plateau annual infiltration passes in most years to depths below 2 – 5 m too rapidly to be subject to ET processes. It was concluded that it is that component of infiltration which largely recharges hillslope aquifers. Packer-based measurements of horizontal hydraulic conductivity in a number of shallow boreholes within a large slope in one such catchment confirmed conductivity does typically lie in the $10^{-7} – 10^{-6}$ m/s range. Tritium measurements on local rainfall, groundwater in Hawkesbury Sandstone, water in a draining stream and two lakes confirmed a significant fraction of the water entering the lakes is comprised of water which has had a significant residence time in hillslope aquifers in weathered bedrock.

Keywords: Woronora Plateau, hydrology, hillslope aquifers.

Hydrologic Studies

Two sub-catchments on the Woronora Plateau, Native Dog Creek which flows into eastern Lake Avon, and Donald's Castle Creek which flows into Cordeaux River (below Cordeaux Dam) were monitored hydrographically for periods over several years. Flow monitoring was conducted using Unidata STARFLOW ultrasonic Doppler flow probes dyna-bolted to gauged natural cross sections in sandstone bedrock of the creek beds and these were connected to bank-mounted solar-powered data loggers (Ecoengineers Pty Ltd. 2006). The flow data and local rainfall data was used in hydrologic modelling to elucidate the major features of the hydrology of these sub-catchments. Fig. 1 below shows a locality plan of these catchments, and other locations discussed herein.

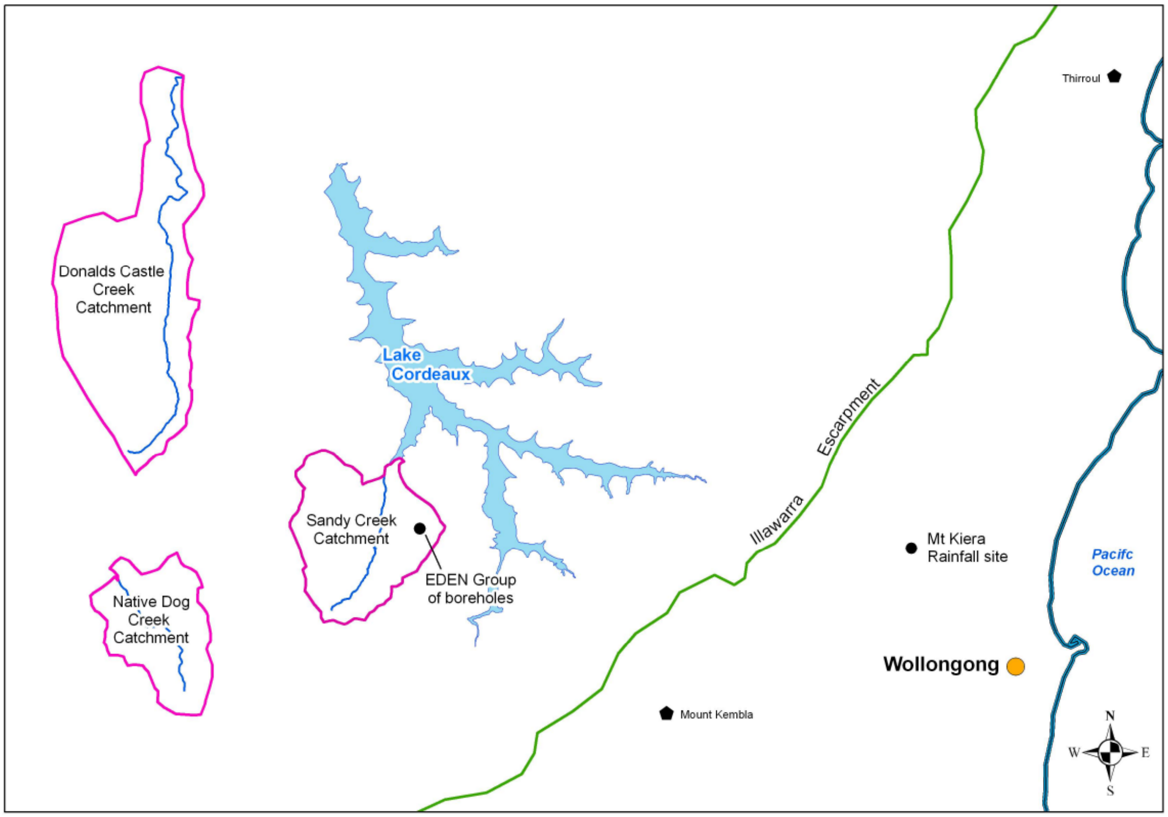
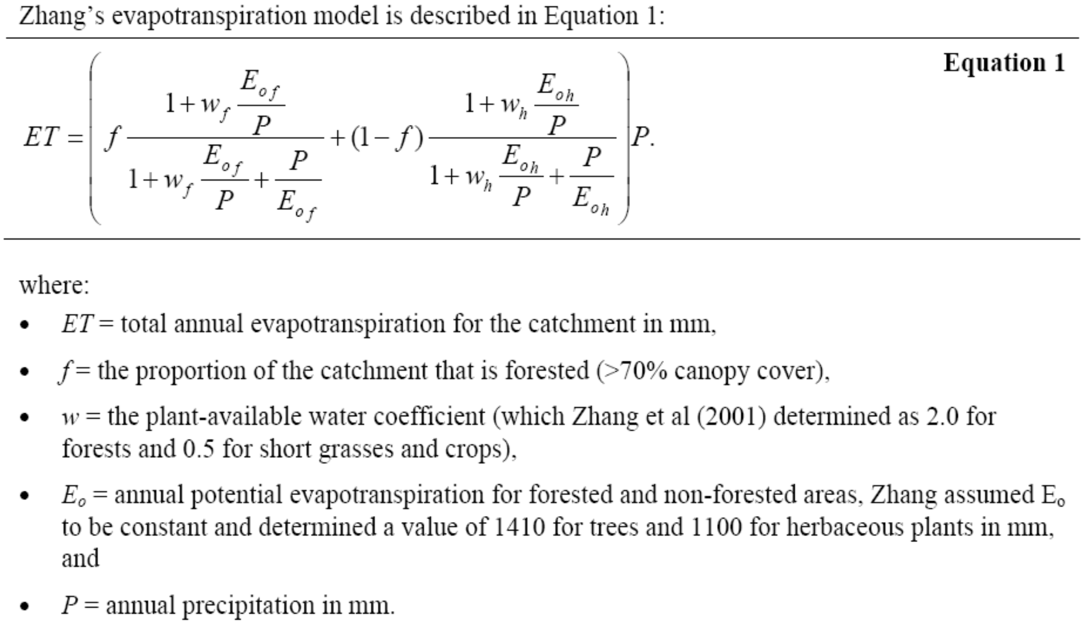


Figure 1 Locality Plan showing catchments studied and Mt. Keira tritium-monitoring rainfall site

Macro-catchment water balances and critical role of evapotranspiration

As well as the usual tests for goodness of fit, to operate any hydrologic model in such a way that it produces an accurate water balance, it is necessary to estimate beforehand, with reasonable precision, at least mean daily evapotranspiration (ET) that would have operated over the gauging/modelling periods and to ensure model outcomes are consistent with that. As ET is often the closure term in making a catchment water balance, we closely reviewed how ET operates in the relatively pristine areas of the Woronora Plateau. We carefully reviewed previously published studies of long term rainfall and flow gauging of macro-catchments on the Plateau (i.e. Lakes Avon, Cordeaux, Cataract and Nepean) and of similar NSW coastal Triassic and Permian sandstone-based catchments of comparable size and annual rainfall (Mongarlowe, Corang, Endrick, and Kangaroo Rivers) (Baki 1993, Boyd and Baki 1998, Thyer and Kuczera 2000), in order to establish long terms means and typical ranges of variability of annual precipitations, gauged catchment outflows and ET.

These ranges of annual rainfall and ET were then assessed against the findings of Zhang et al. (2001) who had studied over 250 catchments worldwide, of which 96 were within Australia, covering a wide range of soil and climate types and where losses to deep storage were zero to negligible. Zhang et al. (2001) found, following on from extensive earlier studies, that under such conditions mean annual ET_a may be well predicted from mean annual precipitation (P_a) by using an equation which takes into account the proportion of woody vegetation (trees, shrubs) and proportion of grasses and low herbaceous species covering the catchment.



Zhang's evapotranspiration model is described in Equation 1:

Equation 1

$$ET = \left(f \frac{1 + w_f \frac{E_{of}}{P}}{1 + w_f \frac{E_{of}}{P} + \frac{P}{E_{of}}} + (1-f) \frac{1 + w_h \frac{E_{oh}}{P}}{1 + w_h \frac{E_{oh}}{P} + \frac{P}{E_{oh}}} \right) P.$$

where:

- ET = total annual evapotranspiration for the catchment in mm,
- f = the proportion of the catchment that is forested (>70% canopy cover),
- w = the plant-available water coefficient (which Zhang et al (2001) determined as 2.0 for forests and 0.5 for short grasses and crops),
- E_o = annual potential evapotranspiration for forested and non-forested areas, Zhang assumed E_o to be constant and determined a value of 1410 for trees and 1100 for herbaceous plants in mm, and
- P = annual precipitation in mm.

By applying this widely adopted equation to the macro-catchments listed above, we concluded that, with the possible exception of the Mongarlowe and Kangaroo Rivers' catchments, for all other NSW coastal Triassic and Permian sandstone-based catchments considered, including in particular the Cordeaux and Avon catchments in which the studied sub-catchments were located, a significant fraction of precipitation ultimately reporting to gauging must have too rapidly infiltrated soils and outcropping rock to a depth below which is no longer accessible for ET processes to have been subject to ET. The minimum long term rate of fast infiltration to groundwater in this manner for the Avon, Cordeaux, Cataract and Nepean catchments was found to lie within a narrow range, being about 184, 241, 346 and 89 mm/year respectively. The gauging records are relatively long at 36 years in all four cases (Thyer and Kuczera 2000). It is noted that equivalent behavior has been found in sandy catchments elsewhere e.g. Petheram (2003).

Hydrologic modelling basis and outcomes

The model RUNOFF2005 was selected for the conceptual analysis and synthesis of runoff hydrographs as being most useful. Not widely known in Australia, RUNOFF2005 is the mature version of a model developed at the Free University of Amsterdam over many years of study of conceptually similar European alpine headwater catchments. The model uses analytical solutions derived for the behavior of groundwater discharge in terms of a time-variable drainage resistance. These lead to a general equation of the drainage resistance as a function of groundwater discharge not restricted to areas with unconsolidated 'Dupuit-Boussinesq aquifers'. This physically-based equation was then implemented in a simple, non-distributed conceptual runoff model making a non-linear Levenberg-Marquardt optimization-based analysis of continuous time series of runoff in the presence of intermittent rainfall (Van de Griend et al. 2002, 2003). The model does not differentiate the catchment into different runoff source areas. Fig. 2 below shows the conceptual form of the RUNOFF2005 model.

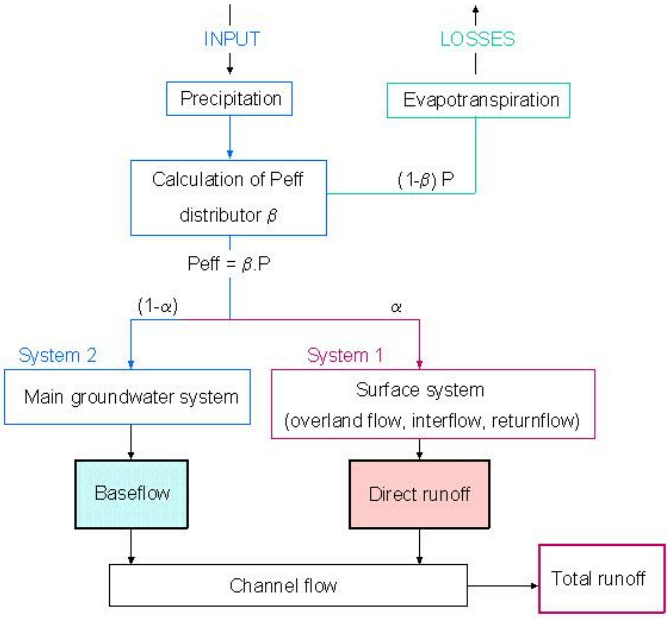


Figure 2 Schematic representation of catchment hydrologic cycle forming basis of RUNOFF2005 model

In calculating best fit *Model Water Balances* for the Native Dog and Donald's Castle Creek catchments the model fit to observed hydrographs was optimized <u>until</u> ET approached closest to the mean of the observed long term deficit between mean annual rainfall and mean annual runoff for the Lake Cordeaux and Lake Avon catchments i.e. 543 mm/year (1.487 mm/day) <u>and</u> the Nash-Sutcliffe goodness of fit (E) parameter exceeded 80%. For a non linear time-variable drainage resistance, the reservoir coefficient Jb = $A/Q^{\mathbf{B}}$ where A and B are dimensionless constants fitted by a non-linear optimization technique. The reservoir coefficient is the bulk recession time constant for the aquifer as a whole and is also identified as *aquifer response time*, *time-scale of response* or *hydrologic response time*. It varies with drainage resistance and will cover a range of values which the RUNOFF2005 model effectively attempts to estimate.

Modelling showed both the Native Dog and Donald's Castle Creek catchment groundwater systems could be satisfactorily fitted with a reservoir coefficient (Jb) of the groundwater system with an equation of the form Jb = $A/Qb^{\mathbf{0.67--1.00}}$. This <u>constrains</u> the effective drainage distance (L) to being either constant or varying inversely with the average head above the drainage base, with horizontal hydraulic conductivity to being either constant or varying in simple linear ratio to the average head above the drainage base i.e. decreasing with depth (Van de Griend et al. 2002). Reservoir coefficients Jb for these catchments typically ranged from <10 to <100 years. The proportions of recharge (i.e. precipitation minus ET) entering this groundwater system were invariably >75% of total recharge. This suggests that the aquifer(s) may typically be located beneath at least 75% of the catchment i.e. slopes, swamps and upland plateaus.

The Hillslope Aquifer Concept and its Hydrogeologic Implications

Mathematically, these observations all imply the groundwater systems generating baseflows in each creek, while exhibiting non-linear variable drainage resistance may, to a first approximation, be idealized by a long, narrow triangular configuration i.e. a hillslope aquifer (or suites of such aquifers). These 'hillslope aquifers' would generally be considered to have a maximum extent running from the groundwater divide at ridgelines, or midpoints of upland plateaus, down to the draining creek line. Saturated zones were considered to occur in weathered rocks of the plateaus, within soil catenas of hill slopes, in deeply weathered sub-cropping sandstone and within weathered outcropping and creek bed sandstone. We investigated the consequences to baseflow characteristics of these catchments being generally driven by a hillslope aquifer by considering the scalar and geometric behavior of an extended idealized hillslope aquifer system in these two catchments. Fig. 2 (Walker et al. 2005) provides an idealized picture of a hill slope aquifer.

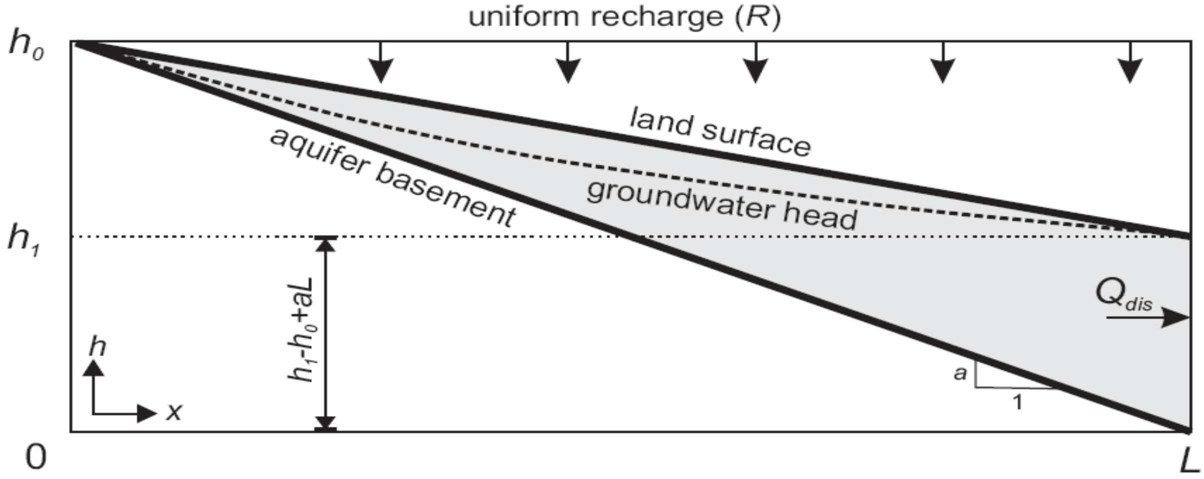


Figure 2 Idealised hillslope aquifer cross section.

We examined the Native Dog Creek and Donald's Castle Creek sub-catchments in terms of representative hillslope aquifer cross sections. Ten hillslope sections were generated by a Geographic Information System for each catchment. An Excel spreadsheet model was then established to determine the effects of actual aquifer length (L), basement slope (a), aquifer thickness at the creek (h_1), aquifer specific yield (S) and mean bulk horizontal hydraulic conductivity (K) on timescales of response (Jb) which might be expected from hillslope aquifers with such cross sections in accord with a non-dimensional, collapsed parameters hillslope aquifer model developed by CSIRO Land and Water (Walker et al. 2005). A specific yield (S) for the aquifer of 0.05 was adopted, being considered reasonable for an aquifer dominated by weathered sandstone. Critical parameters varied in the spreadsheet model were principally h_1 and K.

The hillslope aquifer spreadsheet model provided us with a clear scalar explanation for the hydrologic inference that hillslope aquifer time of response or reservoir coefficients Jb for both catchments were measured in timescales of years to decades. It predicted that bulk horizontal hydraulic conductivities of hillslope aquifers consistent with the range of Jb obtained from hydrologic modelling should principally lie in the range of ~10^{-7} – 10^{-6} m/s i.e. ~3 – 30 m/yr.

Hydrogeologic Investigations

Lugeon type hydraulic conductivity measurements were made within outcropping Hawkesbury Sandstone during the drilling of three deep boreholes in a hillslope of Sandy Creek catchment which drains to Lake Cordeaux (Hammond, 2007). This catchment lies in relatively close geographic proximity to the Native Dog and Donald's Castle Creeks catchments (refer Fig. 1 above).

Hillslope aquifer horizontal hydraulic conductivity determinations

Boreholes were designated EDEN87, 88 and 89 and the base of the Hawkesbury Sandstone was located at 29.6, 30.6 and 45.3 m respectively. For boreholes EDEN87 and 88 the base of the Hawkesbury was found to be the Garie Formation underlain by the Bald Hill Claystone while for EDEN89 the base was found to be the Newport Formation underlain by the Garie Formation. In each case the Hawkesbury Sandstone is underlain by well known aquitards. After each 6.0 m interval was drilled, drill stems were withdrawn 6.0 m, a packer inserted and inflated and water injected under pressure. Four such tests in the Hawkesbury were conducted for EDEN87 and 88 and 6 tests for EDEN89. Table 1 presents the calculated outcomes of those pump tests

Table 12 Estimated hydraulic Conductivities of Hawkesbury Sandstone in three boreholes in a hillslope

Borehole	Number of pump tests conducted	Depth Range (m BGL)	Estimated lognormal mean conductivity (m/s)	Estimated ±one standard deviation range (m/s)
EDEN87	4	8.9 – 29.6	1.6×10^{-8}	$2 \times 10^{-9} – 1.4 \times 10^{-7}$
EDEN88	4	8.6 – 30.6	5.6×10^{-8}	$6 \times 10^{-9} – 5.0 \times 10^{-7}$
EDEN89	6	9.1 – 45.3	8.3×10^{-8}	$2.0 \times 10^{-8} – 3.5 \times 10^{-7}$

Due to the more porous and friable nature of near surface sandstone, packers could only be deployed to obtain a good seal from depths of 8.9, 8.6 and 9.4 m below ground level (bgl) for boreholes EDEN87, 88 and 89 respectively. Pump test results are therefore be regarded as conservatively low in terms of the entire Hawkesbury Sandstone interval from near to the surface i.e. from just below the zone of quickflow down to the underlying aquitards. Nevertheless, these data serve to confirm Hawkesbury Sandstone strata, at least in this hillslope, would typically exhibit a mean bulk horizontal hydraulic conductivity within the range of 10^{-7} - 10^{-6} m/s for an adopted mean bulk specific yield of about 0.05 or slightly lower conductivities for slightly higher mean specific yield.

Hillslope aquifer tritium concentration determinations

The modern tritium level of rainfall measured in closest proximity to the above-mentioned sub-catchments is 3.4±1.6 TU/L (±1σ; n = 15) at Mt. Keira. Much further inland near the southern end of the Plateau it is 2.7±1.2 TU/L ((±1σ; n = 17) at Mittagong (Waring and Peterson 2007). Following completion of the EDEN group of boreholes, samples of Hawkesbury Sandstone groundwater were recovered using a double packer method from them and also from two adjacent shallow piezometers. Table 2 shows the tritium data for these groundwaters, for Sandy Creek itself, for the nearby Sandy Creek Arm of Lake Cordeaux (into which Sandy Creek discharges), for the Cordeaux River Arm of the Lake to the immediate east and for Lake Avon to the west measured over the period 2005 – 2009 and the estimated fraction of modern rainfall less than approximately 50 years old which occurs in such waters, assuming most local rainfall originates from the south and east of the sea and likely dominated by the orographic effects of the Illawarra Escarpment (refer Fig. 1).

Table 2 Tritium concentrations and estimated fraction of 'modern' rainfall (i.e. approx. <50 years old) in Sandy Creek catchment Hawkesbury Sandstone hillslope aquifer groundwaters, in Sandy Creek and within Lakes Cordeaux and Avon nearby.

Borehole and depth of Hawkesbury Sandstone groundwaters recovered or surface water body	Tritium TU/L	Estimated fraction of modern rainfall <approx. 50 years old (as measured at Mt. Keira)
Shallow piezometer EDEN87S 6.8 m	1.74±0.12	
Shallow piezometer EDEN87C 8.9 m	2.23±0.12	
Deep borehole EDEN88 24.3 – 29.3 m	1.81±0.08	
Deep borehole EDEN89 0 – 29 m	2.18±0.12	
Mean of all EDEN group Hawkesbury Sandstone groundwater tritium values	1.990±0.251 (n = 4)	61±39%
Lower Sandy Creek	1.825±0.258 (n = 4)	56±36%
Lake Cordeaux Sandy Creek Arm	1.856±0.190 (n = 5)	57±36%
Lake Cordeaux Cordeaux River Arm	1.970±0.258 (n = 7)	61±38%
Lake Avon (Sydney Water treatment plant)	1.970±0.137 (n = 2)	61±38%

Conclusions

A consistent set of sub-catchment hydrologic, hydrogeologic and tritium isotope evidence shows that the Woronora Plateau Triassic Hawkesbury Sandstone terrain is a relatively permeable landscape. The major draining streams and drinking water reservoirs on the Plateau will always contain a significant fraction of water which has passed slowly through hillslope aquifers in the weathered Hawkesbury Sandstone over periods of decades.

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Surface and groundwater connectivity and salinity in the upper Hunter Valley, New South Wales.

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Abstract

Widden Brook is part of an unconfined alluvial aquifer system in the upper Hunter Valley, eastern Australia. Stream salinity increases downstream consistent with leaching of saline groundwater into the stream. Two groundwater transects were examined during contrasting stream flow conditions to measure stream-groundwater connectivity and salinity. During low flow, Na, Mg, Cl and HCO_3 were the major ions; during full flow, HCO_3 and Cl were the major ions. Salts are mobilised in the groundwaters by mineral weathering of the floodplain and terrace sediments. Higher iron concentrations are observed in the alluvial floodplain indicating reducing conditions; lower ferrous iron in the terraces indicates oxidising conditions. Water chemistry results suggest a Na-Mg-HCO_3-Cl stream-groundwater system in Widden Brook.

Keywords: Hunter Valley; salinity; hydrochemistry; stream-groundwater connectivity; mineral weathering.

1. Introduction

Increases in stream salinity due to the altered hydrology of catchments resulting from changed landuses, coupled with frequent ENSO-related droughts in recent decades, pose a major challenge to sustainable water management in Australia. The Hunter River catchment in south-eastern Australia is one the most productive regional areas in New South Wales. The major industries in the Hunter Valley comprise coal mining, horticulture, wine production, livestock production, horse breeding and grazing. All these industries have competing demands for water resources and sustained extraction of groundwater from alluvial aquifers poses a threat to the ecological function of the hyporheic zone (Boulton, 2000), to water flows and to stream health. A recent study (White *et al*., 2004) suggests that stream salinities in the Hunter catchment are increasing. Replacement of deep rooted native trees with shallow rooted pasture and crops has been widely assumed to be the cause of rises in saline groundwater surfaces with increased saline discharge into streams. The salinity in the groundwater is presumed to be of meteoric origin from atmospherically advected sea salt accumulated in recharge. Shallow fresh alluvial groundwater systems overlying saline groundwater are extracted for use in farming and mining and this may exacerbate salinity problems. This study in Widden

Brook in the upper Hunter Valley, New South Wales, investigates groundwater-stream water interactions and tests the hypothesis that mineral weathering is a source of salts in Widden Brook surface waters.

2. Site Description

Average annual rainfall in Widden Brook varies with elevation and across the catchment from 950 mm at the headwaters in the Wollemi National Park in the southern catchment, to 580 mm at Denman to the north-east. The principal landuses in the catchment are the protected native forests in the National Park in the upper catchment and horse breeding, livestock grazing and cereal production in the lower catchment with significant shallow alluvial groundwater extraction for pasture irrigation in summer.

Widden Brook (Fig. 1) flows north for 40 km from the Wollemi National Park in the upper Hunter and discharges into the Goulburn River, a right bank tributary of the Hunter River. The Widden catchment is located in the northern part of the Permo-Triassic Sydney Basin, and lithology consists of Triassic Narrabeen Sandstone, underlain by interbedded shale, sandstone and Permian coal-bearing sediments which were deposited in continental regressive episodes (Beckett, 1988). Tertiary olivine basalt outcrops in the headwaters at Nullo Mountain and Mt Pomany in the National Park (Wellman & McDougall, 1974). The Watts Sandstone and the Denman Formation of the Newcastle Coal Measures represent marine transgressive phases between the coal deposition episodes and underlie Widden Brook at variable depths between 6-8 m below the creek bed.

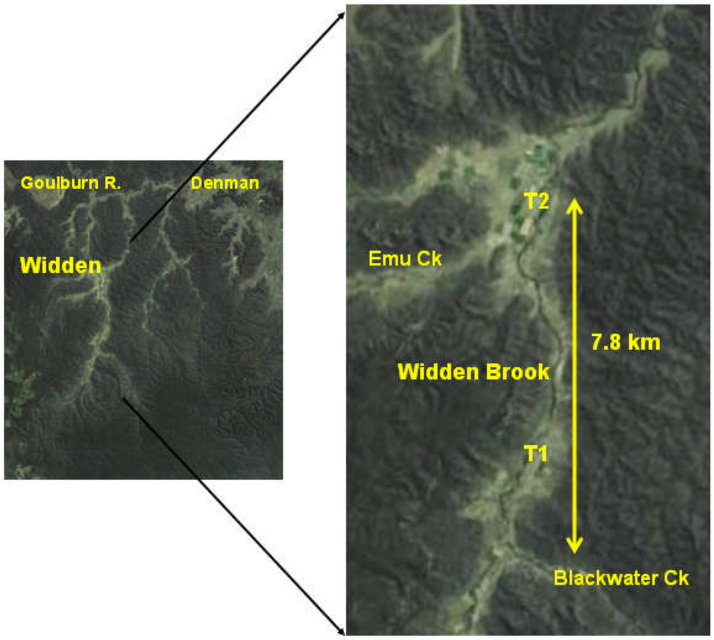

Figure 1. Widden Brook catchment indicating relative location of transects T1 and T2.

In the upper catchment, Widden Brook flows through a narrow valley bounded by Triassic sandstone escarpments 200-300 m high on each side of the creek. In mid-catchment, the Widden incises the floodplain terraces up to 3 m above the stream and groundwater in alluvial fans flows laterally from the escarpments in sections of the creek (Fig. 1). The two main tributaries are Blackwater Creek, which drains the Triassic sandstones from the south-east, and Emu Creek, which flows from the south-west. The terraces give way to broad alluvial floodplains which extend to several hundred metres on either side of the creek which support the horse breeding and livestock in this part of the catchment. In the lower catchment the valley floor narrows and the course of the Widden is constrained by bedrock outcrops at the creek edge. Flow from the fractured bedrock accumulates in this section of creek even during sustained dry periods. During the Holocene, unconsolidated alluvial sediments were deposited along the Hunter and Goulburn Rivers and their tributaries. These deposits form the large unconfined alluvial aquifer system in the Hunter Valley which represents the major source of groundwater in the Hunter Valley (Kellett *et al*., 1989).

The hydrology in Widden Brook was investigated in March 2004 (White *et al*., 2004) which revealed that the stream height was generally above the groundwater surface in the upper catchment above the confluence of Blackwater Creek with Widden Brook (Fig. 2) suggesting recharge of stream flow to the groundwater. Below the confluence however, the groundwater and stream water heights were similar along the reach of the stream to the stream gauge suggesting connectivity between stream and groundwater. The impact of this connectivity on stream chemistry under changing hydrological conditions is investigated in this paper

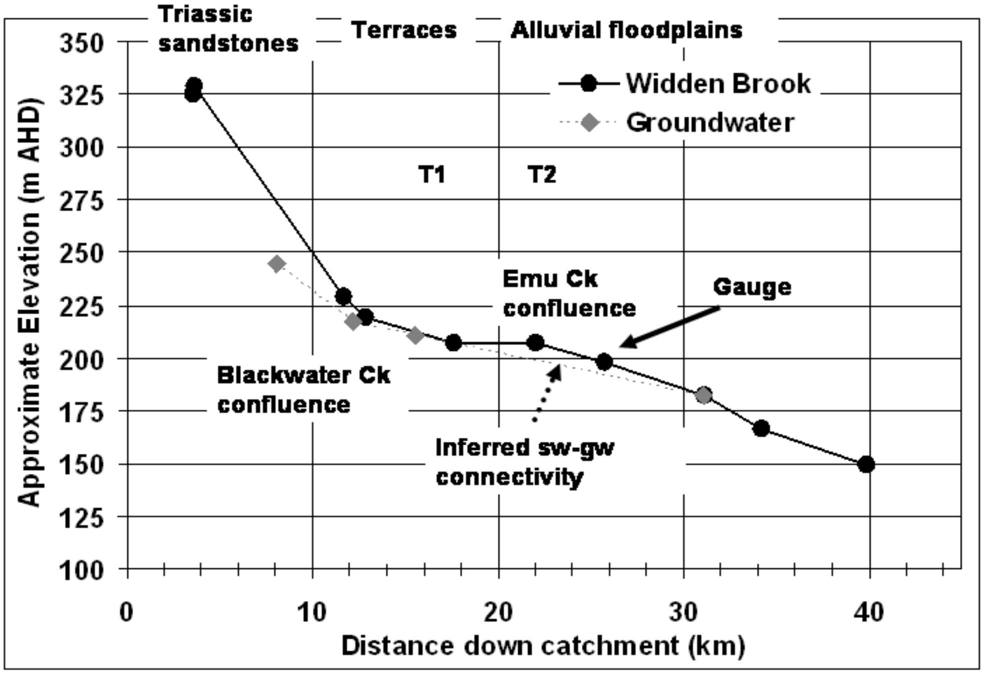

Figure 2. Stream and groundwater heights in Widden Brook. Adapted from White *et al*., 2004. Dotted greyscale line denotes inferred zone of stream-groundwater connectivity.

3. Methods

3.1 Groundwater network

The groundwater network consists of four piezometer transects which were installed to complement existing groundwater bores, wells and spear point wells to varaiable depths 4-5 m below the creek bed surface. The piezometers were constructed from 100 mm PVC and hand-slotted to 1.50 m from the base and covered with a filter sock to prevent clogging by fine-grained sediment. The piezometer network was installed to measure the flux of groundwater between the terraces and stream water and also to measure the water chemistry.

3.2 Stream and groundwater sampling

Stream and groundwater water quality surveys were undertaken between May 2005 and July 2007. Groundwater was collected from piezometers after three well volumes had been purged and from the spear points after pumping for several hours for irrigation. Stream water samples were collected from up to nine sites in the Widden depending on flow conditions. Field pH, electrical conductivity (EC), dissolved oxygen (DO) and redox were measured in the field using calibrated meters. Bicarbonate concentration was measured in the field by titrating 10 ml of sample with 0.1M HCl until a visible change of colour was observed indicating the end point. Concentrations of ferrous iron and sulfide were measured using reagents and a Hach spectrometer. The reagent to measure ferrous iron was prepared in the laboratory according to APHA Method 3120 (APHA, 1995); for sulfide the Hach test kit reagent was used Samples were filtered in the field with 0.45µm membrane filter. One subsample was collected for major anion analysis by ion chromatography. A second filtered subsample was acidified to pH <2 using nitric acid and analyzed for major and trace cation analysis by ICP-AES and ICP-MS respectively. Stable isotopes of oxygen ($\delta^{18}O$), hydrogen ($\delta^{2}H$) were measured. Radiogenic strontium isotope, which can be a tracer of weathering reactions and the origin of salts (Clark & Fritz, 1997), were also measured using TIMS and the NIST-987 standard measured with these samples was 0.710223 +/- 0.00012.

4. Results and Discussion

4.1 Connectivity

Stream water chemistry indicates generally increasing EC (150-700 µS/cm) along Widden Brook (Fig. 3). In the upper Widden Brook, EC is generally <300µS/cm presumably due to surface runoff from the Triassic Sandstones. EC generally increases downstream as the Widden incises the floodplain except for freshwater input from Blackwater Creek and from Emu Creek (at ~27 km). Major ion chemistry is presented for March 2006 and for July 2006 (Fig. 4a-b). These two periods represent, respectively, low flow conditions during the drought 2005-2006 and full flow conditions after 49 mm of rainfall over a four day period ending two days prior to sampling. During full stream flow in July, conditions were hazardous in the upper catchment and sample collection was limited to the area between Blackwater Creek and transect T1 (Fig. 1). There is an increase in stream EC of ~100 µS/cm between March and July 2006 at the 23 km point in the Widden (Fig. 3). During low flow in March, Na, Cl, HCO_3 and Mg were the major ions; during full flow in July HCO_3 and Cl were the major ions.

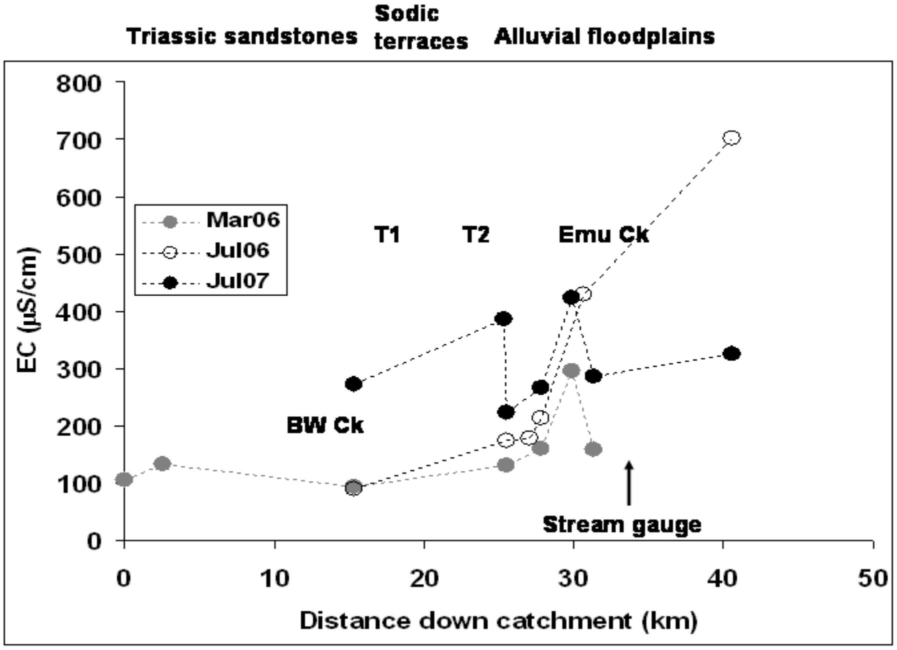

Figure 3. Stream salinity in Widden Brook.

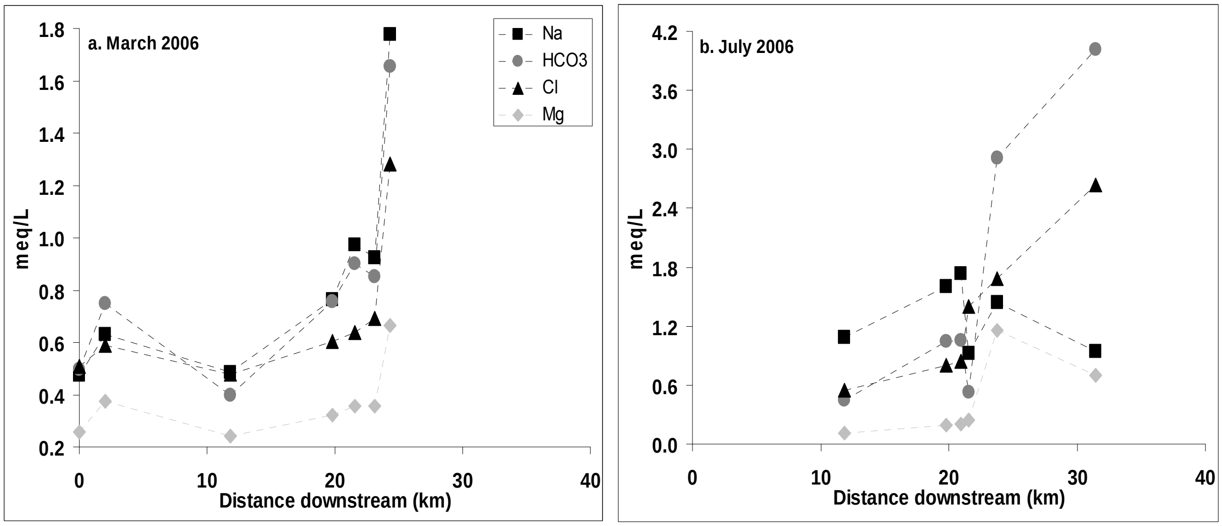

Figure 4a-b. a) Major ions in stream water in Widden Brook for March 2006 and b) for July 2006.

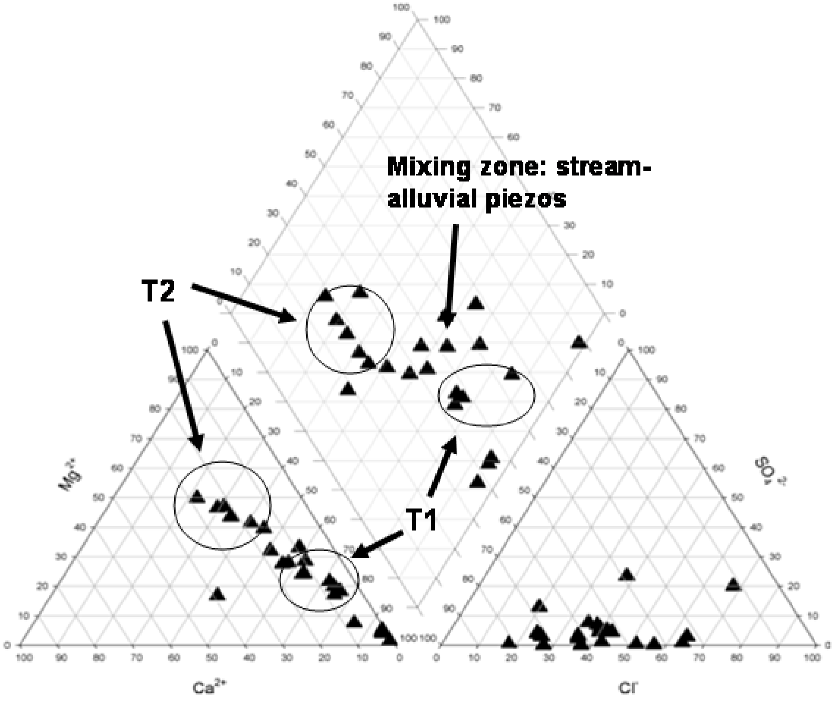

Figure 5. Piper plot of water chemistry for July 2006 illustrating contrast in chemistry between transects T1 and T2.

Groundwater results indicate a clear contrast in salinity between the terraces (sandy loam soils with clay lenses) and alluvial floodplain (coarse sand and gravels). To illustrate, the water chemistry of two piezometer transects separated by a distance of 7.8 km is presented in Figure 5: transect T1 below Blackwater Creek; transect T2 below Emu Creek (Fig. 1). Results are presented for groundwater collected in July 2006.

In transect T1 below the Blackwater Creek confluence, the soils are characterised by a general fining upwards sequence from coarse sand and pebble gravel (channel deposits) to medium sand (bar top deposits and splays) to fine sand and fine sandy loams in the overbank deposits of the alluvial floodplain (Keene *et al.*, 2007). Clay lenses were also observed in the soil profile and at the water table. In the alluvial floodplain groundwater, electrical conductivity (EC) is 1700-2100 µS/cm and pH was circumneutral. Na (>300 mg/l) is the dominant ion, greater than the combined concentrations of Ca, Mg and K and may reflect mobilisation of salt stores in the soil confirmed by the high soluble Cl (>200 mg/l). Alkalinity (600-760 mg/l) is an order of magnitude higher than stream water concentration (60 mg/l) which indicates mineral weathering of the sediments. Sulfate concentrations in the floodplains (20-80 mg/l) are an order of magnitude higher than in the stream. Ferrous iron concentrations up to 17 mg/l in the alluvial floodplain groundwater are consistent with reducing conditions. Very low ferrous iron concentrations however, were observed in groundwater at the piezometer most distant from the stream.

In transect T2 below the Emu Creek confluence, the floodplain is characterised by coarse- to fine-grained sands and gravels to 4 m depth with upward fining sequence. Stream EC at T2 (400-500 µS/cm) is significantly higher than at Blackwater Creek (52 µS/cm). Ferrous iron concentrations are less than at T1 which is consistent with generally oxidising conditions, although 10 mg/l of Fe^{2+} is recorded in the spear point. Na (30-60 mg/l) and Cl (30-90 mg/l) concentrations are also less than at T1. Alkalinity is in the range 90-150 mg/l suggesting minimal mineral weathering in unconsolidated sediments. Stable isotope ($\delta^{18}O$ and $\delta\ ^{2}H$) signatures in stream water Fig. 6) indicate an evaporative signature ($y = 6.23x$, $r^2 = 0.92$). Signature for groundwater (not shown) is $y = 6.17x$, r^2 0.56 which is similar to stream water indicating stream-groundwater connectivity.

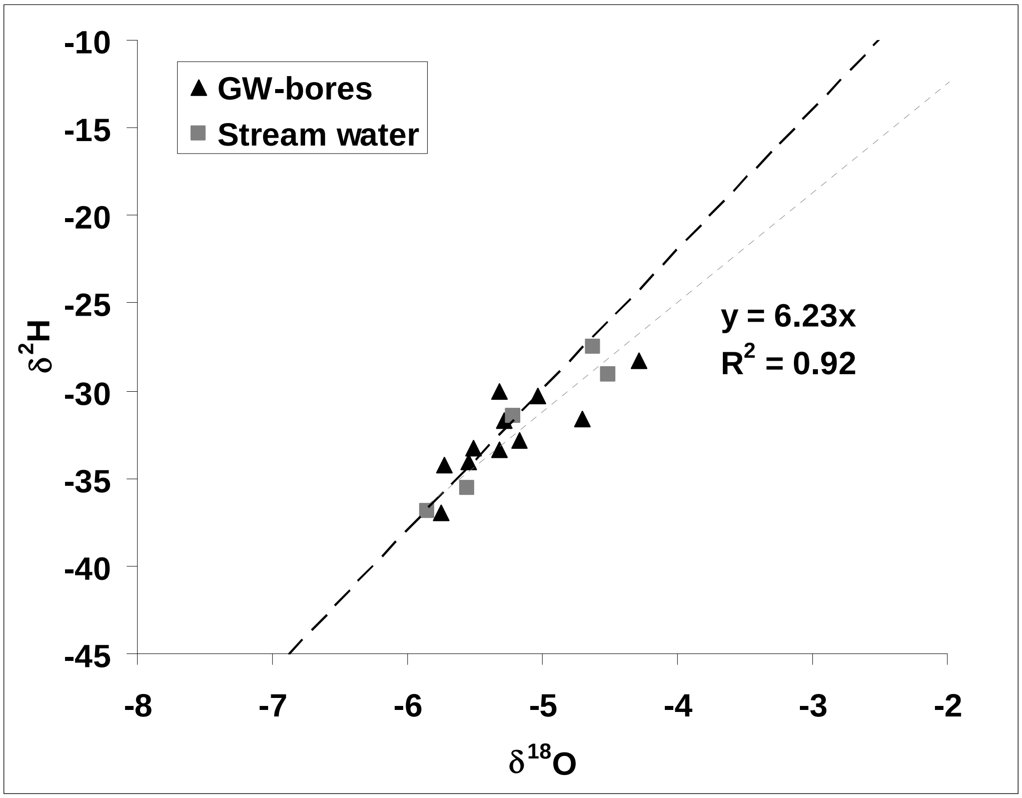

Figure 6. Stable isotopes of oxygen and deuterium for stream and groundwater July 2006.

Dark dotted line is GMWL; dotted greyscale is trend for stream water; trend for groundwater (not shown) is $y = 6.17x$, r^2 0.56.

4.2 Mineral weathering

The bicarbonate/chloride ratio (meq/L) of groundwater at T1 is in the range 1.0 to 1.7 and at T2, 1.3 to 3.4. These values are significantly higher than the seawater ratio (0.004 meq/L). This value suggests that the input of ions from mineral weathering (as a result of water-sediment exchange reactions), in particular divalent cations during low flow conditions (Fig. 4a), is a significant contributor of ions to stream water. The Sr isotope signature (0.70720-0.70995) in T1 is consistent with weathering of shales in the basal layer of the sedimentary units in the floodplain. In contrast, the Sr isotope signature (0.70860-0.71000) at T2 suggests atmospheric input of Sr or input of Sr from weathering of rubidium in the sands of the alluvial floodplain sediments.

Cl/Σanions and HCO_3/Σanions ratios (meq/L) were calculated for both transects with mean values as follows:

	Cl/Σanions	HCO_3/Σanions
T1	0.39 ± 0.03	0.54 ± 0.07
T2	0.38 ± 0.17	0.57 ± 0.19
Stream	0.45 ± 0.12	0.47 ± 0.12

Cl/Σanions ratio is less than HCO_3/Σanions ratio at both transects which is consistent with the bicarbonate/chloride ratios. The similar values for both ratios recorded in the stream is consistent (Fig. 4a-b) with increasing Cl and HCO_3 concentrations downstream and the higher HCO_3/Σanions to Cl/Σanions ratio in the transects indicates the flux of bicarbonate from soil weathering reactions in the terrace soils to the stream.

Silicate concentrations (mg/L) in the groundwater at T1 are in the range 7-13 mg/L, at T2 7-16 mg/L and in the stream 2-14 mg/L. The value of 14 mg/L was recorded below Blackwater Creek at the 12 km point (Fig. 4b) suggesting supsended load in the stream from erosion and runoff from the Triassic sandstones in the upper catchment.

5. Conclusions

Our results show a spatial trend in weathering reactions across the catchment according to depositional environment which is supported by (1) the different Sr isotope signatures in the groundwater at each transect, (2) the variable alkalinity in the groundwater and (3) the increase in alkalinity and salinity downstream.. The findings indicate that mineral weathering is a major contributor to salinity in catchments in the upper Hunter, in addition to the often-invoked models of rising groundwater tables as a result of tree clearance which mobilise salts in the soil zone, and aeolian deposition of salts. These alternative models pose a challenge to the management of salinity in catchments in south-east Australia, notably to identify the sources of salts and to estimate the salt loads in catchments. Elsewhere we discuss the variable salt load in Widden Brook over a hundred year period under changing hydrological conditions (Somerville *et al.,* 2009).

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Hydrology of an interacting unconfined groundwater-surface water system in the upper Hunter Valley, New South Wales.

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Abstract

The hydrology in Widden Brook, a southern, right-bank tributary of the Goulburn River in the upper Hunter Valley, New South Wales, was investigated to examine changes in stream flow and salt loads. We use here both spatially and temporally sparse data to reconstruct spatially interpolated rainfall, stream flow and salt loads in Widden Brook. The Goulburn River contributes approximately 23% of annual stream flow to the Hunter River. Rainfall, stream flow and salt load are highly variable in the period 1910-2007. Flow and salt load for 1950-1979 were 43% and 31% above long-term means; during 1981-2007, they were 51% and 38 % less than the period 1951-79. These conditions have implications for managing the competing demands for water by the mining, viticulture, pasture and horticulture industries which all depend on abstraction of water from surface channels and unconfined alluvial aquifers in the Goulburn and Hunter Rivers. These long-term variations pose particular problems for designing management strategies and assessing whether these strategies have had any impact. Estimation of the impacts of a salinity trading scheme and other management strategies on salt loads is therefore either very difficult or impossible.

Keywords: Goulburn River; stream flow; salt load; climate variability.

1. Introduction

Salinity discharge into the coastal Hunter River, NSW, is a major problem affecting agriculture, mining and rural communities. The Goulburn River contributes approximately 23% of annual stream flow to the Hunter River (DWE, 2008). However, the amount of annual salt discharge to the Hunter River is less well known.

Widden Book is a southern, right Bank tributary of the Goulburn, which drains a significant area of Wollemi National Park. This paper reconstructs stream flow and salinity discharge in Widden Brook.

Conventionally, stream salt load is expressed as the product of stream flow and concentration of salts in the stream water. In turn, stream flow is a function of rainfall. Estimation of rainfall in the Hunter Valley is usually determined from point rainfall data at Bureau of Meteorology (BOM) rain gauges. This assumption that point source rainfall data is applicable to the entire catchment does not take into account the variation in rainfall with variation in elevation across the catchment (Hutchinson, 2007). The change in elevation of Widden Brook from its headwaters to its confluence with the Goulburn River is ~1000m and the use of point rainfall data may significantly underestimate rainfall in the catchment, runoff and salt load. This has wider implications for the estimation of rainfall and stream flow in the Hunter Valley and for salinity management.

Stream flow records often have missing data and are of variable length, and this complictes efforts to accurately estimate the salt load and salt discharge from catchments. An incomplete record of historical stream flows in Widden exists for the period 1955-1978 over a period of above average rainfall in south-east Australia. Flows were also gauged from 2005-2007 during drought conditions. Nearby rainfall data is only available for the period 1960-2008. Using statistical methods, this paper integrates various rainfall and stream flow datasets in Widden Brook and in adjacent catchments to derive a hundred-year record of rainfall, stream flow and salt load trends in the catchment. These trends highlight the problem of climate variability in Australian catchments and the difficulty of predicting long-term stream flows and salt loads.

2. Site Description

Widden Brook (catchment area 708 km^2, Fig. 1) flows 40 km north from the Wollemi National Park (elevation 1100 mAHD) and discharges into the Goulburn River, a right bank tributary of the Hunter River (150 mAHD). The Widden catchment is located in the northern part of the Permo-Triassic Sydney Basin, and lithology consists of Triassic Narrabeen Sandstone, underlain by interbedded shale, sandstone and coal-bearing sediments deposited in continental regressive episodes during the Permian (Beckett, 1988). Tertiary olivine basalt outcrops in the headwaters at Nullo Mountain and Mt Pomany in the National Park (Wellman & McDougall, 1974).

In the upper catchment, Widden Brook flows through a narrow valley bounded by Triassic sandstone escarpments up to 200-300 m height on each side of the creek. In mid-catchment, the Widden incises sodic floodplain terraces up to 3 m above the stream and alluvial fans flow laterally from the escarpments in sections of the creek. The two main tributaries are Blackwater Creek, which drains the Triassic sandstones from the south-east, and Emu Creek, which flows from the south-west. The sodic terraces give way to broad alluvial floodplains below Emu Creek which extend to several hundred metres on either side of the creek. Stream water flow was monitored in this part of the catchment (DWE stream gauge 210034), which represents ~ 90% of the catchment area, for the period 1955-1978. In the lower catchment downstream of the gauge, the

Figure 1. Widden Brook catchment and its intersetion with the Goulburn River, (blue line) Hunter Valley, NSW (Googal Earth)

valley floor narrows and the course of the Widden is constrained by sandstone outcrops at the creek edge.

The principal landuses in the upper catchment are the protected native forests in the National Park and horse breeding, livestock grazing and cereal production in the lower catchment. There is significant shallow alluvial groundwater extraction for pasture irrigation in summer.

3. Methods

3.1 Rainfall

Long term yearly averaged rainfall in the Widden Brook catchment was estimated using the ANUSPLIN spatial interpolation package (Version 4.37, Hutchinson, 2007). This calculates climate surfaces on a monthly timestep from rainfall data supplied by the Commonwealth Bureau of Meteorology (BOM) by applying partial thin plate smoothing splines to a polygon of the Widden Brook catchment. Text files of monthly rainfall surfaces were generated for the period 1969-2008. The purpose of these correlations was to develop a methodology to link spatially, various sources of rainfall data in the catchment at different elevations, and to link temporally, short-term and long-term rainfall trends. To derive a long-term proxy record of rainfall in Widden Brook, the BOM rain gauge data at Denman was correlated with ANUSPLIN rainfall. Denman was chosen because it is located approximately 20 km in a direct line north-east of the stream gauge in the Widden and has a continuous rainfall record since 1883.

The correlation of the Denman monthly rainfall with ANUSPLIN rainfall data for the period 1969-2008 generated a regression coefficient of $P_{Denman} = 0.80xP_{ANUSPLIN}$ ($r^2 = 0.99$). The higher interpolated rainfalls are a result of the higher elevations in the Widden catchment. To express the Denman point rainfall data in terms of ANUSPLIN spatially interpolated rainfall data, the Denman rainfall was adjusted by 1/0.80, thus generating a long-term proxy rainfall data for the Widden for 1883-2007.

3.2 Stream flow

Stream flow data at Widden Brook causeway (gauge 210034) for the period 1955-1978 was supplied by the New South Wales Department of Water and Energy (DWE, 2006). Approximately 16% of this data was missing once anomalous data and missing flow readings were omitted. To in-fill the missing stream flow data, Widden Brook stream data was correlated with Coggan Creek stream flow (DWE gauge 210006, located in the upper Goulburn River) which has a long-term stream flow record from 1913 with minimal (~5%) missing stream flow. Coggan Creek (catchment area 3392 km^2) was chosen because (1) the catchment is located upstream of the confluence of Widden Brook and the Goulburn River and (2) the Widden stream gauge is located upstream of the confluence with the Goulburn, so stream flow at each gauge can be considered independent. This method allowed us to produce a long-term proxy record of stream flow in Widden Brook for the period 1913-2007.

3.3 Runoff

Runoff for the catchment was estimated by correlating the corrected Denman cumulative rainfall (mm) with the proxy Widden Brook stream specific discharge (mm) for the period 1955-78, calculated from the cumulative stream flow (ML) divided by the catchment area up to the stream gauge (640 km^2, or 90% of the catchment area). The correlation produced a regression coefficient of the long-term mean runoff for the catchment in the form of $\Sigma q = a\Sigma P$, where ΣP = cumulative rainfall (mm), Σq = cumulative stream specific discharge (mm) and a = mean runoff coefficient.

3.4 Stream salt load

Salt load (SL) in a catchment can be expressed by the equation SL = Q x TDS, where Q = stream flow (ML) and TDS = total dissolved salts (mg/L). TDS in stream water is calculated as the sum of cations and anions in the water samples (balanced to within 5%). By correlating TDS with electrical conductivity (EC) of the stream water, a regression TDS = bxEC is derived, where b = 0.64 is the slope of the regression. This value for b was derived from EC measurements undertaken in field EC measurements between 2005 and 2007 ($r^2 = 0.86$) and the TDS of the major ions from stream water samples.

The relation between EC and Q was calculated from 31 instantaneous stream flow and EC measurements undertaken in Widden Brook between 1971 and 1979. The regression equation between Q and EC was $EC = 551xQ^{-0.27}$ ($r^2 = 0.86$).

4. Results and Discussion

4.1 Rainfall and runoff

The mean annual spatially interpolated rainfall for the Widden catchment for the period 1913-2007 is 713 mm. Rainfall and runoff are summarised in Table 1 for the periods 1913-1950, 1951-1979 and 1980-2007. Results are presented from 1913-2007 to coincide with the start of stream flow records at Goggan Creek. These groupings are based on large scale climate variability patterns over the past hundred years which are illustrated in Fig. 2. The average runoff coefficient for 1913-2008 using in-filled stream flow data was 8.4%.

Table 1. Mean annual rainfall, stream flow, TDS and salt load in Widden Brook for the periods identified in Fig. 1. Long-term mean annual trends in bold.

Period	**Rainfall (mm/year)**		**Flow**	**TDS**	**Salt load**
	Spatial	Point	(ML/year)	(mg/L/year)	(tonnes/km^2/year)
1913-2007	**713**	585	**25754**	**741**	**1.49**
1913-1950	647	531	21711	762	1.33
1951-1979	769	631	37667	666	1.95
1980-2007	745	611	19308	789	1.22

The period from 1913 to 1950 was characterised by lower annual rainfall (mean 647 mm) compared to the long-term mean (713 mm), prolonged drought during the 1930s to late

1940s (Fig. 3). In comparison, rainfall during the period from the 1951 to 1979 (mean 769 mm) is ~8% higher than long-term mean rainfall. This was a period of major dam constuction and water licensing policies were developed and implemented in south-east Australian catchments based on the assumption of adequate water supply for irrigation (Fig. 3). Mean annual rainfall for the period 1980-2007 (745 mm) is ~ 4% above the long-term mean but marginally less (<5%) than the mean for 1950-1979.

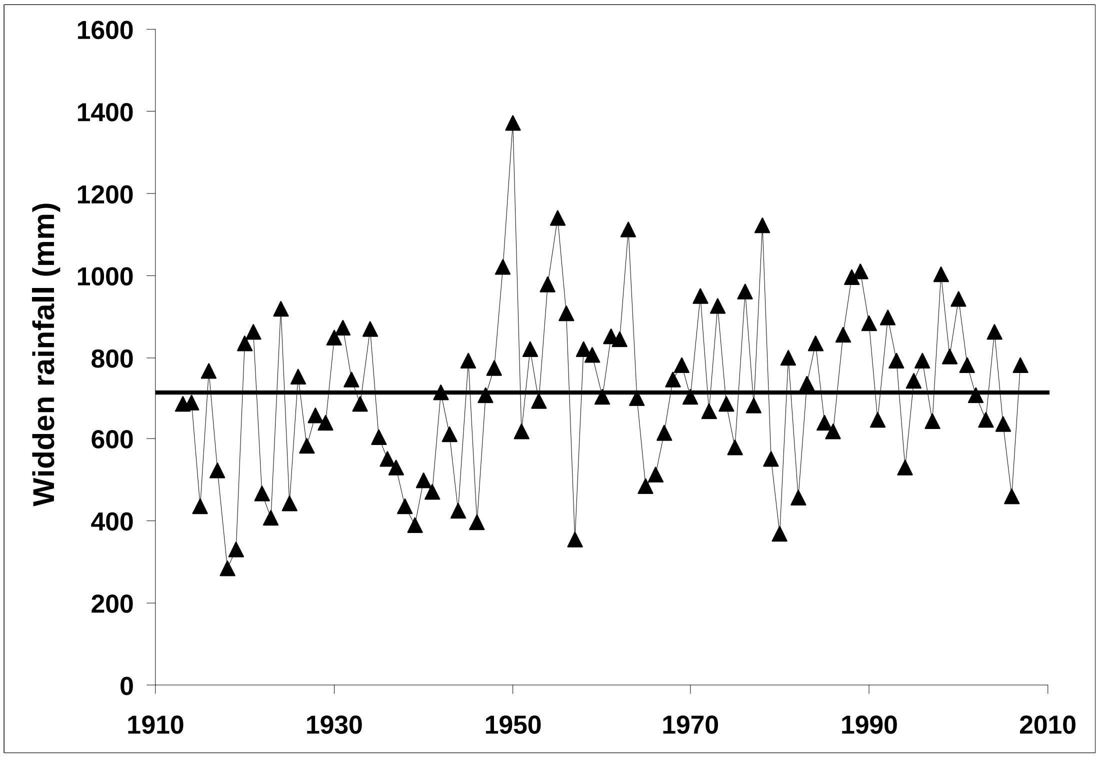

Figure 2. Denman rainfall correlated with ANUSPLIN rainfall for the period 1913-2007 used to estimate spatially interpolated proxy annual rainfalls for Widden Brook (black line is mean annual rainfall of 713 mm).

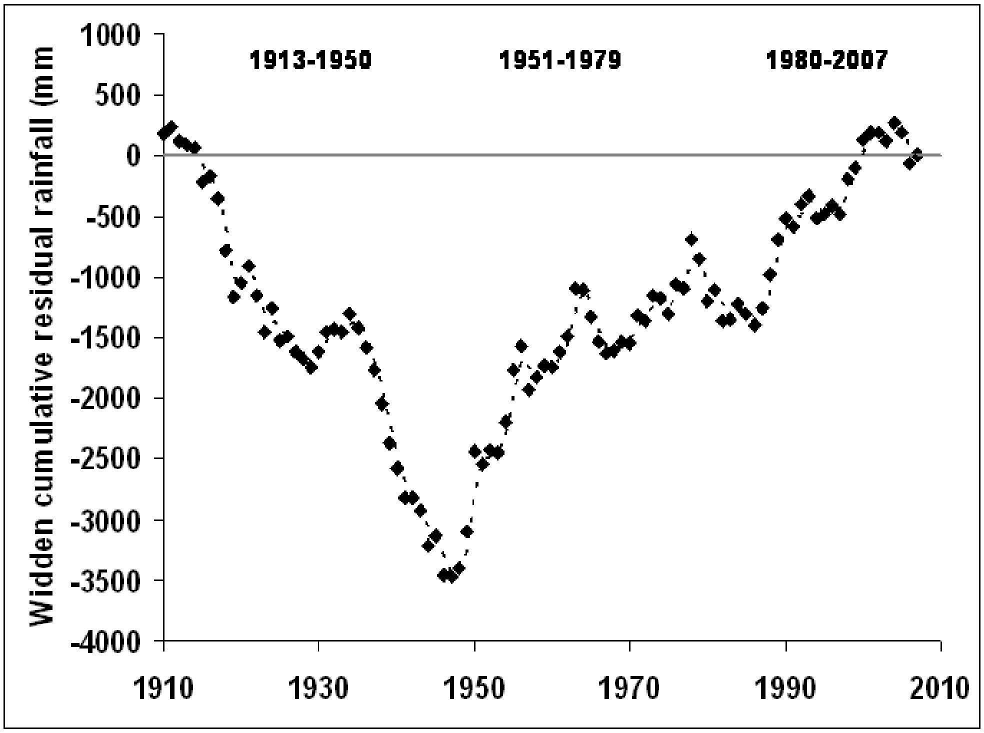

Figure 3. Cumulative residual rainfall in Widden Brook 1913-2007

4.2 Stream flow and salt load

The variability in rainfall in the post-war period is reflected in variations in flow and salt load for the same periods. For the period 1951-1979, mean flow (37,667 ML/year) was 46% higher than long-term mean resulting in a 30% higher mean salt load/catchment area (1.95 tonnes/km^2/year) consistent with the 8% increase in mean rainfall. However, mean flow (19,308 ML/year) and mean salt load/catchment (1.22 tonnes/km^2/year) for 1980-2007 are 51% lower and 38% lower respectively for the period 1951-1979.

The findings in this paper provide some perspective on the current debate about environmental flows and sustainability. Firstly, salt loads have been highly variable over the past century reflected in high standard deviations in salt load for each period. The Commonwealth Water Act of 2007 was introduced, amongst other measures, to provide more water for environmental flows and to implement a water trading market. Stream flow and salt load in the period 1951-79 in Widden Brook were substantially higher than the long-term means. This impies that salt loads increase with increased environmental flows.

Secondly, this long-term variability has an implication for the estimation of rainfall and stream flow in the Hunter Valley and for salinity management. The Hunter Valley Salinity Trading scheme (DWE, 2006) was introduced to regulate salt discharges from mining sites in the lower Hunter Valley and to monitor salt flows in the Hunter River. Stream salt loads have clearly varied naturally with prolonged long-term wet and dry periods in the Hunter. Estimation of the impacts of a salinity trading scheme and other management strategies on salt loads is therefore either very difficult or impossible.

5. Conclusions

We have used here both spatially and temporally sparse data to reconstruct spatially interpolated rainfall, stream flow and salt loads in Widden Brook, a tributary of the Goulburn River in the Hunter catchment NSW. Taking into account the 1000 m range of elevations in Widden catchment, the catchment-wide spatially interpolated rainfall was 25% higher than the point rainfall data just outside the lower catchment. Once missing data was in-filled, we were able to reconstruct stream flow and salt loads in the Widden from 1913 to 2007. This showed large long-term variations in stream-flow and salt loads. These long-term variations pose particular problems for designing management strategies and assessing whether these strategies have had any impact. Elsewhere we discuss the alluvial groundwater contribution to salt loads in Widden Brook and the sources of salinity in the Widden (Somerville *et al.,* 2009)

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Analysis of aquifer tests in Mesozoic sandstones in western Sydney, Australia

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Abstract

Pump tests are conducted to measure aquifer and well hydraulic parameters with a view to either assessing the capacity of an aquifer and well to provide water, or to use the parameters as a basis for aquifer simulations. In this report, results for several pump tests conducted in Mesozoic (generally quartzose) sandstones in western Sydney are analysed by automatically estimating parameter values using an equivalent porous medium and other concepts. The parameter estimation incorporates simultaneous analysis of drawdown traces from several piezometers for the same test. Results indicate that at the scale of these tests the aquifer has responded in a way similar to an equivalent porous medium, and estimated parameter values are useful for verification of porous medium three-dimensional flow models that may be developed to simulate the aquifer groundwater level response from a range of applied stresses. Results are also compared to the hydraulic conductivity / depth relationship commonly seen for Mesozoic sandstones in the Sydney Basin.

Keywords: Aquifer testing, sandstone, fractured rock.

1. Introduction

The recent drought across New South Wales has prompted water authorities to seek alternative sources to supplement existing water infrastructure during extended periods of low rainfall. As part of the Metropolitan Water Plan the NSW State Government initiated a groundwater resource investigation targeting the Hawkesbury Sandstone beneath Sydney and its surrounds. Leonay (west of Sydney) was selected as one of seven priority sites to be investigated based on favourable geological and hydrogeological conditions (Hawks et al., 2009).

The Leonay investigation area is located in the central part of the Sydney Basin, at the western edge of the mapped extent of the Wianamatta Group (predominantly shale and siltstone). The geology of the area is shown in Figure 1. The relationship between the various geological units is shown in Figure 2 along cross section A-A’. The area is located in the floodplain between the Nepean River and the Blue Mountains foothills and is covered by Quaternary alluvium of the Cranebrook Formation (typically 8m to 14m thick). In this area the majority of the existing Wianamatta Group comprises Ashfield Shale, which consists of dark grey to black claystone, siltstone, and fine sandstone-laminite. The Mittagong Formation is a transitional unit between the overlying Wianamatta Group and the underlying Hawkesbury Sandstone, and is characterised by fine grained sandstone interbedded with sandy shale layers.

The Hawkesbury Sandstone attains a maximum thickness of about 260m in the investigation area. It is a medium to coarse grained quartzose sandstone with some shale, and is underlain by the Early Triassic Narrabeen Group. The upper part of the Narrabeen Group consists of (in descending stratigraphic order) the Burralow Formation (mainly a quartz to quartz-lithic sandstone), the Wentworth Falls Claystone (massive to slightly fissile claystone, usually around 3 to 4m thick with a maximum recorded thickness of 9m), and the Banks Wall Sandstone (a quartz to quartz-lithic sandstone with some shale and claystone).

Groundwater in the area is present in both alluvium and rock. The Wianamatta Group underlies the alluvial sediments. The groundwater resource investigation at Leonay (conducted between September 2006 and November 2007) included the drilling and construction of eighteen bores in the investigation area. Following borehole construction, comprehensive groundwater sampling, test pumping and resource evaluation were conducted.

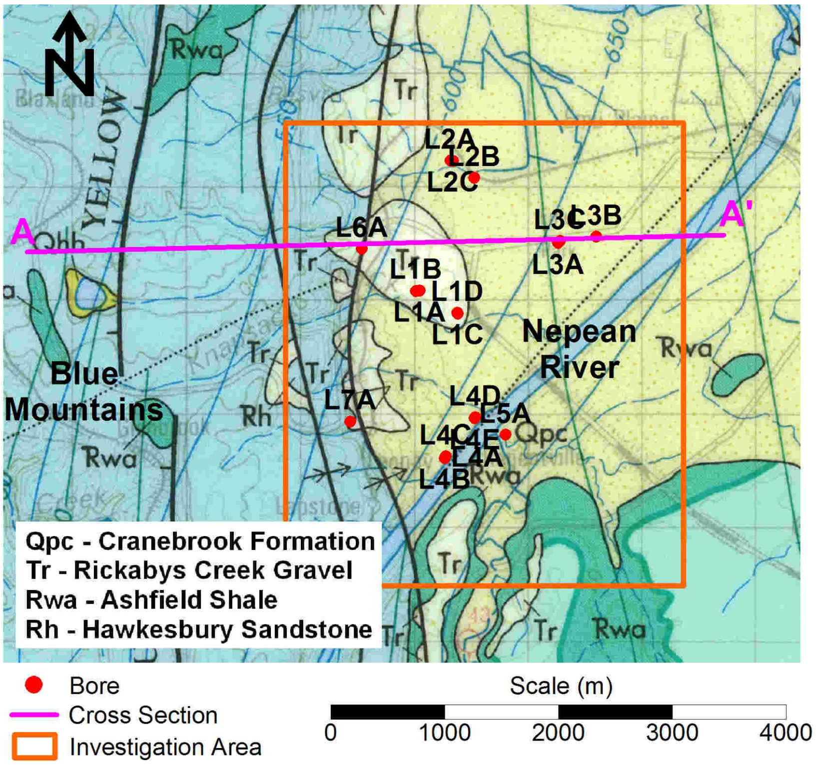

Figure 1. Geology of the investigation area and bore locations.

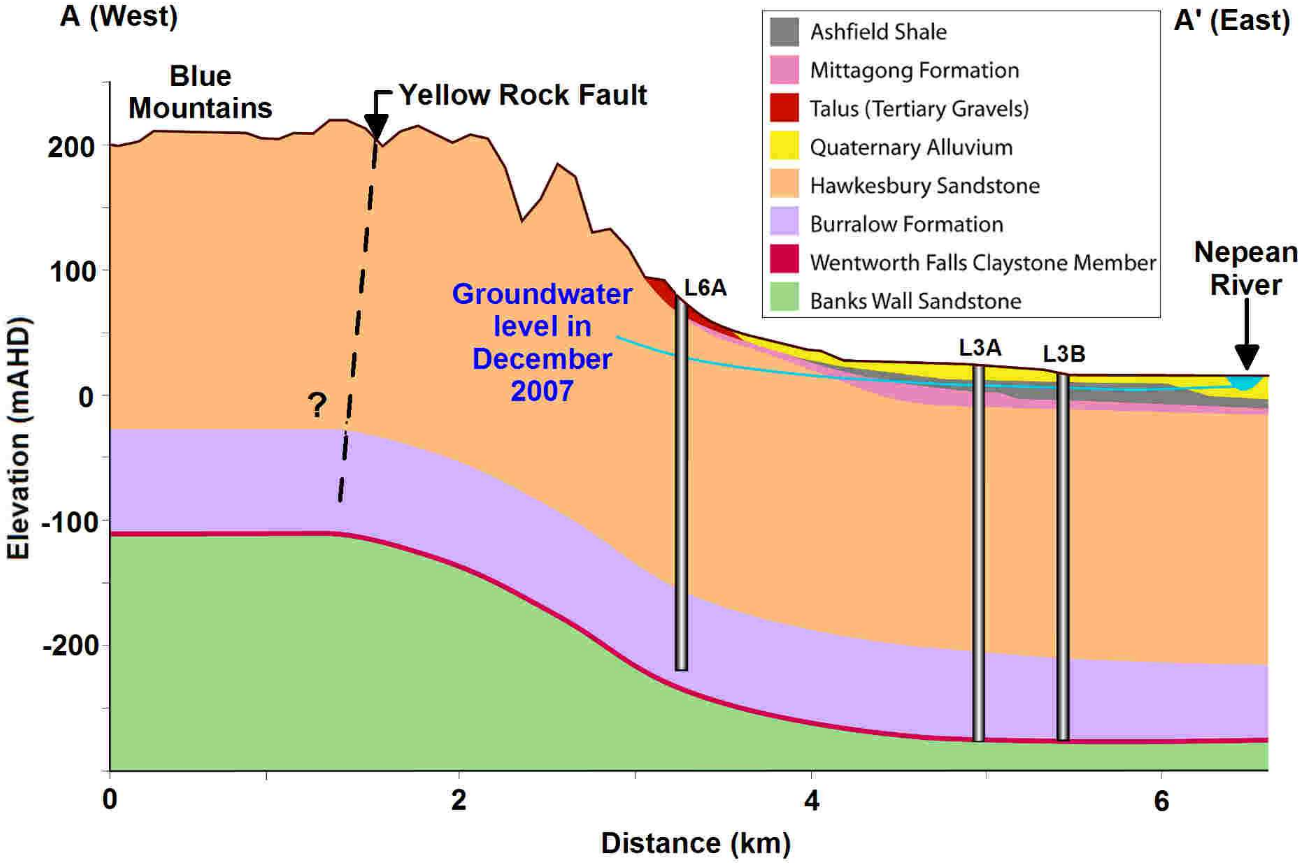

Figure 2. Hydrogeological cross section A – A' (see Figure 1 for location).

2. Aquifer Properties of Mesozoic Sydney Basin Sandstones

Previous work (Tammetta and Hewitt, 2004) identified a decreasing hydraulic conductivity with depth for Hawkesbury Sandstone that is free of major structural deformities in the northern Sydney metropolitan area. This is primarily related to increasing overburden pressure and increasing horizontal stress with depth. Figure 3 shows the results from numerous other packer tests conducted in the Hawkesbury Sandstone and Narrabeen Group in the Sydney metropolitan area and wider Sydney Basin.

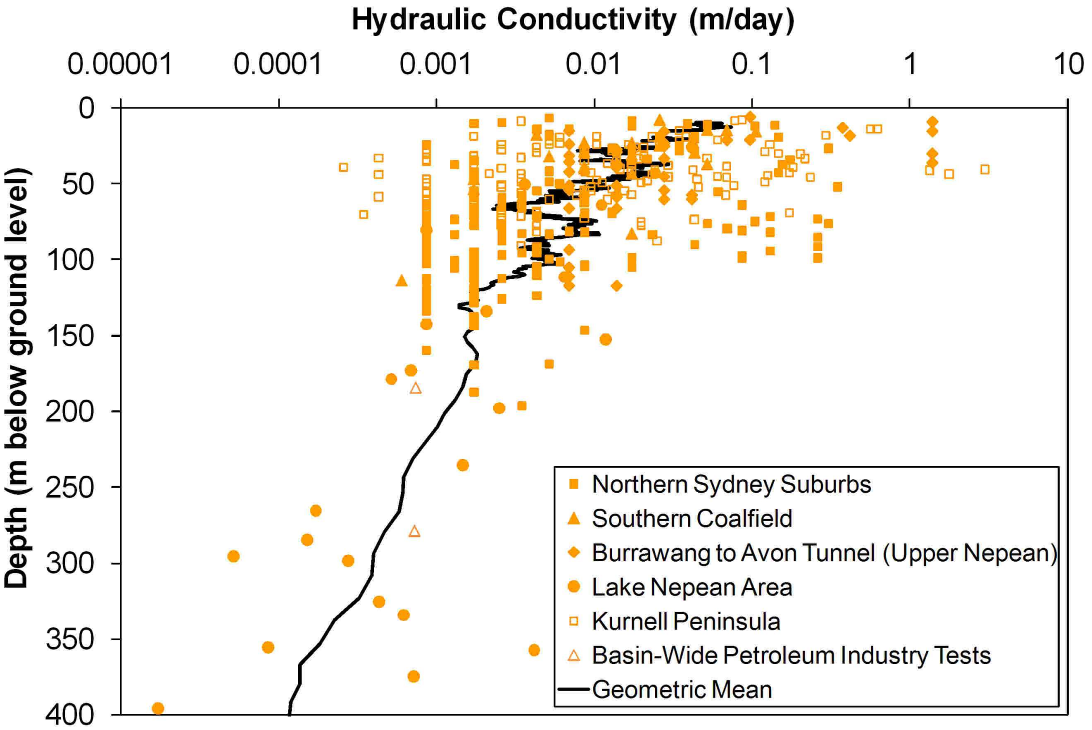

Figure 3. Calculated hydraulic conductivity from packer tests in Mesozoic quartzose sandstones in the Sydney Basin.

3. Aquifer Tests

The results of two pumping tests at Leonay Oval (WSP, 2007) and one pumping test at Koloona Reserve (PB, 2008), in the Leonay investigation area, are the focus of this paper.

Leonay Oval is a recreation park near the centre of the investigation area. Four bores (L1A, L1B, L1C, and L1D – see Figure 1) were installed for testing. Open intervals are 48m to 174m depth for L1A, 162m to 311m for L1B, 171m to 300m for L1C, and 49m to 175m for L1D. Two long-term single bore pumping tests were conducted at bores L1A (Test 1) and L1B (Test 2). Monitoring was conducted at all bores, with data from L1C and L1D used here. The radial arrangement of bores for both tests is shown in Figure 4. For both tests, the arrangement of bores provided a unique opportunity to meaningfully assess vertical hydraulic conductivity, given the low amount of overlap between monitoring bore open intervals. Program WTAQ (Barlow and Moench, 1999) uses the conceptual model of Moench (1993) to compute drawdowns in partially penetrating wells in an equivalent porous medium. WTAQ was used in conjunction with the public domain version of PEST (Watermark Numerical Computing), a model-independent inversion platform, to automatically estimate aquifer parameters. The incorporation of partial penetration of piezometers was important for these tests. Data for the second test required compensation for continuing recovery from the first test.

Koolona Reserve is a recreation park in the northern part of the investigation area. A long-term single bore pump test was conducted at bore L2A (see Figure 1). Monitoring was conducted at a large number of bores. Monitoring data from bores L2B, L1B, and L4A (see Figure 1) is used here. Open intervals are 90m to 264m depth for L2A, 162m to 311m for

L1B, 84m to 276m for L2B, and 84m to 288m for L4A. The radial arrangement of bores for this test is shown in Figure 5. WTAQ in conjuction with PEST was used to analyse this test also. Additionally, analyses were conducted using the optimisation capacity of Excel (Microsoft Corporation) in conjunction with equations describing a double porosity medium with full penetration (Moench, 1984), and the Barker model (Barker, 1988) which uses the concept of a fractional flow dimension that is controlled by the nature of the fracture population.

For each test, measured drawdowns from two or more observation piezometers were used simultaneously during an inversion run, with equal weighting applied to all observations.

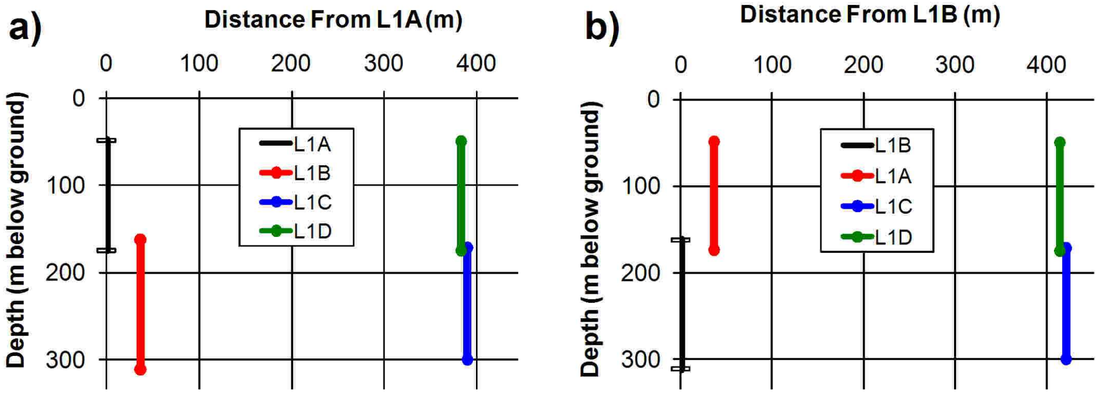

Figure 4. Radial arrangement of bore open intervals for Leonay for a) Test 1 and b) test 2.

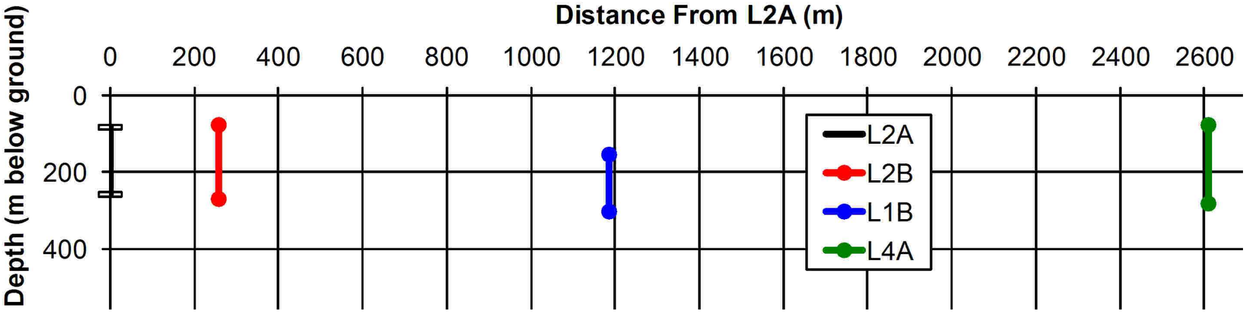

Figure 5. Radial arrangement of bore open intervals for the Koloona test.

4. Aquifer Conceptual Models

The single porosity model used here (Moench, 1993) consists of a homogenous and anisotropic aquifer of constant thickness. Anisotropy is incorporated by constraining the principal directions of the hydraulic conductivity tensor to being parallel to the coordinate axes (in this case, vertically and laterally). WTAQ (Barlow and Moench, 1999) allows partial penetration of piezometers, and can treat the aquifer as confined or unconfined by choice of the way in which the upper boundary is treated in the solution. For all three test analyses, the water table and confined options were both trialled with almost identical results.

A double porosity medium consists of two interacting and overlapping continua (Moench, 1984): a continuum of low permeability primary porosity (matrix) blocks and a continuum of high permeability, secondary porosity fractures (fissures), with hydraulic parameters defined for each continuum. Flow to the well occurs through the fractures only. The model used in this work assumes full penetration of piezometers and transient block-to-fracture flow. It also incorporates the concept of fracture skin, where the fracture faces are coated with a thin film of low permeability material (such as chemical precipitates or weathered rock material). Fracture skin is a relatively important concept, and is incorporated in the model as the dimensionless quantity $F = k'b_s / k_s b'$ where k' is the block hydraulic conductivity, k_s the hydraulic conductivity of the skin, b_s is the average skin thickness, and b' is the matrix slab half-thickness. This model provides no estimate of vertical hydraulic conductivity due to the assumption of full penetration.

Barker (1988) generalised the radial form of the transient groundwater flow equation to a variable, non-integral flow dimension by assuming that flow takes place through an n-dimensional sphere, with $1 < n < 3$ (Le Borgne et al., 2004; Marechal et al., 2003), creating the concept of the fractional flow dimension, n. In this continuum, drawdown does not necessarily evolve in two dimensions during an aquifer test. The size of the water cross-flow area A (the frontal equipotential surface) is a function of the radial distance from the bore to the water source point r, and is proportional to r^{n-1} (Rafini and Larocque, 2009). Figure 6 (after Figure 6 of Marechal et al., 2003) illustrates the concept of variable flow dimension. The generalised aquifer transmissivity T, and storativity S, are given by $T=k_f b^{3-n}$ and $S=S_s b^{3-n}$ respectively, where b is the "transversal" extent of the flow region, k_f is the fracture system hydraulic conductivity, and S_s is the specific storage of fractures. Matrix blocks play no part in the system. The Theis solution (Theis, 1935) is the 2-dimensional (cylindrical) form of this generalised system, with b corresponding to the aquifer thickness.

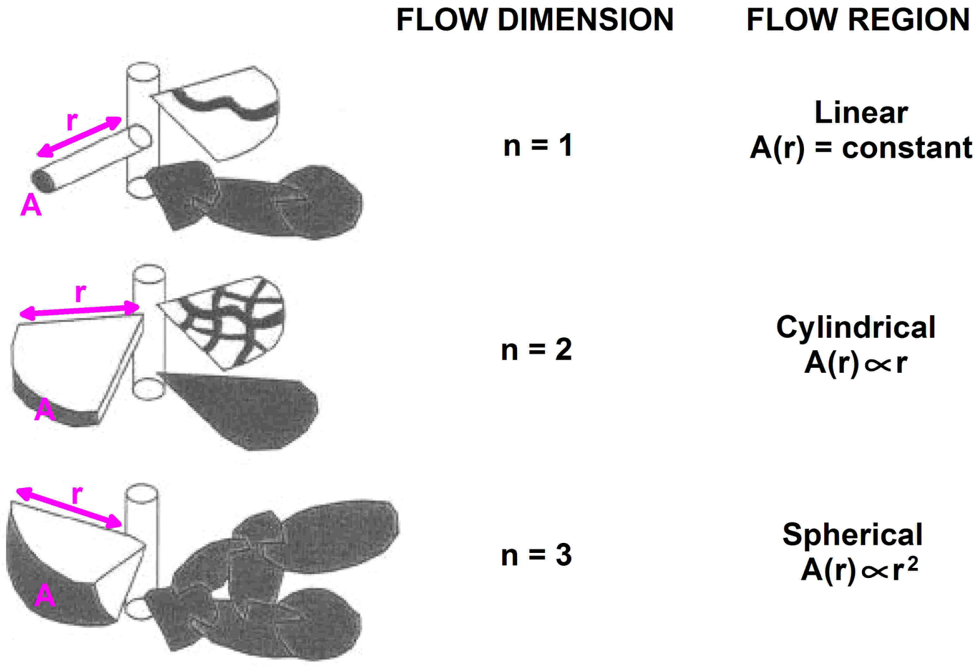

Figure 6. Schematic representation of a bore and various flow geometries according to the flow dimension of the Barker (1988) model (after Figure 6 of Marechal et al., 2003).

5. Analysis

5.1. Leonay Oval

Figure 7 shows the results of inversion for the single porosity medium (WTAQ) for Tests 1 and 2. Optimised aquifer parameters were remarkably consistent between tests, with an aquifer thickness of between 220m and 250m, a transmissivity of between 60 and $70m^2$/day, and a specific storage of $4.5x10^{-6}m^{-1}$.

In contrast, estimates of vertical hydraulic conductivity k_z divided by lateral hydraulic conductivity k_r varied significantly. k_z/k_r for the first test (pumping from L1A, the shallow bore) was estimated to be 0.026, and for the second test 0.00004. This disparity is probably due to the variation (decrease) of k_r down the aquifer profile, deviating from the assumptions of the conceptual model used in the WTAQ solution (constant k_r versus depth). The estimates of k_z/k_r are similar to values required for calibration of a numerical groundwater flow model used to simulate the response of a Hawkesbury Sandstone groundwater system to various potential pumping stresses in the southern highlands (Coffey, 2008), and provide added verification for this all-important parameter.

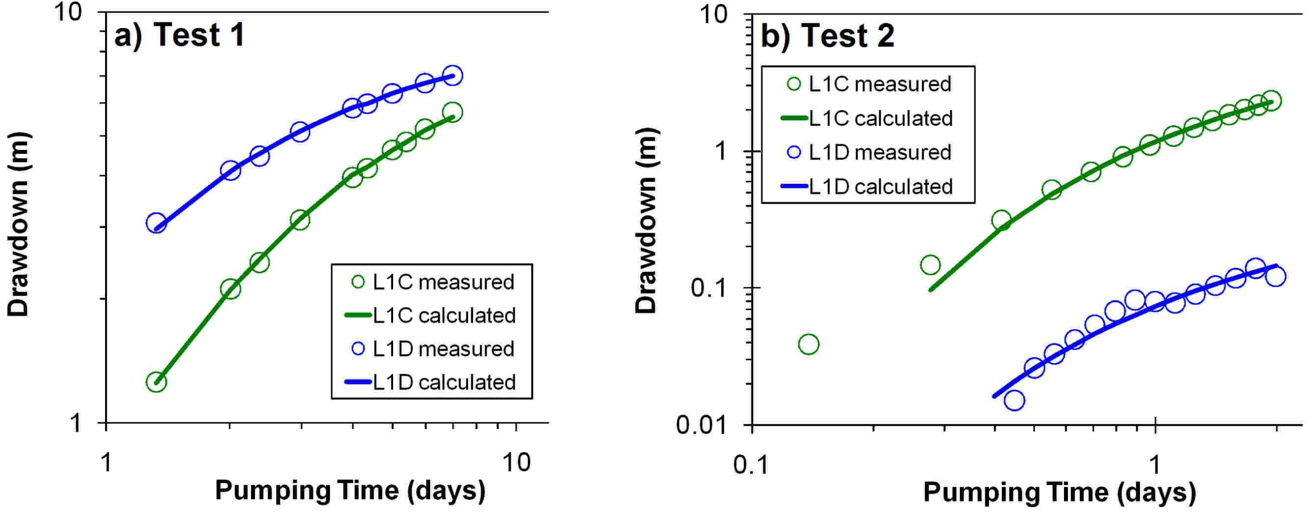

Figure 7. Comparison between measured and calculated drawdowns for the optimal single porosity (WTAQ) models for Leonay Oval for a) Test 1 and b) Test 2.

5.2. *Koloona Reserve*

Figure 8 shows the results of inversion for the single porosity medium (WTAQ), double porosity medium (with and without fracture skin), and fractional flow dimension system.

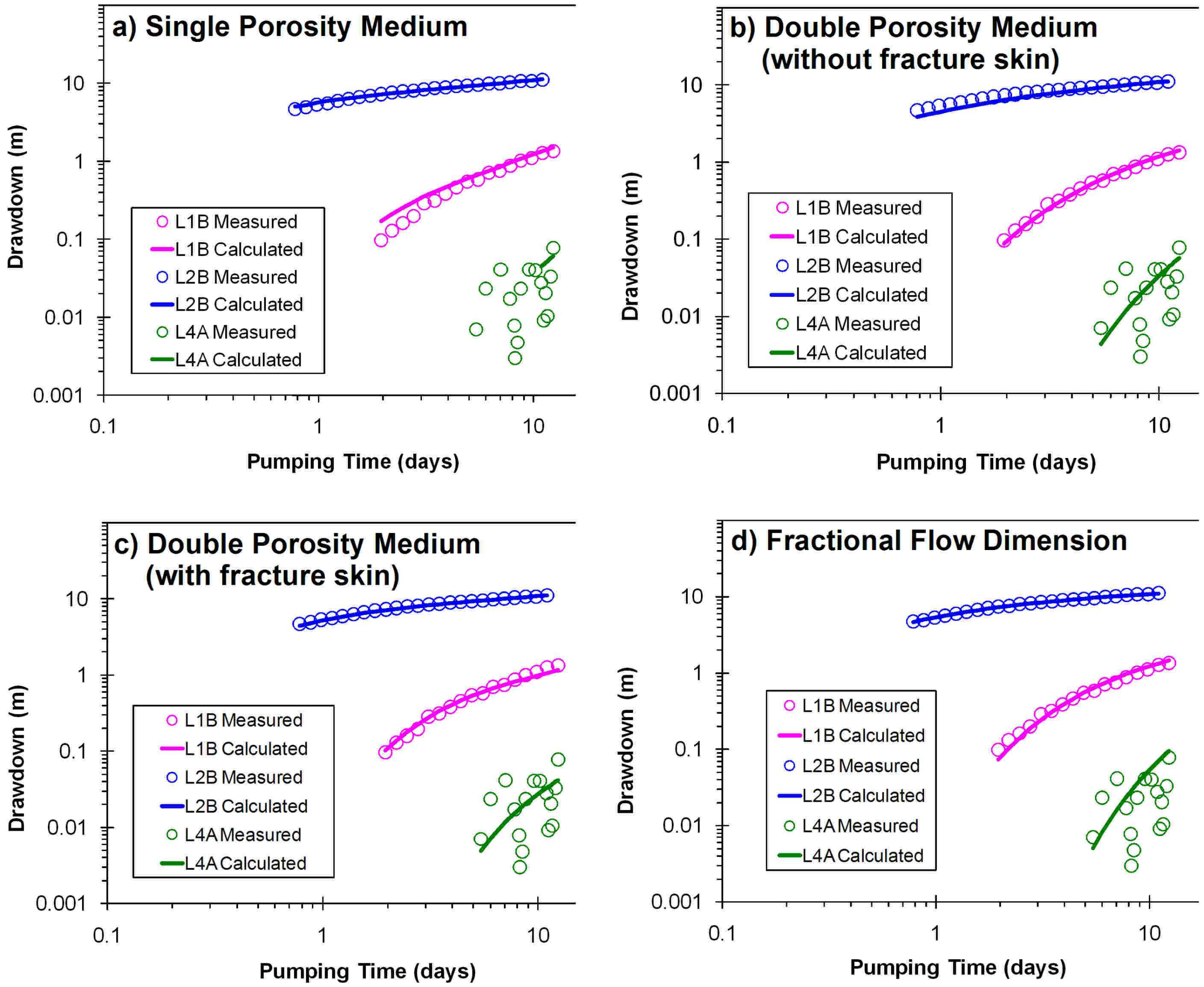

Figure 8. Comparison between measured and calculated drawdowns for the optimal a) single porosity (WTAQ), b) double porosity without fracture skin, c) double porosity with fracture skin, and c) fractional flow dimension models for the Koloona test.

For the single porosity model, results were an aquifer thickness of around 250m, transmissivity of $27m^2$/day, and specific storage of $1x10^{-6}m^{-1}$. k_z/k_r was estimated to be 0.16, however this value may be biased by the extensive overlap of monitoring piezometer screens, with minimal measurement of hydraulic heads at relatively large vertical distances from the top and bottom of the pumping well screen (that is, the predominance of lateral flow in the measured drawdowns). Drawdowns less than about 0.05m were not calculated due to the nature of the numerical solution scheme in WTAQ and the precision of the computer processor used.

For the double porosity model, two cases were run. The first case comprised a fixed matrix slab thickness of 3m, a fixed aquifer thickness of 250m, and no fracture skin (clean fractures). Results were a transmissivity of $23m^2$/day, fracture specific storage of $1x10^{-5}m^{-1}$, matrix block hydraulic conductivity of $1x10^{-7}$m/day, and matrix block specific storage of $2x10^{-4}m^{-1}$. Block hydraulic conductivity was considered unreasonably low so the second case comprised the same slab and aquifer thickness as the first case, but with a fixed matrix hydraulic conductivity of 0.001m/day and the presence of fracture skin. Results for the second case were a transmissivity of $20m^2$/day, fracture specific storage of $1x10^{-5}m^{-1}$, matrix block specific storage of $4x10^{-5}m^{-1}$, and a fracture skin of 490 (dimensionless). Results for both cases indicate that some impedance may be present in the flow of water from matrix blocks to fractures (such as a low block hydraulic conductivity or the presence of a low hydraulic conductivity fracture skin).

The generalised radial flow model of Barker returned a flow dimension of 2.6 (intermediate between cylindrical and spherical flow), a fracture system hydraulic conductivity of 0.05m/day, a “transversal” flow region extent of 300m (with an associated generalised transmissivity of $15m^{1.4}$/day), and a fracture specific storage of $7x10^{-7}m^{-1}$. The generalised transmissivity does not apply to a classical cylindrical flow system. The calculated fracture system hydraulic conductivity is neither the k_z nor the k_r of the system, but in this case (n=2.6) could probably be viewed as some combination of the two.

6. Discussion

Pump tests recently conducted in Mesozoic sandstones in western Sydney have provided relatively rare and important datasets for characterisation of fractured rock aquifer hydraulic characteristics. Results indicate that at the scale of these tests, the aquifer has responded in a way similar to various analytical concepts. The simultaneous use of drawdowns from two or more observation piezometers significantly reduces the uncertainty in aquifer parameter estimates.

Results of analysis of the pump test data lend support to calibrated aquifer parameter values used in a numerical flow model for Mesozoic sandstone in the southern Sydney Basin. Most aquifer test solutions do not incorporate a decreasing hydraulic conductivity with depth, requiring judgement in assessing aquifer test results where this situation may exist.

Acknowledgements

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Quantifying the potential impact of leaky boreholes

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Leaky boreholes can potentially impact on groundwater flow and water quality. Shales overlying Hawkesbury sandstones in the Sydney area containing saline water should be sealed off using pressure cementing techniques during drilling. However, due to various factors, current practice does not always comply with bore construction and abandonment guidelines. This poster presents an example of a poorly constructed bore, calculated mixing ratios of saline and fresh groundwater, and an example of numerical modelling to quantify bore leakage volume in a stressed aquitard-aquifer system.

Thousands of bores have been drilled through sediments into underlying rock in NSW. Provided that sealing procedures in the Australian Standard and NSW DPI standards are adopted (ADIA, 2003; DPI 1997), drilling for water, testing or mineral resources is a negligible risk to groundwater quality. However, improperly constructed bores and failed aging bores may have impacted on groundwater quality in some locations.

Possible borehole leakage pathways are shown in Figure 1, compared with a borehole constructed and maintained according to best practice. Five possible leakage pathways are shown, including leakage through a poorly sealed annulus.

International studies on leaky bores have led to extension programs in areas to provide information and support for proper bore construction and abandonment. In one country, there is an estimated 30,000 leaky water supply bores that have passed their life expectancy of 30-50 years. Diagnosis of leakage pathways to support effective rehabilitation or abandonment should be based on a combination of evaluation tools (Santi et al, 2006). Testing of three leaky borehole sites found that calculation of flow rates for various leakage pathways was the most useful diagnostic method. Numerical modelling by Lacombe et al. (1995), found that an entire contaminant plume, or a significant portion of it, could be diverted to a lower aquifer via an open borehole subjected to high hydraulic gradient.

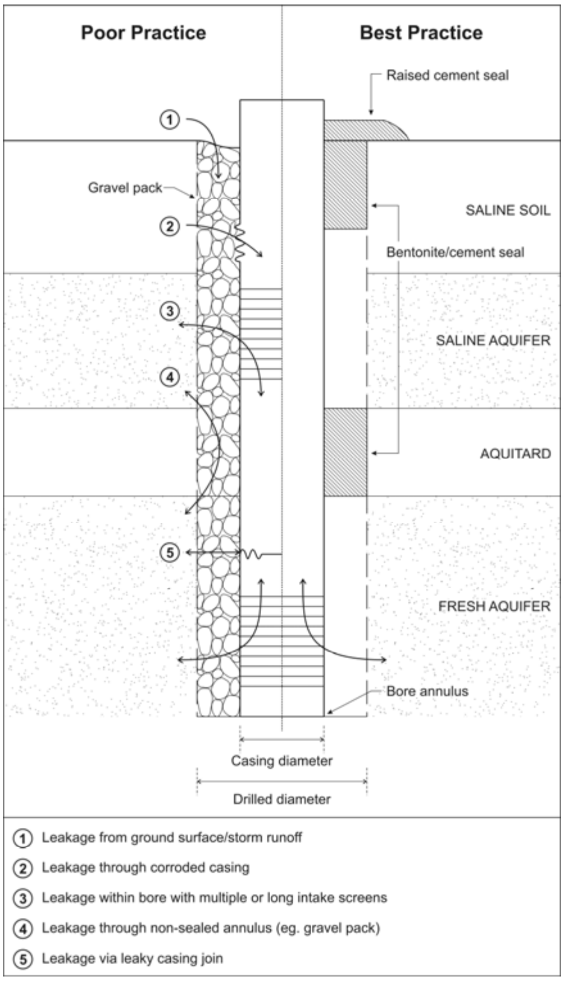

Figure 1. Poor practice and best practice borehole condition.

Drilling through saline shale

A bore recently installed in the Bankstown area yielded groundwater that was too saline (7,900 mg/L TDS, 12,520 µS/cm) for irrigation. By comparison, water in the Hawkesbury sandstone is known to be saline with TDS values >3000 mg/L reported in this area by Russell (2007). The bore was drilled to 240 m using rotary air and mud techniques with no record of pressure cementing or attempts to seal between shale and an underlying sandstone groundwater source. The bore was completed with open-ended PVC casing through shale to 42 m depth and completed as an open-hole bore below that depth. Airlift yield estimates were 3 L/second with most of the inflow at about 200 m depth. It is possible, though unproven that saline leakage from the shale occurs in the borehole, given the relatively high groundwater salinity that was observed in the Hawkesbury sandstone.

Mixing ratios of salt and freshwater were calculated to assess possible solutions for bore remediation and irrigation usage. Figure 2 shows mixed salinities for non-reactive or conservative mixing at the Bankstown site (1), compared with a reactive mixing of a saline and fresh groundwater at an unidentified site (2). At the Bankstown site, a saline groundwater with 12,000 µS/cm is mixed with fresh dam water of 200 µS/cm. Alternatively, although there is no site specific data, the fresh water value could represent fresh groundwater. It is significant that a relatively small proportion of saline water (1.7%) would result in a doubling of salinity to 400 µS/cm. For this borewater to comply with irrigation guidelines (5,200 µS/cm for tolerant vegetation) a mix of 42% saline plus 58% fresh water would be required. Irrigation water drawn from this bore must therefore be mixed with a larger volume of fresh dam water.

Downhole geophysical logging and chemical tracing techniques were recommended as an independent check on borehole construction and the salinity profile in rock surrounding the casing to enable the bore to be modified and produce lower salinity water. However, the potential costs of diagnosis and rehabilitation of this bore meant that alternative water sources were pursued.

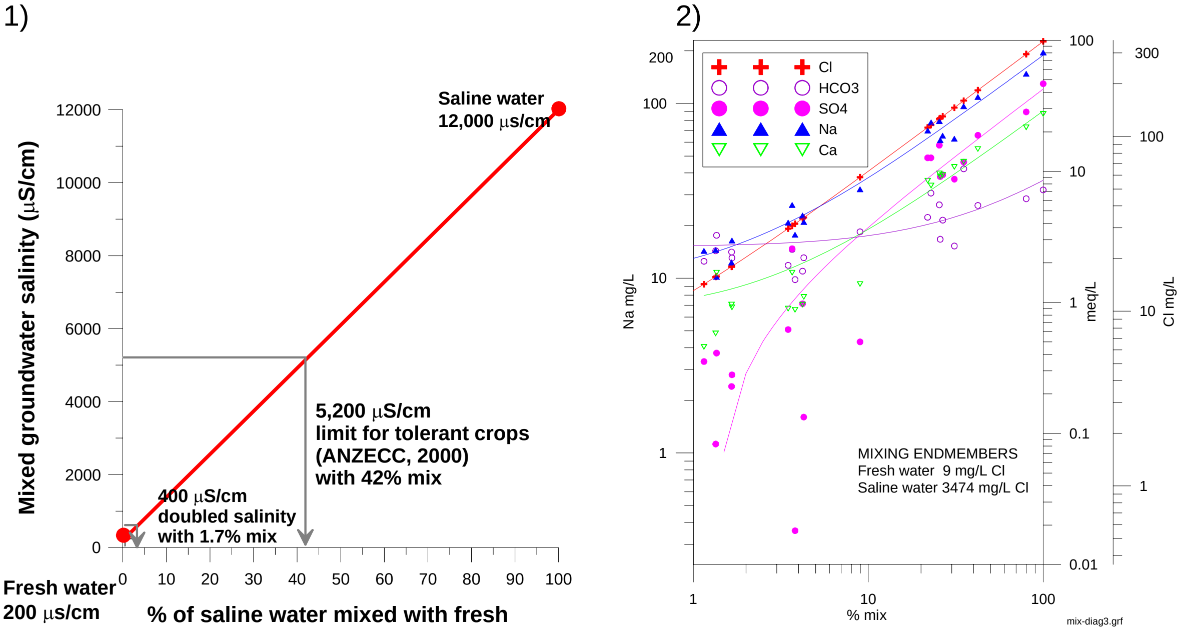

Figure 2. Groundwater salinity mixing diagrams 1) Conservative mixing at Bankstown site and 2) Mixing diagram for a site with linear trend for chloride (conservative mixing) and non-linear trends for bicarbonate, sulphate, sodium and calcium (reactive mixing).

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Numerical modelling of leaky boreholes

Although leaky boreholes potentially impact on groundwater quality, numerical modelling indicates that the volume of leakage compared to aquifer flow may not be significant. A multi-layered axisymmetric FEFLOW model (Figure 3) was developed to quantify fluxes in an aquifer-aquitard system that was stressed by an irrigation bore (Timms, 2001). A rectangular mesh, with mesh enrichment around a single bore was developed including a leaky gravel pack in the annular space (0.2-0.4 m radius) with a vertical hydraulic conductivity of 40-100 m/day.

The leaky annulus accounted for 0.04-1.2% of total volume extracted from the irrigation bore, and was of minor importance relative to horizontal flow in the multiple layered aquifers. Total flow rate through the borehole was very sensitive to borehole radius similar to findings by Lacombe et al. (1995) who showed that bore flux Q was proportional to bore radius, r^4.In this example, horizontal flow and vertical leakage through aquitards were of greater significance than a single leaky borehole for vertical flow (Figure 4), particularly where natural discontinuities occurred in the aquitard.

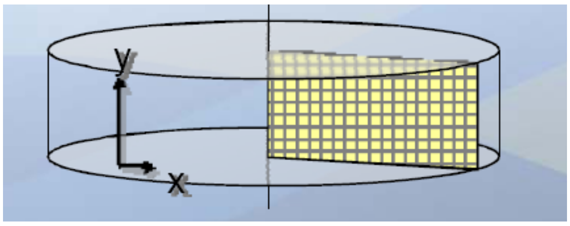

Figure 3. Axisymmetric flow (DHI-WASY, 2009)

Table 1. Leakage via a borehole annulus compared to other flow pathways as a % of groundwater extracted.

Bore radius (m)	Annulus K* (m/day)	Flow pathway %		
		Bore annulus	Vertical aquitard	Horizontal aquifer
0	-	-	19.7	80.3
0.2	40	0.035	19.7	80.3
0.2	100	0.084	20.1	79.9
0.4	40	0.24	19.1	80.6
0.4	100	0.58	-	-
0.4	200	1.16	-	-

*K = hydraulic conductivity

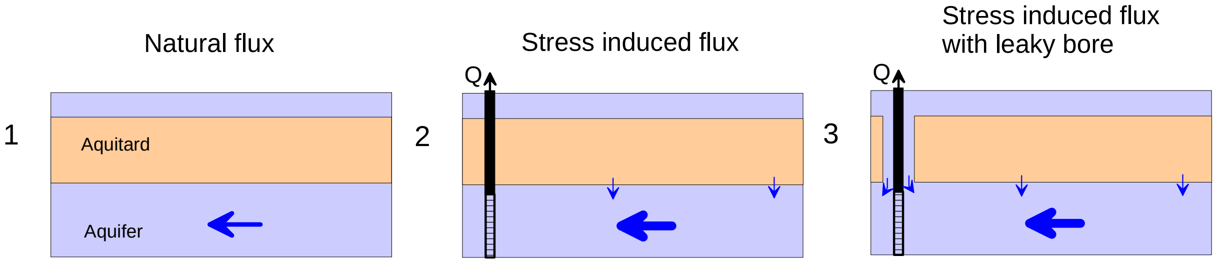

Figure 4. Conceptual models of an aquifer-aquitard system with a continuous aquitard where flux is proportional to the number and size of arrows. Scenario 1 Natural flux. Scenario 2 Stress induced flux. Scenario 3 Leaky borehole flux.

Conclusions

These examples indicate that depending on site s conditions, bore leakage may account for a relatively small proportion of flow (0.04-1.2%), however a small proportion of leakage (1.7%) can result in a doubling of salinity if there is a source of highly saline groundwater. The potential impact of transient flow conditions, and more than one leaky borehole could be further assessed by numerical modelling. Geophysical and chemical tracing techniques are recommended for assessing aging bore infrastructure. The proper abandonment of unsatisfactory bores is considered to be both an opportunity for the drilling industry and essential for sustainable groundwater resources. Improved training, supervision and auditing of water bore drillers is recommended to ensure good environmental practice.

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Measurement of Hydraulic Conductivity, Porosity and Lithology by Neutron Activation Borehole Logging at high spatial resolution increments

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Abstract

A new method of measuring the continuously variable hydraulic conductivity at 20 cm increments surrounding a borehole is described. The method requires injection of a tracer solution and measurement of the variable distance the tracer has moved by prompt gamma neutron activation analysis (PGNAA) geophysical logging. Gamma spectra collected by PGNAA logging from 0.16 to 10 MeV are analysed to provide a relative abundance of elements H, Si, Al, Fe, Cl and possibly others if sufficiently abundant. The distance a NaCl or KCl tracer solution has migrated into the rock surrounding the borehole is calculated from the greater energy attenuation of a 1.95 MeV low energy Cl gamma emission compared to a 6.1 or 7.4 MeV high energy Cl emission. The differential gamma attenuation is verified by experiment.

A simple but sensitive method for measuring relative porosity surrounding a borehole is also presented by measuring the elemental abundances of common rock forming minerals and water, allocating elements to minerals and presenting a water/rock ratio. Relative porosity may be further simplified to H/(H+Si) particularly for sandstones typical from the Sydney Basin. Many boreholes of hydrological interest are drilled into sedimentary rocks and alluvium dominated by abundant quartz and clay, which can be quantified by relative Si and Al. Similarly, many sedimentary lithologies may be defined by variations in their mineralogy reflected in proportional changes in elemental abundance. Subtle variations in lithology not apparent by visual inspection such as degree of cementation or clay pore filling in sandstone may also be detected. Porosity and lithology estimation by PGNAA geophysical logging does not require a tracer solution to be injected and may be measured through borehole casing with screened or unscreened intervals.

Keywords: hydraulic conductivity, geophysics, neutron activation, porosity, borehole logging, PGNAA

Introduction

Hydraulic conductivity measurement

Current methods for calculation of hydraulic conductivity are based on the Darcy's law, which relates the rate of fluid flow to the applied hydraulic gradient. In practice these methods typically require measurement of changing pressure or head height difference with time. A difficulty with this approach is the measurement only provides a single average hydraulic conductivity value over an isolated screened interval or over the entire borehole beneath the standing water level. Multiple zones cannot be isolated for measurement in a single borehole without considerable difficulty and expense. If multiple aquifers or significant lithological heterogeneity is anticipated, multiple boreholes are often drilled for individual assessment of target zones. Significant or even the dominant flow zones in a borehole may be missed if not targeted for measurement. Higher flow rates from fractures cannot be distinguished from distributed porous media flow when averaged across significant measurement intervals.

A nuclear geophysical logging technique, Prompt Gamma Neutron Activation Analysis (PGNAA) is used to trace the flow of an injected salt solution into fractures and into the porous and permeable sandstone surrounding the borehole. The variable distance the salt tracer moves into the porous rock under a known pressure increase (above standing water level), over a known time and tracer volume allows calculation of hydraulic conductivity at 20cm increments along the length of the borehole. If there is significant flow of the tracer into fractures and beyond the PGNAA measurement range a relative tracer movement distance is provided by the PGNAA log, rather than hydraulic conductivity. Other relevant lithological and hydraulic parameters such as porosity may be derived from measured Si, H, Cl, ±Fe, ±Al elemental abundance provided by PGNAA borehole logging.

Sandstone aquifers within the Sydney Basin have been identified as a significant source of emergency groundwater supply for Sydney that may be affected by longwall mine subsidence. Considerable variation in flow rates under pump tests is observed for closely spaced boreholes (PB 2006). The variability may be due intersection of fractures or interpreted as significant variations in sandstone composition and inter-granular fabric. Distinction between these interpretations and definition of preferential flow paths is possible with the high spatial resolution offered by the PGNAA logging technique. Hydraulic conductivity, porosity and lithological measurements from PGNAA logging of boreholes in the Hawkesbury Sandstone are compared to pump test and laboratory measurements. Passive environmental tracer techniques are widely used to assess surface – groundwater interactions (eg. Michel & Turk 1996), and within the Sydney Basin (Waring et al 2007a), whilst the PGNAA hydraulic conductivity measurement technique requires a tracer to be actively injected.

Technique and equipment

Neutron activation analysis

Neutron activation analysis is a family of extremely useful quantitative elemental analysis techniques that have not been widely applied to field applications because of previous hardware limitations, availability and cost. Precise laboratory neutron activation measurements have utilised either a nuclear reactor for delayed Neutron Activation Analysis (NAA) or a pulsed neutron generator (Nargolwalla & Przybylowicz 1973) for prompt gamma neutron activation analysis (PGNAA), combined with DNAA and inelastic neutron scattering (INS) techniques.

Field techniques cannot use high neutron flux reactor neutron sources and must rely on either low neutron flux isotope neutron sources (^{252}Cf & AmBe) to limit radiation exposure risk to the operator or old design Penning diode neutron generators. The latter are miniature high-voltage accelerator D-T nuclear fusion devices which have a limited lifetime before wearing out and requiring expensive tube replacement. Large oil and gas industry service companies have built geophysical borehole logging tools incorporating neutron generators but have not sold the equipment. Commercially available neutron activation analysis field equipment is currently limited to some large industrial conveyor belt online analysis applications using accelerator neutron generators (eg Sodern) or the use of low-flux isotope neutron sources in borehole logging equipment (eg CSIRO Exploration & Mining). New design accelerator neutron sources with pulsed operation, high-flux and a long lifetime are now available and are likely to be incorporated into the next generation of neutron activation field equipment.

The other essential component to neutron activation analysis field equipment is the gamma scintillation detector. Laboratory NAA has long used cryogenically cooled High Purity Germanium (HPGe) detectors for very high gamma spectral resolution and long static count times. Field applications of NAA have been restricted to coarse spectral resolution provided by NaI or BGO (Bismuth Germinate) detectors, which do not require cooling. New $LaBr_3Ce$ scintillation detectors are now available with 3 times the spectral resolution of BGO and do not require cryogenic cooling.

The combination of new design high-flux neutron generators that can be switched off for safe handling and new scintillation detectors promises greater sensitivity and precision for in-situ Neutron Activation elemental analysis.

PGNAA geophysical logging

CSIRO Exploration and Mining build and supply PGNAA borehole logging tools, which use an isotope neutron source and a BGO gamma detector. An upgraded modification to this configuration substituting the BGO detector with a $LaBr_3Ce$ detector is currently being used by ANSTO. The SIROLOG logging tool has 480 channels (gamma energies), is 72mm diameter, 1.8m long and uses an AUSLOG single conductor winch for logging borehole depths up to ~500m. The SIROLOG equipment may also be operated without the neutron source to give the natural gamma radiation variation up the borehole due to K, U, & Th in the surrounding rock.

To measure subtle lithological or porosity variations for hydrogeology applications is a simple standard logging procedure, withdrawing the logging tool up the borehole at <2m per minute. Gamma spectra are acquired and integrated over 20cm increments up the borehole. These stacked gamma spectra may be viewed graphically during logging. Gamma spectral analysis software identifies peaks from a spectral library, measures peak area and quantifies the elemental abundance by comparison with known standards. Major elements found in the sandstones of the Sydney Basin (H, Si, Fe, Cl, ±Al) are able to be measured with the standard SIROLOG configuration. The new $LaBr_3Ce$ detector is likely to improve sensitivity and allow measurement of some minor to trace elements (Na, K, Ca, Mg, S, Ti, ..) if sufficiently abundant.

Tracer injection and parameter monitoring

The principle requirement for the tracer injection is to be able to reduce the measured tracer gamma counts firstly to a radial distance from the borehole and then to a hydraulic conductivity within the detection limits of the borehole logging equipment

(Waring et al, 2007). Prior to tracer injection pressure, flow and electrical conductivity sensors are placed in the borehole. The tracer flow is monitored and controlled by borehole and surface pumps. A simplified practical tracer injection procedure described has a repeatable sequence.

First stage involves mixing a uniform concentration of the tracer solution in the bore as well as in the surface tank whilst maintaining the constant equilibrium SWL. Compensation for density change is required.

Second stage injection step applies a pressure head to the solution in the bore by draining tracer from the surface tank to effect the injection. After the tracer has been injected into the rock surrounding the bore the bore is logged by the PGNA logging equipment. Multiple steps of tracer injection followed by PGNA logging are possible to observe incremental change of tracer movement. The tracer may also be removed from the bore and replaced by fresh water at constant SWL (with density compensation), in effect the mix stage in reverse. Further addition of fresh water will push the tracer further into the rock allowing measurement biased to tracer signal further from the detector.

Tracer injection by this method will produce a radial distribution of the tracer at constant concentration away from the borehole, described as the 1) Smooth uniform injection case, (described below). Other methods of injection where the tracer is progressively diluted throughout the injection 2) Fast injection case, and where the tracer diffuses into the rock 3) Diffusive intrusion, are also developed.

An important advantage of the technique is the independence of the radial distance calculation from variations in tracer concentration due to variations in porosity of the host rock. Tracer concentration variations do not matter so long as the concentration and distance remains within the detection limits of the equipment. The radial distance travelled by the tracer is derived by measuring the ratio of 2 tracer gamma peaks, one at low energy and one at high energy. Low energy gamma radiation will be attenuated by the intervening rock more than high energy gamma radiation. Tracer concentration variations will affect both peaks similarly but not affect the peak area ratio.

Method

Hydraulic conductivity calculation method description

The method of calculating hydraulic conductivity is dependent upon measuring the variable distance a tracer moves into permeable rock surrounding a borehole under a known hydraulic gradient over a known time interval. The hydraulic gradient in this case is the head difference from the standing water level and the duration of the tracer injection. Calculation of the average hydraulic conductivity over the injection interval is a derivation from Darcy's Law.

$$\mathbf{V}_{sp} = -K\nabla\Psi ,$$

(Eq. 1)

where Vsp is the seepage velocity in m/s, K is the hydraulic conductivity in m/s, Ψ = ψ + p/(ρg) is the total pressure head in meters with ψ being the liquid head, p – atmospheric pressure, ρ – liquid density, g – acceleration due to gravity, and □ stands for the gradient operator. In cylindrically-symmetrical 1D case Darcy law simplifies and reads as

$$V_{sp} = -K \frac{d\Psi}{dr},$$

(Eq. 2)

where Vsp is the radial component of the seepage velocity, and r is the radial coordinate. This formula can be inverted to obtain K via seepage velocity and pressure-head gradient:

$$K = -\frac{V_{sp}}{d\Psi / dr}.$$

(Eq. 3)

Thus, to calculate the hydraulic conductivity one needs to know a local value of the seepage velocity Vsp(r) and pressure-head gradient dΨ/dr as a function of r. However, the detail knowledge of both these values is practically unavailable, therefore Eq. (3) can be used in its approximate finite-difference form to obtain at least an estimation of the hydraulic conductivity:

$$K \approx -V_{sp} \times \frac{\Delta r}{\Delta\Psi} \approx -\frac{\Delta r}{\Delta t} \times \frac{\Delta r}{\Delta\Psi} = -\frac{(\Delta r)^2}{\Delta\Psi \Delta t}.$$

(Eq. 4)

In this equation not only the pressure-head gradient was replaced with its finite-difference approximation $d\Psi/dr \approx \Delta\Psi/\Delta r$, but also seepage velocity was also replaced by the finite-difference approximation too $Vsp(r) \approx \Delta r/\Delta t$, where Δt is the time interval needed for the liquid to pass on distance Δr within the porous medium. If the drop of the pressure-head ΔΨ over distance Δr is known and time interval over which this drop occurs is also known, one can estimate the hydraulic conductivity on the basis of Eq. (4), provided that the distance Δr can be measured somehow.

Tracer distance model relationship

The key parameter for the variable hydraulic conductivity calculation is the measurement of the variable distance the tracer has moved from the borehole. A simple mathematical basis for relating measured injected tracer gamma-radiation counts in a borehole to the distance the tracer has moved is developed. Gamma-radiation comes from the distributed radiotracer source in the form of either a radioactive solution or a solution containing a high gamma yield activatable element such as Cl. A theory is developed in general for 2D and 3D cases and in a detail for the 1D case. Different types of distribution functions are considered for the last case and the results compared.

The first section contains a theoretical background for calculating gamma-radiation counts in a borehole. It is supposed that the gamma-radiation comes from the distributed source (radiotracer). The theory is developed in general for 2D and 3D cases (Waring et al. 2007) and in a detail for the 1D case here.

Laboratory experiments of gamma-radiation attenuation from different radioactive sources (Co-60, Cs-137) were conducted to verify the theory developed. The measurements were conducted in air, water and river sand (both dry and water saturated). The decay rate of gamma-radiation has been measured as a function of distance for all types of media mentioned above. The experimental data can be interpreted within 1D theory with the appropriate model of distribution function.

Theoretical basis for injected tracer distribution

1D case

Considering first a 1D model when the radioactive tracer is distributed along the axis x (Fig. 1).

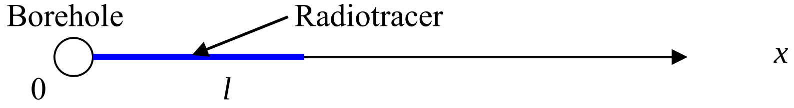


Figure 1 A schematic diagram showing a 1D case of radial tracer distribution around a borehole

Assume that the radioactive tracer is distributed non-uniformly with a density of distribution characterised by the function $F(x) = I_0(x)e^{-t\ln 2/\tau}$, where τ is the half-life time of radioactive material.

The intensity of received gamma-radiation by a detector placed into the borehole from a volume dx at distance x is $F(x)dx = I_0(x)e^{-t\ln 2/\tau}e^{-\mu x}dx$, where $\mu(E)$ is the attenuation factor which depends on the excitation energy. Hence, the total intensity of the received gamma-radiation at a borehole from the whole interval $[0, l]$ is:

$$I_{tot}(l) = e^{-t\ln 2/\tau}\int_0^l I_0(x)e^{-\mu x}dx \,. \qquad \text{(Eq. 5)}$$

This value depends both on the spatial interval l across which the radioactive tracer is distributed and on the distribution function $I_0(x)$. We consider three particular cases, which model different regimes of radiotracer injection.

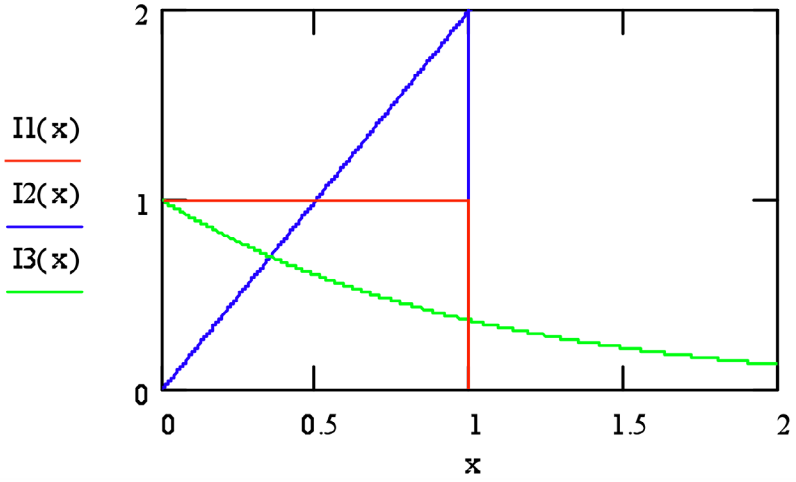


Figure 2 Tracer concentration vs distance from borehole. Three different types of tracer injection distribution functions; smooth uniform injection (red), fast injection (blue), diffusive intrusion (green). I = concentration, x = dimensionless distance from borehole

1) "Smooth uniform injection case". In this case the radioactive material supposed to be uniformly distributed on the interval $0 < x < l$ with the density $I_0 = M/l$ = const, where M is the total "mass" of radioactive material. Formula (1) gives

$$I_{tot}(l) = \frac{M}{\mu l}\left(1 - \mathrm{e}^{-\mu l}\right)\mathrm{e}^{-t \ln 2/\tau} \qquad \text{(Eq. 6)}$$

This dependence is illustrated in Fig. 2 (red curve) in normalised variables:

$$Y1(z) = \frac{1}{z}\left(1 - \mathrm{e}^{-z}\right), \qquad \text{(Eq. 7)}$$

where $Y1 \equiv \frac{I_{tot}}{M}\mathrm{e}^{t \ln 2/\tau}, \quad z \equiv \mu l$.

2) "Fast injection case". It is supposed that the radioactive material is distributed linearly with the density of distribution $I_0(x) = 2Mx/l^2$ at $0 < x < l$. Formula (1) gives

$$I_{tot}(l) = \frac{2M}{\mu^2 l^2}\left[1 - (1 + \mu l)\mathrm{e}^{-\mu l}\right]\mathrm{e}^{-t \ln 2/\tau}. \qquad \text{(Eq. 8)}$$

This dependence is illustrated in Fig. 2 (the blue curve) in the same normalised variables:

$$Y2(z) = \frac{2}{z^2}\left[1 - (1 + z)\,\mathrm{e}^{-z}\right]. \qquad \text{(Eq. 9)}$$

3) "Diffusive intrusion". Radiotracer is assumed to be distributed exponentially: $I_0(x) = (M/l)\mathrm{e}^{-x/l}$. Formula (1) gives

$$I_{tot}(l) = \frac{M}{1+\mu l} e^{-t \ln 2/\tau} \quad \text{(Eq. 10)}$$

In the normalised variables it can be represented as (see the green curve in Fig. 2):

$$Y3(z) = \frac{1}{1+z} \quad \text{(Eq. 11)}$$

The results obtained show that for all three types of distribution function, the dependence of gamma-radiation counts on distance is qualitatively the same. The larger the distance the radiotracer is distributed the smaller the signal received by the detector placed in the borehole. The decay rate of the received signal decreases faster (slower) if a maximum of distribution function is shifted in the space to the remote (nearby) part of a domain of distribution.

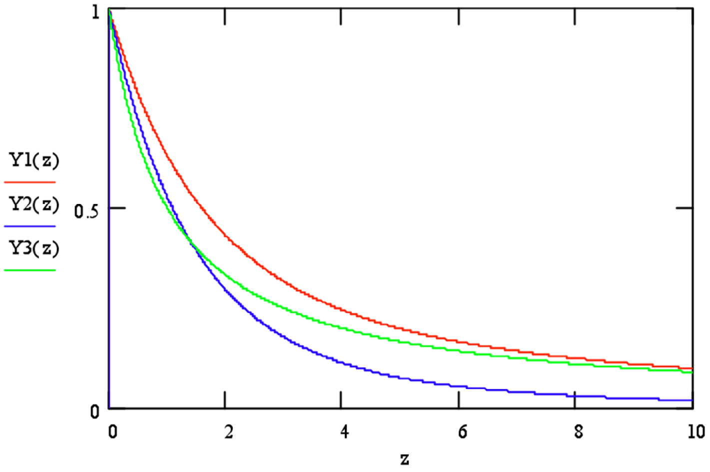


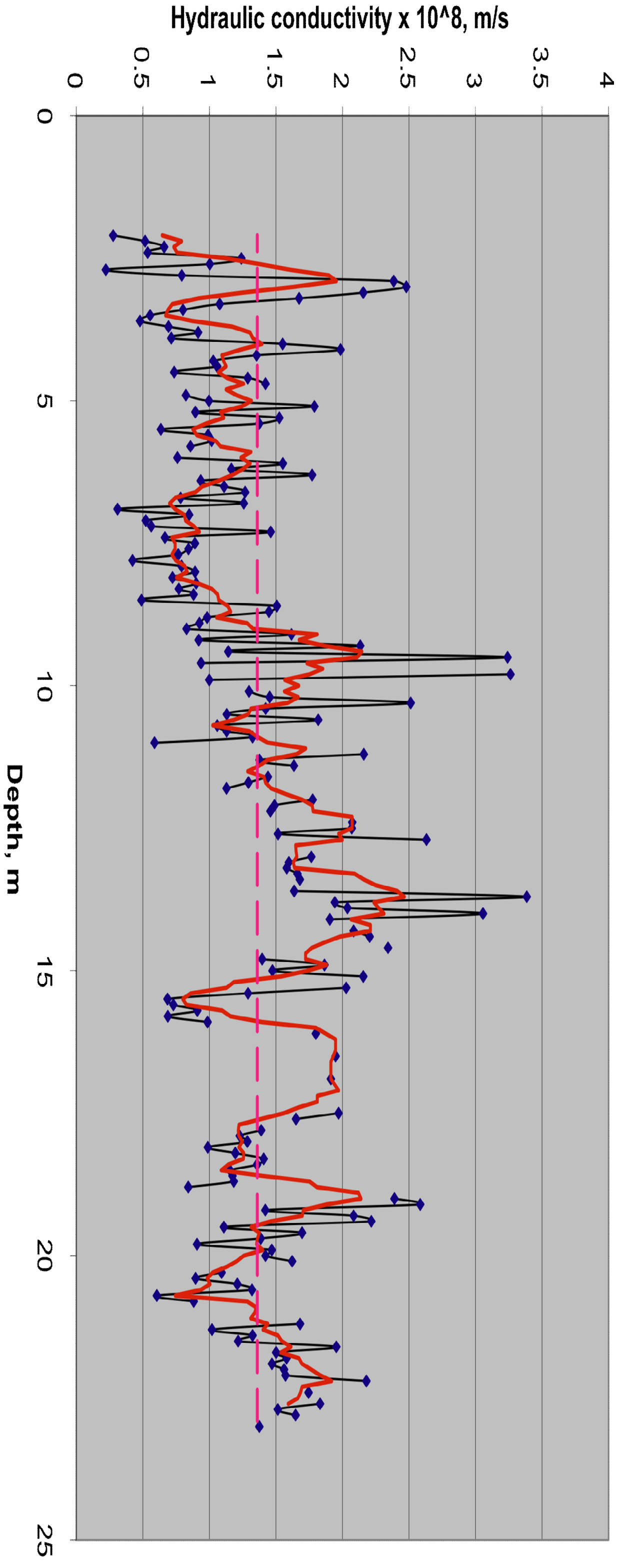
Figure 4 Tracer gamma counts vs distance from borehole. Three different types of tracer injection distribution functions; smooth uniform injection (red), fast injection (blue), diffusive intrusion (green). Y = gamma counts, z = dimensionless distance from borehole

In reality, when a tracer solution is injected into a borehole flow is assumed to be horizontal, with uniform radial distribution around the borehole. This is the 2D injection case, which differs from the 1D injection case presented above only in its greater geometrical / mathematical complexity. The 2D tracer injection case (Waring et al. 2007) is beyond the scope of this paper.

Results

Field results MW6

Several shallow open boreholes were drilled into Hawkesbury Sandstone on site at Lucas Heights for geophysical testing, adjacent to 28 cased monitoring wells. One of these open boreholes MW6 is 24m deep with a standing water level at 2m below the surface. Average hydraulic conductivity has been measured by conventional pump test in the adjacent shallow (0.5 – 9.5m interval, $K = 7.8 * 10^{-8}$ m/sec) and deep (18.5 – 24.5m interval, $K = 3.7 * 10^{-10}$ m/sec) monitoring wells after installation (PPK Environment & Infrastructure 2000).


Hydraulic conductivity x 10^8, m/s
0
0.5
1
1.5
2
2.5
3
3.5
4
Depth, m
0
5
10
15
20
25

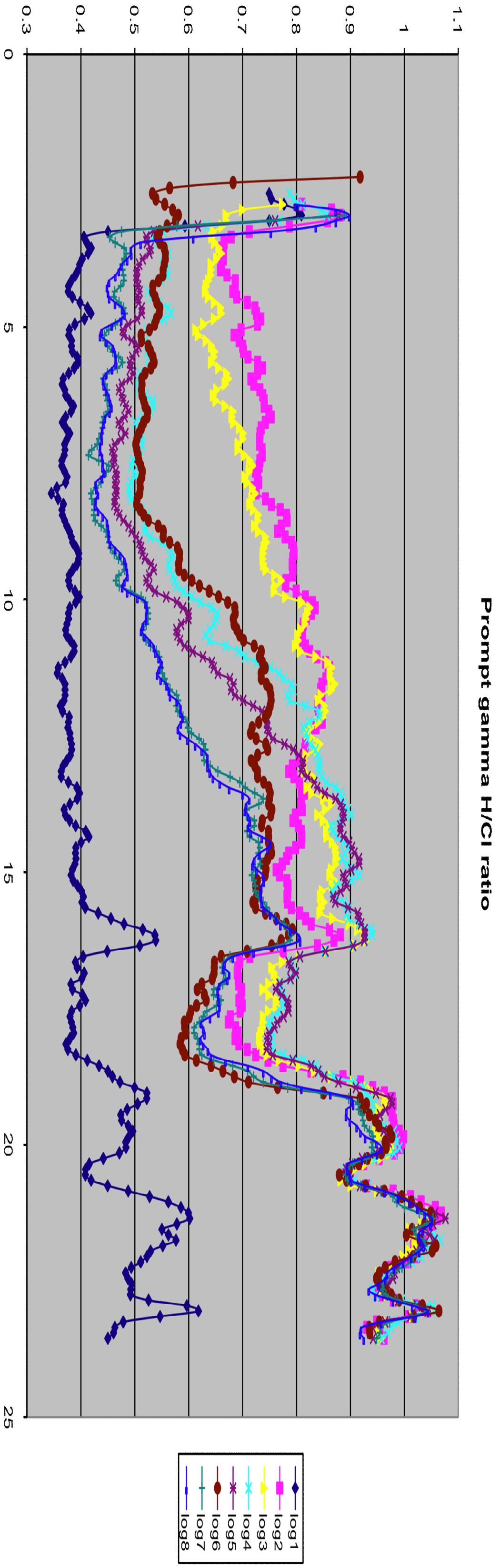

Prompt gamma H/Cl ratio
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
log1
log2
log3
log4
log5
log6
log7
log8

Figure 5 a) Hydraulic conductivity in MW6 borehole with 5 point running mean (red) & hole average (pink) b) Cl/H gamma count ratio for 7 sequential tracer injections. Note dark blue trace is the original Cl/H prior to NaCl tracer injection. The first NaCl injection traces (pink & yellow) are separated from later injections at the top of the borehole but are coincident at the bottom.

The 20cm incremental hydraulic conductivity has been calculated for MW6 by the method described above with a 5 point (1m) smoothing function also applied (Fig. 5a). MW6 bore-log does not distinguish any visible changes to the Hawkesbury Sandstone, yet significant subtle variations in hydraulic conductivity are apparent.

Figure 5b shows the presence of the NaCl tracer in a series of sequential tracer injections. These data are presented as Cl/H gamma count ratio. The gamma counts measured for Cl and H, each from a single peak are proportional to the respective Cl and H concentration. The H concentration will vary with porosity surrounding the borehole and will not vary between successive NaCl tracer injections. Effectively the successive traces show the cumulative amount of tracer surrounding the borehole normalised for the porosity. The results show an unexpected diminution of Cl at the top of the borehole with successive PGNAA logs over 2 days and a small 20 L additional injection of fresh water. There appears to be less tracer in the top zone of MW6 due to the tracer moving beyond the zone of detection or due to advective circulation through the adjacent sandstone. A simple volumetric calculation of the cumulative amount of tracer solution injected (50L 5% NaCl + 20L fresh water) with a uniform cylindrical distribution through sandstone with 8% porosity (~1,500 L) does not exceed the 50cm detection distance. The alternate mechanism, advective circulation is caused by a density contrast between the saline tracer in the borehole and fresh water in the sandstone. The denser salt water in the borehole has an effective head to continue to flow into the sandstone at the bottom of the borehole, assuming a constant SWL. If the denser salt tracer continues to flow out into the sandstone at the base the SWL in the borehole will fall relative to the surrounding sandstone, causing an inflow to the borehole at the top. This advective circulation model also shows that the sandstone surrounding the borehole is hydraulically connected over the 24m vertical length of the borehole.

Conclusion

Porosity and hydraulic conductivity

PGNAA borehole logging is capable of detecting subtle variations in relative porosity in otherwise homogeneous sandstones without tracer injection. A new method for measuring high spatial resolution increments of hydraulic conductivity in a borehole is described and demonstrated in practice.

Vertical hydraulic connection

Sequential tracer injection and PGNAA logging can identify advective circulation cells in sandstone adjacent to a borehole. This method could identify aquitards to vertical flow in thick sandstone sequences with variably low hydraulic conductivity. In the Sydney Basin establishing vertical hydraulic connection by either porous media flow or by fractures could be very useful in assessing the impact of longwall mining on the groundwater hydrology.

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The Lapstone Structural Complex and Hydrogeological Implications - Leonay and Wallacia drilling programs

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Abstract

One of the drought management strategies in the Metropolitan Water Plan (MWP) for Sydney is to investigate the potential use of groundwater reserves in the Sydney Basin. Two of the seven priority investigation sites identified by Sydney Catchment Authority were Leonay and Wallacia to the west of Sydney. The Leonay and Wallacia areas were selected due to the close proximity to the Lapstone Structural Complex and the likelihood of substantially fractured and hence more permeable strata. The Hawkesbury Sandstone was the target aquifer for the drilling program and the individual bore yields were largely influenced by its secondary porosity ie characteristics related to the degree of fracturing.

The Lapstone Structural Complex is a major structural feature of the Sydney Basin, and overlies a deep seated basement structure. The Lapstone Structural Complex is indicated by north south structural lines that extend over 160 kilometres, from Bargo/Picton in the south to Howes Valley/Richmond in the north. The system separates the Blue Mountains Plateau in the west from the Cumberland Basin in the east and therefore marks the distinct topographical boundary of the Blue Mountains Escarpment.

The drilling at Leonay was west of the Nepean River at the base of the Lapstone Monocline and resulted in high yielding bores of low salinity. The subsequent drilling at Wallacia (20 km to the south of Leonay) was undertaken at the base of the Nepean Fault but did not produce the same consistently high yielding and low salinity bores that were expected (based on the previous investigations).

The Lapstone Structural Complex at Leonay is expressed as the Lapstone Monocline but at Wallacia it is expressed as the Nepean Fault. The significance of the difference in expression is fundamental in understanding the hydrogeology and groundwater resource development potential in this area. A detailed study of the geological structure combined with more detailed hydrochemical sampling and analysis provided a more accurate conceptualisation of groundwater flow and recharge/discharge processes.

Keywords: Sydney Basin, hydrogeology, Lapstone Structural Complex, Hawkesbury Sandstone

Introduction

In 2004 the New South Wales Government released the Metropolitan Water Plan (MWP), which was updated in May 2006. The MWP outlines measures for Sydney to achieve a sustainable and secure water supply for people and rivers for the next 25 years. The strategies to ensure Sydney's water future are through optimising water supplies from the existing system, recycling, tapping new water supplies and sustainable usage of industrial and domestic water supplies. One of the drought management strategies set out in the MWP is to investigate the potential use of groundwater reserves in the Sydney Basin to supplement water supply during severe drought. Seven priority investigation sites were identified in an earlier desktop study (PB, 2003) and have since been investigated. The MWP was revised in early 2006 and groundwater was confirmed as one of the main drought water supply options for Sydney. In November 2006, Government announced that pilot investigations at Leonay and Wallacia were to continue. If successful then borefield development would be considered for these areas.

Extensive groundwater investigations were undertaken at Wallacia-Warragamba and Leonay-Emu Plains in western Sydney they being two of the seven priority sites.

Drilling, geophysical logging and test pumping of multiple test production and monitoring bores were conducted. The aim was to characterise the geology and hydrogeology of the area and to confirm the presence and variability of a groundwater resource within the Hawkesbury Sandstone strata with potential to supplement Sydney's water supplies during periods of severe drought.

Drilling and testing at the Wallacia and Leonay sites targeted the Hawkesbury Sandstone and a major regional structural feature, the Lapstone Structural Complex, which is known to have increased the fracturing and permeability of the sandstone. The secondary fracturing associated with the Lapstone Structural Complex proved to be a key variable in the final yield from bores during this drilling program.

This paper discusses the geology and hydrogeology of the Wallacia-Leonay area, and considers the significance of the Lapstone Structural Complex on the groundwater conditions associated with the structure from both a permeability and hydrochemistry perspective.

Physiographic setting

The study area is located approximately 60 km west of Sydney, at the foothills of the Blue Mountains and adjacent to the Nepean River. Leonay-Emu Plains is adjacent to the Nepean weir pool and the M4 motorway crossing while Wallacia is located approximately 20 kilometres to the south.

The investigation area at Leonay is in an urban environment consisting of residential dwellings and parkland (PB, 2008). Mulgoa and Wallacia is a rural setting consisting largely of farms and residential dwellings surrounding the townships of Mulgoa, Wallacia, Warragamba and Silverdale (PB, 2009). To the west the investigation area is flanked by the natural bush land of the Lower Blue Mountains at Leonay and the Warragamba State Conservation Area and the Blue Mountains National Park at Wallacia

The majority of the investigation bore sites are located on the western margin of the Cumberland Plain and also on the western edge of the Nepean River floodplain or associated high terraces. Immediately west of these sites there is alluvium and talus/scree slope masking the exact location of the Lapstone Monocline - Nepean Fault complex. Beyond the fault the land rises sharply to the Blue Mountains Plateau. There are several monitoring bore sites located on the immediate upgradient plateau areas.

Geology and Hydrogeology

The study area is located within the central portion of the sedimentary Sydney Geological Basin. The deposition of Sydney Basin sediments has occurred from the Carboniferous (298 million years ago) through to the latter part of the Triassic (200 million years ago) (Schiebner and Basden 1998). The area of interest for water supply is the upper geological sequences of the Sydney Basin, primarily being the mid Triassic Hawkesbury Sandstone. The exposed geology and structural features for the area are shown in the geology map (Figure 1), along with the locations of all bores drilled for the groundwater investigations.

The Hawkesbury Sandstone is a dual porosity regional aquifer system that occurs across the whole of the Sydney Basin. Groundwater flow is highly variable throughout the Hawkesbury Sandstone, and it is generally dominated by secondary porosity and fracture flow associated structures such as faults and fracture zones. The primary porosity ie voids relating to intergranular pore spaces of the rock matrix within the Hawkesbury Sandstone is low, and a bore that does not intercept major fractures or fissures is likely to yield less than 5 Litres per second (L/s). However, a bore in the Hawkesbury Sandstone that intercepts major fractures and fissures can yield in excess of 40 L/s. Locally (or sub-regionally) there maybe separate recharge and discharge areas for the Hawkesbury Sandstone.

The Nortons Basin Diatreme was located in the investigation area near Wallacia and is intersected by borehole W1A. It is one of 14 diatremes identified on the Penrith 1:100,000 geological map sheet. The diatremes are believed to be short lived explosive vents of Jurassic age, and commonly consists of greenish grey fine grained basaltic lapilli, within a fine grained greenish grey to black matrix. The zone of igneous bodies across the Penrith map-sheet correlates with a basement fault known as the Lachlan River Lineament (Schiebner, 1974 and Brownlow *et al,* 1987).

The Ashfield Shale overlies the sandstone across much of the study area, and where absent the Hawkesbury Sandstone outcrops (to the west of the Lapstone Structural Complex). However, in some areas adjacent to the Nepean River, the Ashfield Shale has been eroded and the Mittagong Formation and/or Hawkesbury Sandstone is in direct contact with the overlying alluvium.

A summary of the hydrogeology associated with each lithology encountered is provided in Table 1.

Table 13 Geological units in the Wallacia Leonay area and their respective hydrogeological properties

Lithology	Likely Quantity (yields in a production bore)	Likely Quality (salinity and pH)
Alluvium	< 1 L/s	100-300 µS/cm salinity 6.5 - 7.5 pH neutral
Ashfield Shale	aquitard	5000 - > 50,000 µS/cm salinity > 7 pH generally alkaline
Hawkesbury Sandstone	5 – 50 L/s (depending on fractures)	< 200 – 3000 µS/cm salinity 5.5 – 6.5 pH slightly acidic
Burralow Formation	< 2 L/s	Likely to be similar to Hawkesbury Sandstone
Wentworth Falls Claystone	aquitard	Unknown
Banks Wall Sandstone	Uncertain - low	Brackish
Nortons Basin Diatreme	1 – 100 L/s (depending on fractures)	1,000 - 2,500 µS/cm salinity pH 7.99 to 8.08 slightly alkaline

Figure 1 - Geology

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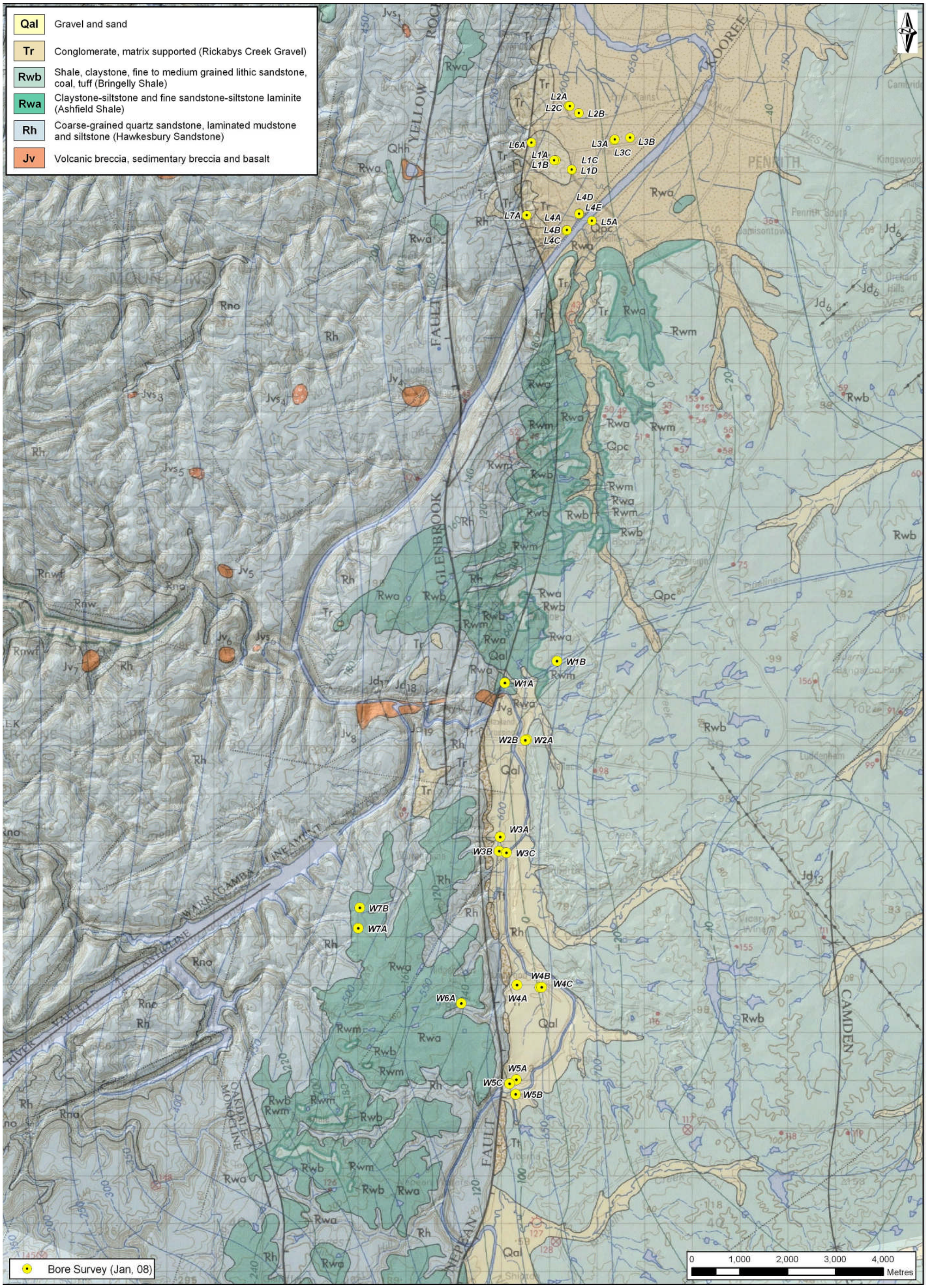


Structure

On the Penrith 1:100,000 scale geological map sheet (NSW Dept of Minerals and Energy, 1981) and Southern Coalfields map sheet (Mineral Resources NSW, 1999), the major structural feature is the Lapstone Monocline - Nepean Fault system (generally termed the Lapstone Structural Complex). The system runs north south, and separates the Blue Mountains Plateau in the west from the Cumberland Basin in the east, and therefore marks the distinct topographical boundary of the Blue Mountains Escarpment (CSIRO, 1992).

The Lapstone Structural Complex is a major structural feature of the Sydney Basin, and overlies a deep seated basement structure (Branagan and Pedram, 1990). The Lapstone Structural Complex is indicated by structural lines that extend over 160 kilometres, from Bargo/Picton in the south to Howes Valley/Richmond in the north. It is a prominent feature, both physiographically and tectonically and is thought to have significant groundwater potential.

The escarpment is east facing, and is commonly referred to as a monocline, but in reality changes from north to south between a monocline and a series of en-echelon faults. The Lapstone Structural Complex is generally described as a number of north south related faults and folds, which plunge to the south.

The Lapstone Structural Complex is believed to overprint pre-existing faults within the basement geology. The faults associated with this activity are oriented north-south and north-north-east, and the extension direction was oriented approximately east-west. The Branagan and Pedram (1990) report has proposed that an extension of the deep seated basement structure Eden-Comerong-Yalwal Rift would underlie the Lapstone Structural Complex, and also notes that the lowest part of the Complex is in an area where the Lachlan Lineament and the Bathurst Batholith would intersect. This may provide a focal point for episodic movements (Branagan and Pedram, 1990).

Fergusson (2006) comments that the Lapstone Structural Complex is related to either steep east dipping extensional faulting, or moderate to steep west dipping contraction faults with seismic information supporting the latter. He also proposes that strike slip displacement may also have played a role in the development of the Lapstone Structural Complex, and that the age of deformation due to compression in the south is likely to be Cretaceous to Cainozoic. The moderately west dipping faults of the underlying Lachlan Fold Belt may have reactivated under the present day compression.

The development of the Lapstone Structural Complex has resulted in fracturing and faulting of the Sydney Basin sedimentary rocks, including the target Hawkesbury Sandstone aquifer. The most productive water supply bores within the Hawkesbury Sandstone are those which intercept significant fractures. Areas adjacent to the Lapstone Structural Complex have therefore been targeted for drilling investigation due to the likely secondary porosity (fracturing), and potentially high yielding bores.

Both the Nepean Fault and Lapstone Monocline are a result of two separate episodes of tectonic activity, an east-west extension event during the Late Triassic into the Jurassic, followed by an east-west compression event at some stage post Jurassic.

The extensional event is considered to have occurred throughout the Late Triassic through to Jurassic associated with Tasman Sea Rifting which resulted in the development of the monocline and the Lapstone Structural Complex. At the end of the extensional event there were some igneous intrusions and normal faulting activated along structures which were influenced by the basement architecture. The igneous intrusions occurred in a zone across the Penrith map-sheet and correlate with Lachlan River Lineament basement fault.

The compressional event immediately followed, oriented west over east, and is considered to have occurred following the Jurassic period. The move to a compressional regime is thought to have caused the cessation of the volcanic intrusions in this area. The compressional event resulted in varying deformation styles along the north and south areas of the Lapstone Structural Complex.

Discussion

Conceptual structure model

The Leonay area differs from the Wallacia area in terms of how the basement geological structure is expressed within the overlying sedimentary rocks. Both areas have experienced extensional stresses, from the Triassic to the Tertiary, followed by compression post Jurassic. The Lapstone Structural Complex at Leonay forms a monocline, including a number of associated folds and faults, which has resulted in intense flexural fracturing, over the width of the monocline. At Wallacia, the development of the complex has been more brittle, and is expressed as the Nepean Fault.

The Nepean Fault at Wallacia is interpreted from the 1987 seismic reflection data to be a high angle west dipping thrust fault, coupled with minor east dipping reverse faults located both to the east and west of the main Nepean Fault.

The Nepean Fault transitions to the South Lapstone Monocline in a northerly direction just to the east of the Warragamba River, and around the location of the Norton Basin Diatreme. The Nortons Basin Diatreme is likely to be located at a point of weakness, and the change in the Lapstone Structural Complex from a monocline to a fault at that location is likely to be the hinge zone of the northern end of the Nepean Fault.

The present configuration of the Lapstone Monocline is likely due to the same sequence of geologic events as the Nepean Fault. An extensional event led to the development of the monocline and normal faulting. Later compression occurred, and at Leonay the deformation was ductile rather than brittle and a monocline formed at Leonay rather than a fault (as at Wallacia). It is possible that the compression has been absorbed by the Nepean Fault to the south and Mount Riverview Fault to the north. This is also in agreement with the fault, monocline, fault, monocline pattern of the Nepean Fault, south Lapstone Monocline, Mt Riverview Fault and North Lapstone Monocline generally set in an en echelon pattern. The east west compression may have further increased the degree of deformation of the Lapstone Monocline resulting in shatter zones (i.e. fracturing of an already structurally prepared zone) in addition to secondary faulting to the east of the Lapstone Monocline. The sequence of tectonic events and likely development of the Lapstone Structural Complex is summarised in Table 2.

Table 2 - Sequence of tectonic events

Era	Period	Epoch	Lithology	Tectonic Episode	Summary Comments
Cainozoic	Quaternary	Holocene	Cranebrook Formation - Alluvial	East West Compression	The switch to compression signified the end of volcanism in the area, and a cessation in the development of the monocline. Continued compression at Leonay led to fracturing and faulting at the base of the monocline, and at Wallacia lead to the development of the Nepean Fault
		Pleistocene	Cranebrook Formation - Alluvial		
	Tertiary	Pliocene	Rickabys Gravels		
		Miocene			
		Oligocene			
Mesozoic	Cretaceous				
	Jurassic		Nortons Basin Diatreme	East West Extension	The extensional event resulted in reactivation of the basement fault and the development of the monocline (and the greater Lapstone Structural Complex)
		Late Triassic			
	Triassic	Mid Triassic	Bringelly Shale		
			Ashfield Shale		
			Hawkesbury Sandstone		
			Burralow Formation		
		Early Triassic	Wentworth Falls Claystone Member		
			Banks Wall Sandstone		
			Burra-Moko Head Sandstone		
			Caley Formation		
Palaeozoic	Permian	Late Permian	Illawarra Coal Measures		
			Shoalhaven Group		

Conceptual hydrogeology model

Groundwater recharge occurs on the Blue Mountains plateau to the west of the Lapstone Structural Complex. In the Wallacia area the construction of Warragamba Dam and the formation of Lake Burragorang appear to have increased water levels in the Hawkesbury Sandstone. Groundwater flow is then eastwards across the Lapstone Structural Complex towards the Nepean River and the Cumberland Plain.

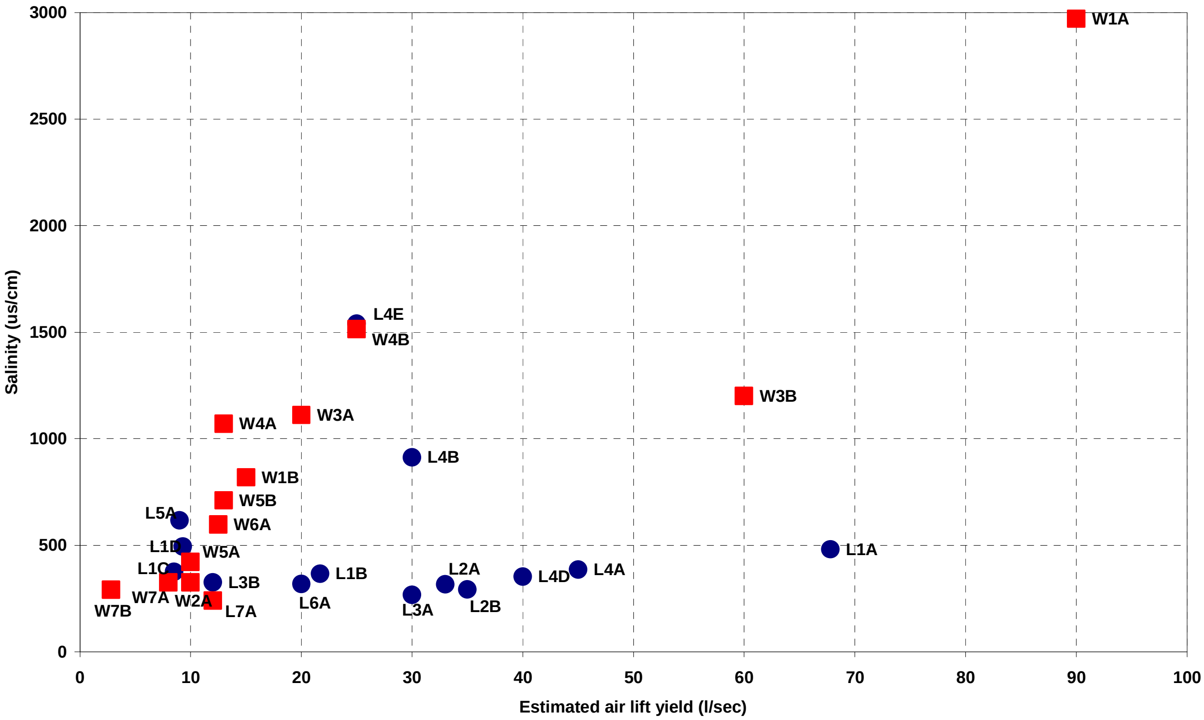
Groundwater quality improves with depth through the Hawkesbury Sandstone but it becomes more saline along the regional flow path from west to east. At some sites where the Ashfield Shale overlies or is immediately up gradient of the Hawkesbury Sandstone, saline groundwater from this aquitard contributes to the brackish salinity observed in the upper part of the sandstone. Possible upward flow or migration of brackish to saline groundwater along fractures from underlying Narrabeen Group aquifers or Permian Coal Measures may be contributing to brackish conditions in the deeper Hawkesbury Sandstone on the eastern side of the Lapstone Structural Complex.

The bores constructed at Leonay were located at the eastern margins and to the east of the main Lapstone Monocline structure. The intense flexural fracturing is likely to have resulted in a series of fractures and faults at this location. Bores constructed at Leonay intercepted these highly fractured sandstone sedimentary rocks, and subsequently the bores at Leonay were all high yielding. The secondary fracturing is likely to underlie the talus and alluvium associated with the Nepean River, and is therefore not expressed at the surface.

The main fracturing at Wallacia has been movement on the main Nepean Fault, and not warping or secondary fracturing that occurs at Leonay. At Wallacia the width of alluvial sediments is only 1km, and the secondary fracturing on the eastern side of the structure appears to be limited. There is only evidence of one fault zone or horst graben structure located immediately to the east of the Nepean Fault in the vicinity of bore W3A. The substantially lower yields at Wallacia may be explained by the lack of secondary fracturing at the drilled locations, or the localisation of compressive stress/strain within larger more discrete existing structures (i.e. reverse faulting, strike slip development and block “jostling”).

Bore yield/salinity information at Leonay and Wallacia as part of the SCA drilling programs is presented in *Figure 2*. The Leonay and Wallacia areas are compared based on airlift yields and end of hole electrical conductivity. It can be clearly seen that test production bores at Leonay have consistently lower salinities and generally higher yields than those at Wallacia. The exception to this is a bore at site W3 at Wallacia, where yields of 30 and 60 L/s were encountered in the initial drill program and W1A at Wallacia which was a bore drilled into the Nortons Basin diatreme.

Figure 2 - Comparison of bore yield and salinity between Leonay and Wallacia



Conclusion

Extensive groundwater investigations were undertaken at Wallacia-Warragamba and Leonay-Emu Plains in western Sydney. Drilling and testing at the both Wallacia and Leonay sites targeted the Hawkesbury Sandstone and a major regional structural feature, the Lapstone Structural Complex, which is known to have increased the fracturing and hence permeability of the sandstone. The area of interest for water supply is the upper geological sequences of the Sydney Basin, primarily being the mid Triassic Hawkesbury Sandstone.

The Hawkesbury Sandstone is a dual porosity regional aquifer system that occurs across the whole of the Sydney Basin. Groundwater flow is highly variable throughout the Hawkesbury Sandstone, and is generally dominated by secondary porosity and fracture flow associated structures such as faults and fracture zones. The primary porosity of the rock matrix within the Hawkesbury Sandstone is low, but bores that intercept major fractures and fissures can be very high yielding (in excess of 40 L/s).

The Lapstone Structural Complex is a major structural feature of the Sydney Basin and overlies a deep seated basement structure (Branagan and Pedram, 1990). The complex extends over 160 kilometres, from Bargo/Picton in the south to Howes Valley/Richmond in the north.

Both the Nepean Fault and Lapstone Monocline are both a result of two separate episodes of tectonic activity, an east-west extension event during the Late Triassic into the Jurassic, followed by an east-west compression event at some stage post Jurassic. At the end of the extensional event there were some igneous intrusions and normal faulting activated along structures which were influenced by the basement architecture. The igneous intrusions occurred in a zone across the Penrith map-sheet and correlate with Lachlan River Lineament basement fault. The compressional event immediately followed, oriented west over east, and is considered to have occurred following the Jurassic period. The compressional event also resulted in varying deformation styles along the north and south axis of the Lapstone Structural Complex with the reactivation of the Lapstone Monocline at Leonay, and further to the south at Wallacia, the development of the Nepean Fault.

The Lapstone Structural Complex at Leonay forms a monocline, including a number of associated folds and faults, which has resulted in intense flexural fracturing, over the width of the monocline. This wide area of consistent fracturing has resulted in the bores constructed at Leonay being consistently higher yielding than those at Wallacia. At Wallacia, the development of the complex has been more brittle and is expressed as the Nepean Fault. The vertical displacement of the fault at Wallacia is significant and is approximately 200 metres. However, the lateral extent of the fracturing associated with the compression regime is localised and has resulted in largely a single primary fault with some minor localised and discrete secondary fracturing or horst graben structures.

The bores constructed at Leonay were located at the eastern margins, and to the east of the main Lapstone Monocline structure. The intense flexural fracturing is likely to have resulted in a series of fractures and faults at this location. Bores drilled at Leonay intercepted these highly fractured sandstone sedimentary rocks, and consequently they were all high yielding. The secondary fracturing is likely to underlie the talus and alluvium associated with the Nepean River, and is therefore not expressed at the surface.

The main fracturing at Wallacia has been movement on the main Nepean Fault, and not the warping or secondary fracturing that occurs at Leonay. At Wallacia the secondary fracturing on the eastern side of the structure appears to be limited. The consistently lower yields at Wallacia may be explained by the lack of secondary fracturing due to the single primary fault (the Nepean Fault) and the limited lateral extent of fracturing associated with it.

The occurrence of groundwater within the Hawkesbury Sandstone is largely influenced by secondary porosity and permeability, such as fractures and fissures along bedding planes and joints. The highest bore yields within the Hawkesbury Sandstone are located at sites where the aquifer has the highest secondary porosity and permeability. Identification of these fractures prior to drilling is critical when determining future bore locations.

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Assessment of Sustainable Limits for the Greater Metropolitan Region Groundwater Sources

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Abstract

This paper focuses on the administrative processes involved in developing long term average extraction limits for the major aquifers in the Sydney metropolitan region and on mechanisms for protecting their groundwater-dependent systems from the impacts of groundwater extraction.

The 1994 Council of Australian Governments' (COAG's) Water Reforms drove the replacement of the NSW Water Act 1912 with the Water Management Act 2000 (WMA). This was followed by the National Water Initiative in 2004. The WMA requires water sharing plans to be developed for regulated rivers, unregulated rivers and groundwater in NSW.

Several water sharing plans covering groundwater have become operational in NSW under the WMA (2000). Water sharing plans for the remaining major aquifers in NSW – termed "groundwater sources" in the Act - will cover either several groundwater sources or a mix of both surface water and groundwater sources. This approach, known as the "macro" planning approach, has three broad components, viz.:

- determination of a long term average extraction limit for each groundwater source based on a risk assessment,
- reservation of environmental water for each groundwater source, and
- development of localised provisions for protection of important, and specified, groundwater-dependent ecosystems.

Technical assessment of the parameters needed for groundwater sharing plans is based on at least 20 years of historic piezometric and groundwater pumping data, together with at least 70 years of climate and river flow information. Where available, calibrated groundwater flow models underpin the plans. Where models were not available, basic hydrogeological principles were used to estimate a water budget. An expert panel was convened and given the tasks of defining sustainability factors for each groundwater source and to oversee development of rules for limiting extraction impacts. An inter-agency panel endorsed both the definition and the rules.

The Draft Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources is the first groundwater-specific macro plan to be developed in NSW. It covers 13 groundwater sources in the Sydney Basin with several important groundwater-dependent ecosystems. Estimates of long term available extraction limits (LTAEL) for the 13 groundwater sources range from 430 ML/yr to 250 000 ML/yr, and the current entitlement as a percentage of those limits ranges from 4% to 82%.

INTRODUCTION

Management of groundwater resources in the Sydney Basin is subject to the same planning processes as groundwater generally in NSW. This paper outlines the approach taken to protect the long term sustainability of major aquifers in the Greater Metropolitan Region which includes Sydney, the Blue Mountains, the Hawkesbury-Nepean and Wollongong/Illawarra. A Draft Water Sharing Plan has been developed that will reserve a portion of the long term average annual recharge as a volume of environmental water and provide for localised protection of groundwater-dependent ecosystems (GDEs). While groundwater management is at the aquifer scale the plans are being developed to coincide with surface water catchment boundaries.

This paper focuses on the processes involved in developing sustainable yields (extraction limits) for each of the major aquifers and mechanisms for protecting groundwater-dependent systems. It describes the processes involved in their definition and the rules designed to protect them. .

Water sharing planning for groundwater in NSW

Since the *Water Management Act 2000* was introduced in NSW, 37 water sharing plans have commenced operating, all since 2004. Several of these plans cover groundwater, and collectively they include most of the high yielding aquifers in the State. Each of these plans covers only one or two major aquifers.

The remaining 100 or so major aquifers which have been defined in NSW - termed "groundwater sources" in the Act - have been mapped and a "macro" planning process commenced in 2004 to complete water sharing planning arrangements for them. Each proposed macro water sharing plan will cover several major aquifers.

While groundwater management is at the aquifer scale the plans are being developed to coincide with surface water catchment boundaries. This enables consistent and compatible communication at all scales with all stakeholders. It will also enable reporting to water users, state monitoring and evaluation reporting (MER) for catchment management authorities (CMA), and national water accounting for Bureau of Meteorology (BoM)

An additional requirement of current groundwater management is the need to ensure protection of ecosystems associated with groundwater. Under the *Water Management*

Act 2000 each water sharing plan must address the protection of the relevant water source and also the protection of its dependent ecosystems. This is consistent with the Intergovernmental Agreement on a National Water Initiative that was agreed in 2004 and signed by all Australian governments in 2006. NSW has also adopted a State Groundwater-Dependent Ecosystems Policy (Department of Land and Water Conservation, 2002).

Water sharing plan for greater metropolitan region groundwater resources

The Draft Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources (the Draft Plan) is the first in NSW to cover several major aquifers in one plan. It is also the first to include karst areas in its list of high priority GDEs.

The 13 groundwater sources in the Greater Metropolitan Region, to be covered by this Plan, are shown in Figure 1. A macro water sharing plan for the Greater Metropolitan Region's surface water resources is being developed in parallel with the groundwater sharing plan. Technical work on plan development is completed and both plans are expected to be finalised in the near future, following community consultation.

Definition of groundwater extraction limits and reservation of environmental water

Long term average monthly rainfall recharge rates summed to an annual rate, which vary according to hydrogeological characteristics, were assessed for each of the groundwater sources in the Draft Plan area. The estimated volume of recharge water was then partitioned into two categories, termed consumptive pool water and environmental water.

First, nearly all of this rainfall recharge over high conservation areas, such as national parks, karst conservation areas and nature reserves, has been reserved as environmental water. Only a small percentage of this recharge has been allowed for extraction in some of these areas.

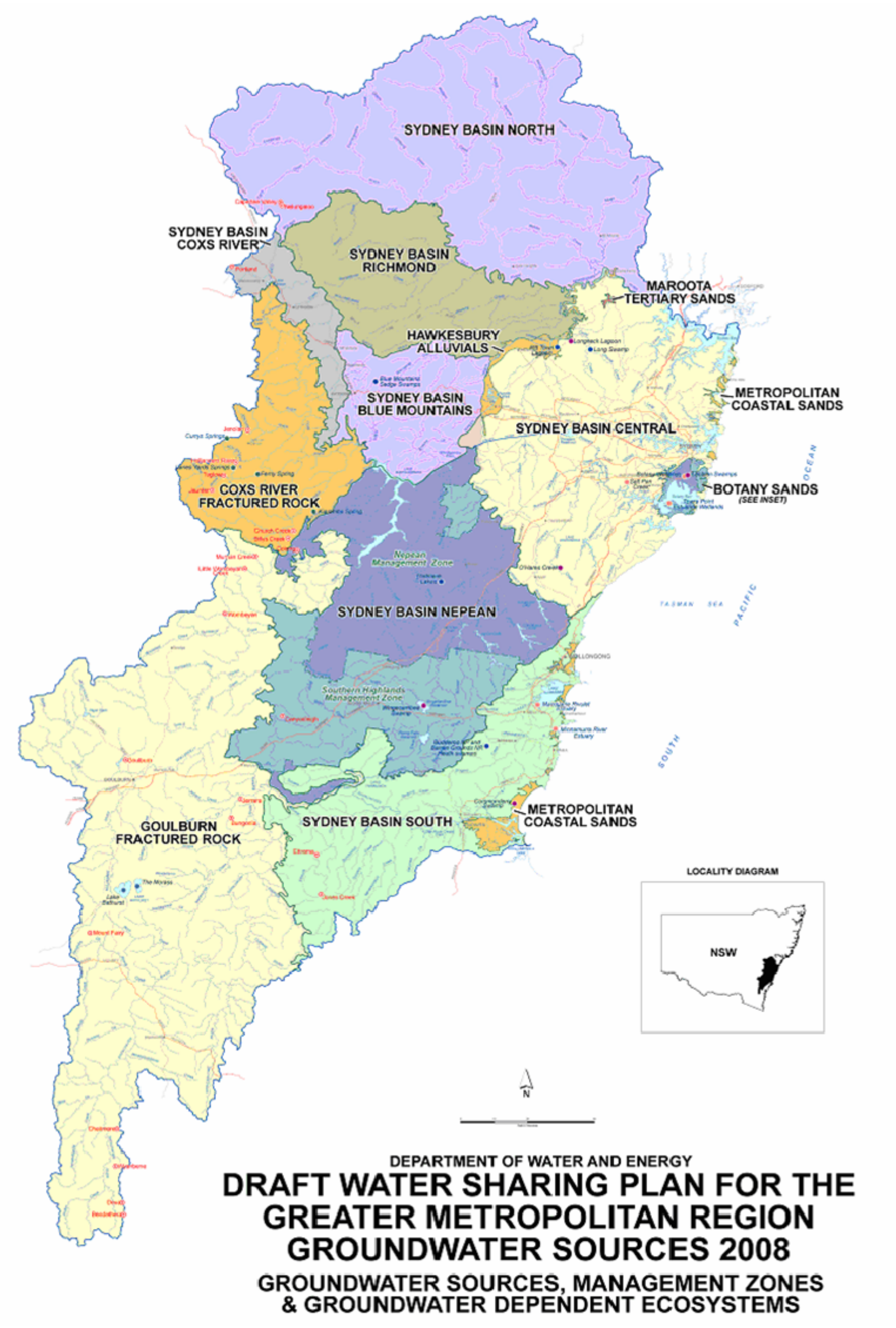

Figure 25: Groundwater Sources in the Sydney Metro Groundwater Sharing Plan

Secondly, in the remaining parts of each of the groundwater sources between 30 and 95% of the long-term average annual rainfall recharge has been reserved as environmental water. Again, the infiltration rates differ according to hydrogeological characteristics. The percentages of recharge reserved as environmental water were set through an expert panel and an inter-agency panel risk assessment process, which involved weighing up the environmental and socio-economic values of each of the groundwater sources. The remaining percentage of the long term average recharge is translated into a volume which defines the sustainable yield volume, described in the Plan as the "long term average extraction limit", for each groundwater source. This methodology is described in more detail by Bish et al (2006).

This reservation of environmental water for each groundwater source aims, at a broad scale, to support the long term viability of both the aquifers and their dependent ecosystems.

The current extraction limits and groundwater entitlement volumes for each groundwater source are given in Table 1. It does not include all water taken through aquifer interference activities (such as mine voids), which is required for a full water balance to be developed.

Table 14: ***Recharge estimates, environmental water and extraction limits for the Greater Metropolitan Region Groundwater Sources as at 2006***

Groundwater Source	Estimated Long-term Average Annual Recharge (ML/year)	LTAEL (ML/year)	Total Planned Environmental Water (ML/year)	Aquifer access licences (ML/year)	Domestic and Stock rights (ML/year)	Local water utility access licences (ML/year)	% Allocated
Botany Sandbeds	30,424	14,684	15,740	10,677	1,436	0	82
Maroota Tertiary	1,075	645	430	181	16	0	31
Metropolitan Coastal Sands	60,802	27,206	33,596	844	339	0	4
Sydney Basin North	269,187	19,682	249,504	401	579	0	5
Sydney Basin Richmond	127,878	21,103	106,775	618	1,175	29	9
Sydney Basin Central	229,223	45,915	183,308	1,671	2,250	0	9
Sydney Basin Blue Mountain	78,474	3,894	74,580	82	321	0	10
Sydney Basin Nepean	224,483	99,568	124,915	11,970	4,807	13	17
Sydney Basin South	225,326	69,892	155,434	2,466	1,607	0	6
Hawkesbury Alluvium	5043	1228	3,814	715	237	0	78
Sydney Basin Coxs River	31,312	17,108	14,204	317	331	0	4
Goulburn Fractured Rock	259,784	53,074	206,709	1,696	2,232	0	7
Coxs River Fractured Rock	66,297	6,806	59,491	102	140	0	4

Localised rules for groundwater-dependent ecosystems

The Draft Plan, like earlier water sharing plans, also includes rules aimed at protecting GDEs at a more localised level. This is consistent with the State's Groundwater-Dependent Ecosystem Policy (2002). This Policy defines GDEs to include wetlands, terrestrial vegetation and caves (karst ecosystems).

More recently, Eamus et al (2006) has proposed three primary classes of GDE, namely:

1. aquifer and cave ecosystems, where stygofauna (groundwater-inhabiting organisms) live within the groundwater,

2. all ecosystems dependent on the surface expression of groundwater including wetlands and base flow in rivers and streams, and
3. all ecosystems dependent on the subsurface presence of groundwater including terrestrial ecosystems.

Existing water sharing plans covering groundwater in NSW have listed “high priority” karst and wetlands GDEs in a schedule (or made provision for their inclusion during the life of the plan, where none were identified) and included rules for their protection. Terrestrial vegetation ecosystems are described but have not been geographically identified. All high priority GDEs listed in existing water sharing plans for groundwater fall into the second and third of these three classes.

In the proposed Plan for the Greater Metropolitan Region, terrestrial ecosystems are to be protected by a 200 meters stand-off, for new bores, from any sandstone escarpment where hanging swamps or base flow to rivers is supported by groundwater. There is a depth condition such that the upper 30 meters of new bores must be cased so that these shallow aquifers cannot be directly tapped.

Surface water environmental flow releases in the Hawkesbury River are to be protected in the Plan by groundwater “cease to pump” rules that are in the Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources 2008 (the surface water plan). In addition, no bores are allowed within 40 meters of the high bank of the River as defined in the surface water plan.

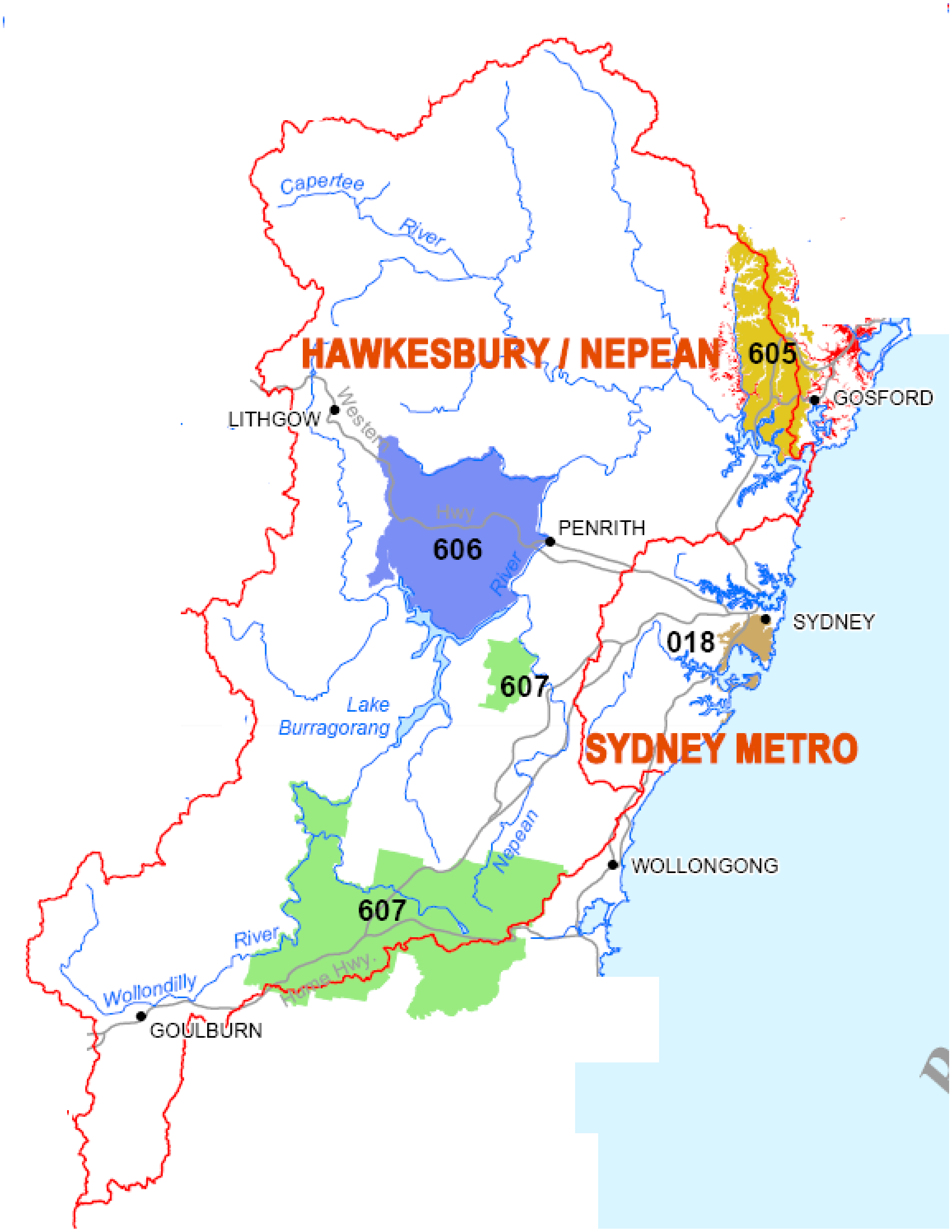

Figure 26: Areas embargoed for additional groundwater entitlements

General conditions

Major utility (urban water) access licences are for drought reserve or for maintenance purposes. These licences are not transferable.

The Plan includes distance rules for separation of works that use access licences to 100 to 400 metres and 50 to 200 metres for basic landholder rights. No new works are allowed within 1000 metres of a local or major utility works.

CURRENT MANAGEMENT

There is considerable development pressure on the groundwater resources in some parts of this area.

Four of the groundwater sources are currently embargoed or partially embargoed from new groundwater licence applications mainly due to high levels of entitlement. They are the Hawkesbury Alluvials (605), Botany Sandbeds (018), Blue Mountains Sandstone (606) and parts of the Nepean Sandstone (607) as shown in Figure 2.

There is no routine metering of access licence use in any of these groundwater sources, although several enterprises collect usage information on a monthly basis and this is available to the Department of Water and Energy on request.

There 201 piezometers at 173 locations for regional monitoring in the Plan area. Most of them were constructed to allow continuous recording of water levels. These tend to be in areas where groundwater extraction is causing community concern due to bore interference, potential impacts on groundwater-dependent ecosystems or base flow, or where there is mining.

CONCLUSION

The Draft Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources is the first groundwater-specific macro plan in NSW under development. It covers thirteen groundwater sources and includes a list of important GDE.

The Draft Plan provides an extraction limit and reserves specific volumes of environmental water for each of the 13 groundwater sources within the Plan area. It includes conditions designed to protect river base flow and GDE for groundwater works in all groundwater sources. The extraction limits and the rules for assigning conditions to groundwater works were developed through expert and inter-agency panels.

ACKNOWLEDGMENTS

Several staff from the NSW Department of Water and Energy reviewed and commented on a draft version of this paper. Further, a high level of interagency co-operation was the key factor in developing the list of priority GDE and associated rules for managing groundwater extraction.

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Keyword Index

Keyword is followed by page number and author(s)