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, with MAR schemes commissioned at UNSW, and 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 secure groundwater supply by mitigating saline intrusion and also improve water quality flowing in to Manly Lagoon, incidental aquifer recharge could be boosted with appropriate MAR systems, such as the addition of a recharge pond and adjustable weir. Although the magnitude, extent and impact of mounding is likely to be minor, conditions may not comply with draft Australian Guidelines for Water Recycling in urban areas.

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

1. 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.

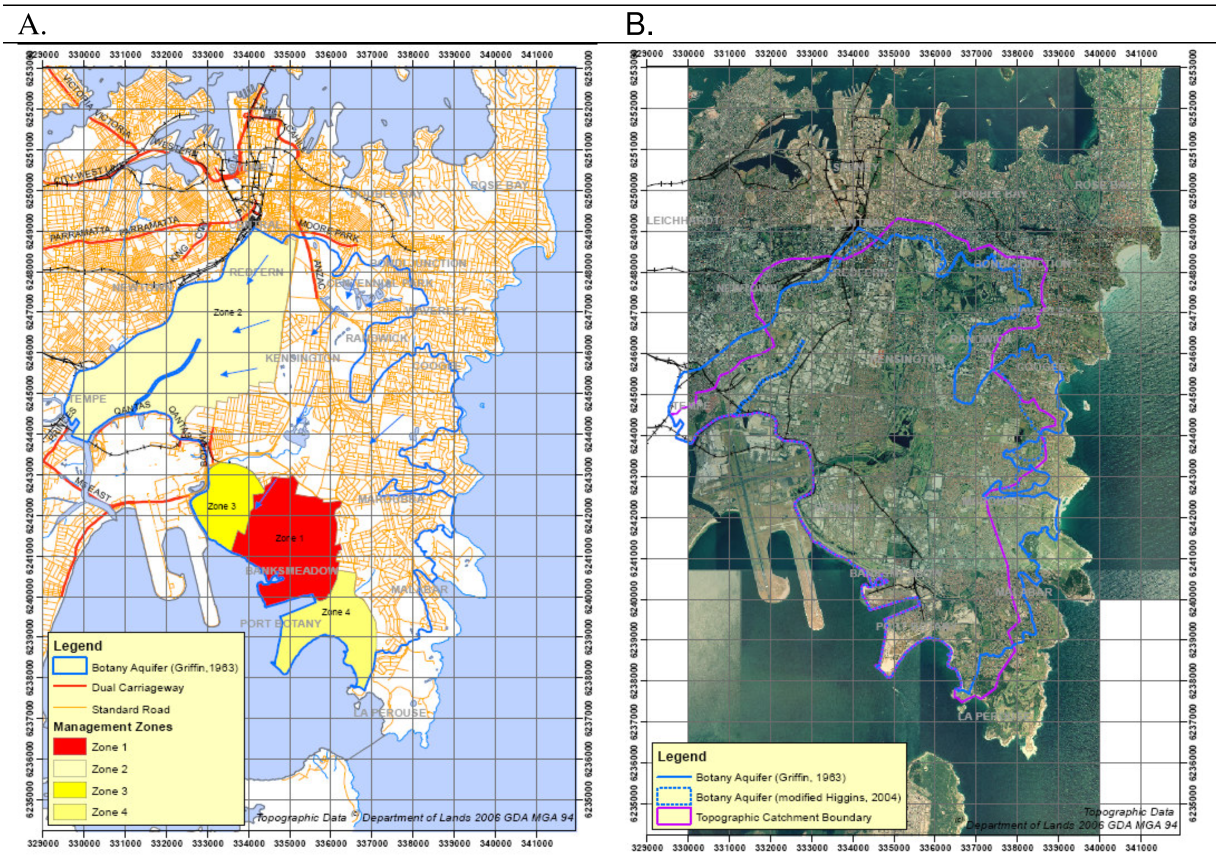

Figure 1: A) Botany aquifer location, management zones and groundwater flow directions and B) catchment and aquifer boundaries.

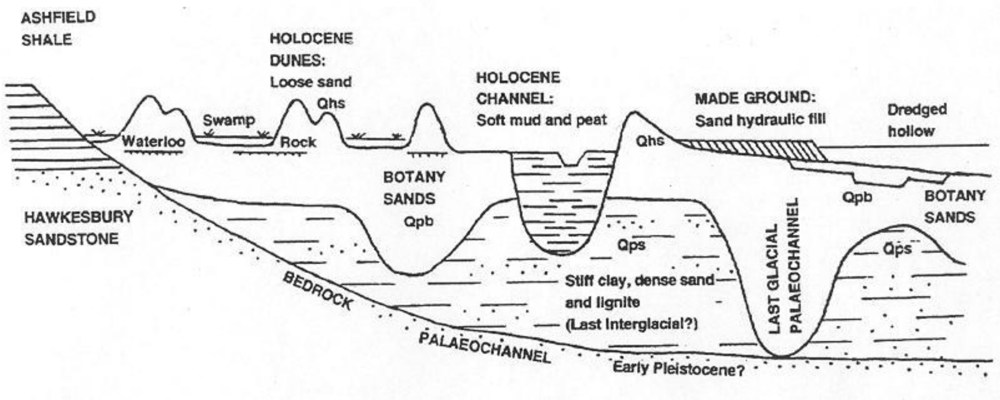

Figure 2: Section through the Botany aquifer north-east to south-west (McNally and Jankowski, 1998).

2. Large Scale MAR – Botany Aquifer

2.1. 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. However, a detailed evaluation of complete groundwater level data, including recent automated logger data is not publicly available.

2.2. 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 varioua groundwater models in 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 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.

2.3. 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 (n=9, 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.

2.4. Potential Water Sources for Recharge

Recharge water could be provided by additional stormwater diversions or by the addition of high quality treated wastewater. The 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 but flashy urban runoff. Available volume could be supplemented with stormwater from adjacent catchments.	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.

2.5. 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 - Use 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 recovery some distance away to take advantage of water treatment and delivery capacity of the aquifer. Advantageous when land is scarce.

2.6. 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.

3. 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 scheme 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 GPT. 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 yields 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.

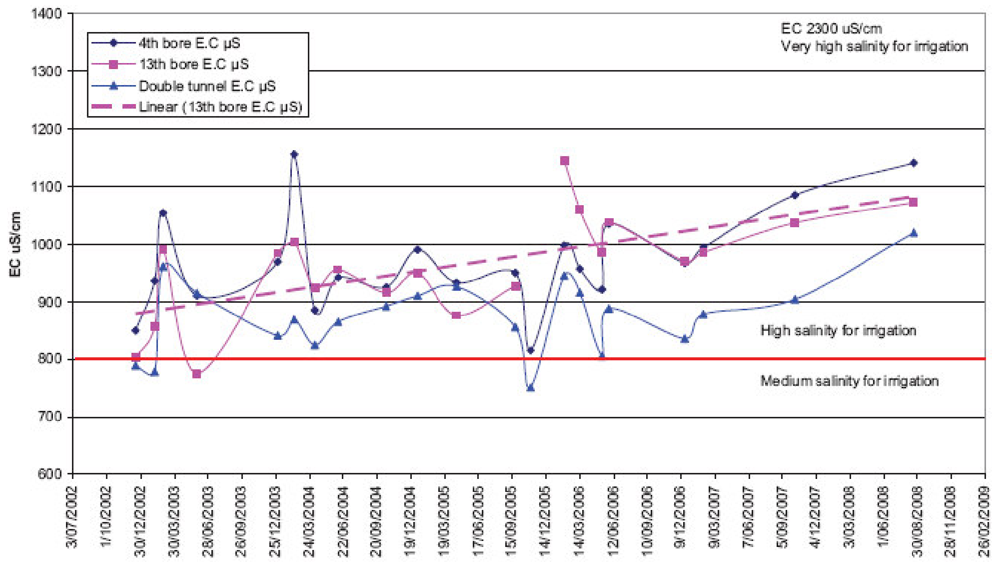

Figure 3: Measured Groundwater Salinity at MGC bores 2002-2009

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 know 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.

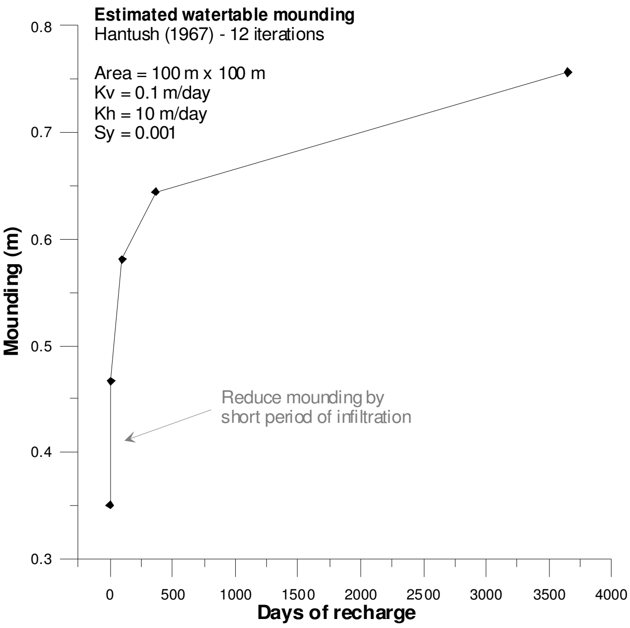

Figure 4: Mounding relative to no. recharge days

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 assume 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 Peoter, 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.

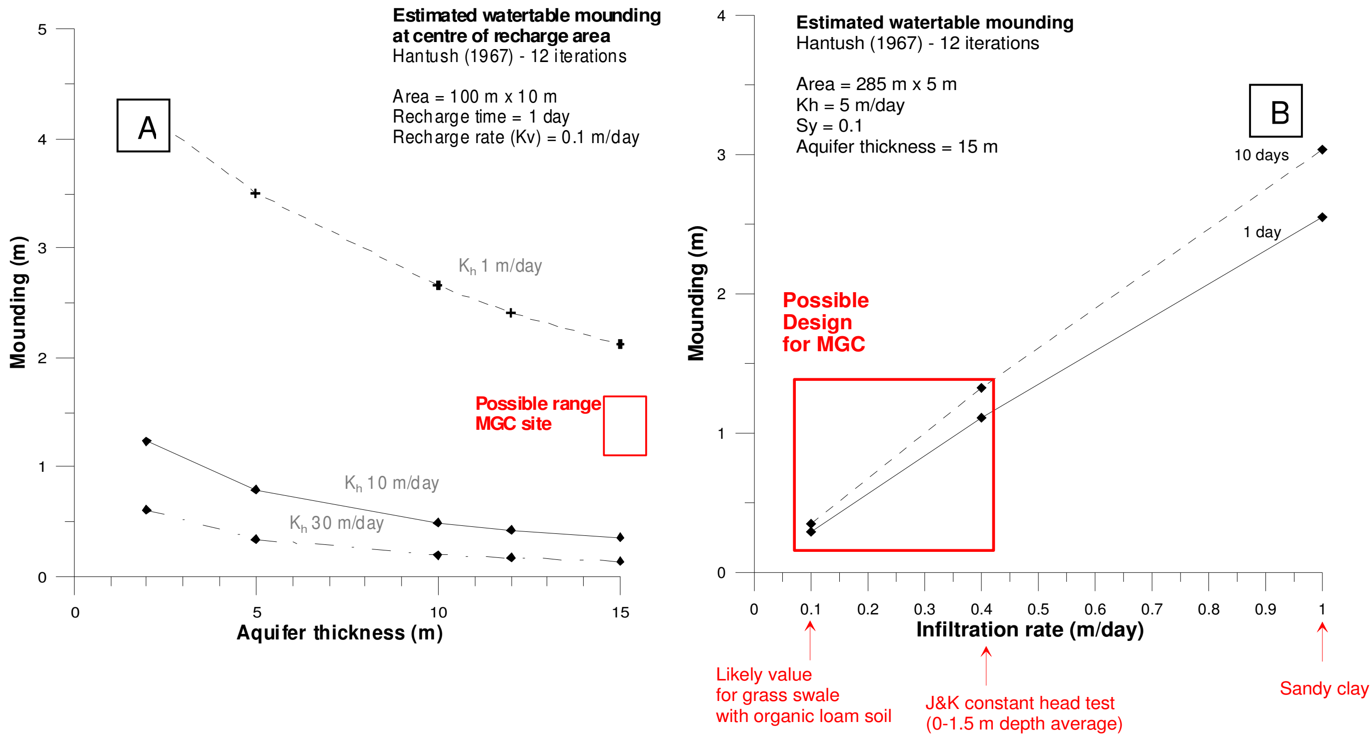

Figure 5: Preliminary Design Estimate of Water Table Mounding

Stormwater quality may be improved by infiltration in a MAR scheme, thereby having less impact on Manly Lagoon than direct stormwater discharge. Groundwater below Manly Golf Course has already been impacted by nutrients and metals, however both stormwater and groundwater satisfy ANZECC (2000) criteria for irrigation, for all parameters other than phosphorous. Without treatment, the high concentrations of phosphorous would limit the use of the waters to only short term (< 25 years). Due to the mobility of nitrates, groundwater contamination by nitrates may pose the highest risk to groundwater quality.

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 3.

Table 2: Advantages and Disadvantages of MAR proposal for MGC

Advantages	Disadvantages
• Improved quality of catchment discharge to Manly Lagoon • Minor change to current situation if grassy channel is used • Moderate change to current situation if 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 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.

4. 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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References

Acworth, R.I. and Jorstad, L.B., 2006, 'Integration of multi-channel piezometry and electrical tomography to better define chemical heterogeneity in a landfill leachate plume within a sand aquifer'. *Journal of Contaminant Hydrology*, vol. 83, pp. 200-220.

AGC Woodward-Clyde Pty Ltd, 1992, *Groundwater Investigations, March-May 1992.*

Albani, A., 1981, 'Sedimentary environments and Pleistocene chronology of the Botany Basin, NSW, Australia'. *Geo-Marine Letter,* vol.1, pp. 163-167.

ANZECC 2000, *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.* National Water Quality Management Stategy

ARQ (2006). *Australian Runoff Quality – A Guide to Water Sensitive Urban Design.* Editor in Chief THF Wong. Engineers Australia.

Bish, S., Realica, S.A. and Wischusen, J. 2000, *Botany Sand Beds GWMA018 Botany Basin, NSW - Northern, Southern and Western Zones, Status Report No. 2*, NSW Department of Land and Water Conservation, Sydney-South Coast Region.

Dillon, P. and Pavelic, P., 1996, *Guidelines on the quality of stormwater and treated wastewater for injection into aquifers for storage and reuse*., Urban Water Research Association of Australia Research Report No 109.

Dillon, P.J. 2005, 'Future management of aquifer recharge'. *Hydrogeology Journal*, vol 131, pp. 313-316.

EPHC, 2008. *Australian Guidelines for Water Recycling – Managed Aquifer Recharge*. Draft for Public Consultation. Environment Protection and Heritage Council, National Health and Medical Research Council, Natural Resource Management Ministerial Council, May, 2008.

Gale, I. (ed), 2005, *Strategies for Managed Aquifer Recharge MAR in semi-arid areas*, UNESCO International Hydrological Programme.

Griffin, G.N., 1963, *The Botany Basin*, Geological Survey of New South Wales, Bulletin No. 18

McNally, G. and Jankowksi, J., 1998, *Environmental geology of the Botany Basin*, Geological Society of Australia, EEHGS Collected Case Studies in Engineering Geology, 4th Series.

Merrick, N., 1994, "A groundwater flow model of the Botany Basin", *IAH/IEA Water Down Under '94*, Adelaide, Australia, 21-25 November, 1994.

NSW Government (2006), 2006 Metropolitan Water Plan. NSW Government, *Water for Life,* Sydney.

Poeter, E., McCray, J., Thyne, G. and Siegrist, R., 2005, *Guidance for Evaluation of Potential Groundwater Mounding Associated with Cluster and High Density Wastewater Soil Absorption Systems*, Report No WU-HT-02-45. International Groundwater Modelling Centre, Colorado School of Mines, Golden, USA.

Sydney Water 2006, *Sewer Mining – How To Establish An Operation*. Sydney Water, May

Timms, W., Acworth, I., Merrick, N. and Badenhop, A., 2006. *Pre-feasibility assessment of managed aquifer recharge in the Botany aquifer*. UNSW Water Research Laboratory Technical Report 2006/33. http://www.nwc.gov.au.

Toze, S., Bekele, E., 2009. Managed aquifer recharge with secondary treated wastewater. AWA *Water*, March 2009, p 43-47.

Woodward-Clyde, 1996, *ICI Botany Groundwater Stage 2 Survey*. Contract S2/C3 Water / Soil Phase 2. Final Report 3390R1-D for ICI Engineering Australia Pty Ltd. August 1996.

Wright, A. and Parsons, R., 1994, "Artificial recharge of urban wastewater, the key component in the development of an industrial town on the arid west coast of South Africa". *IAH/IEA Water Down Under '94*, Adelaide, 21-25 November 1994.

Yu, X., 1994, *Study of physical and chemical properties of groundwater and surface water in the Northern Part of the Botany Basin, Sydney*., Unpublished PhD thesis, University of New South Wales.