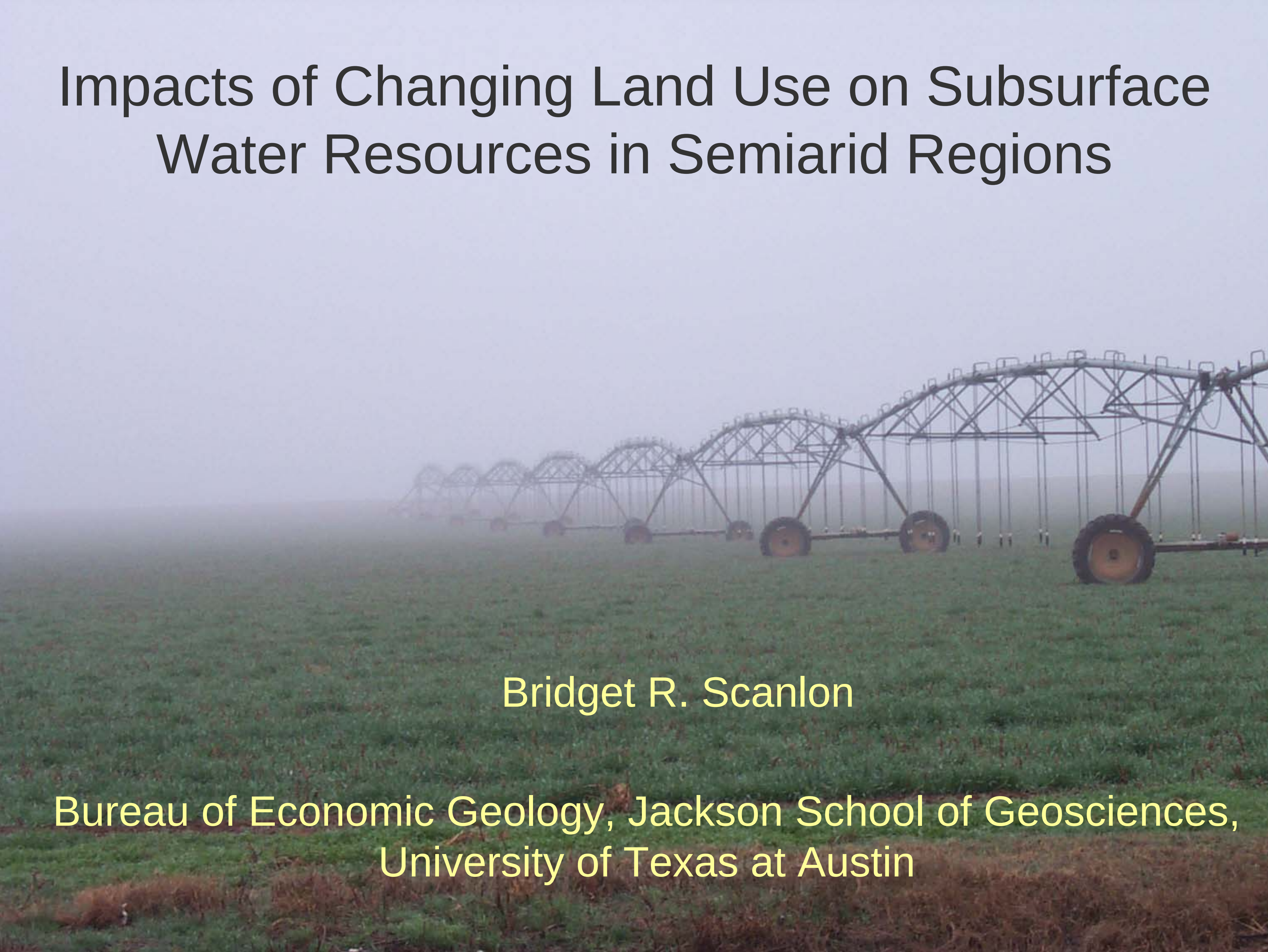
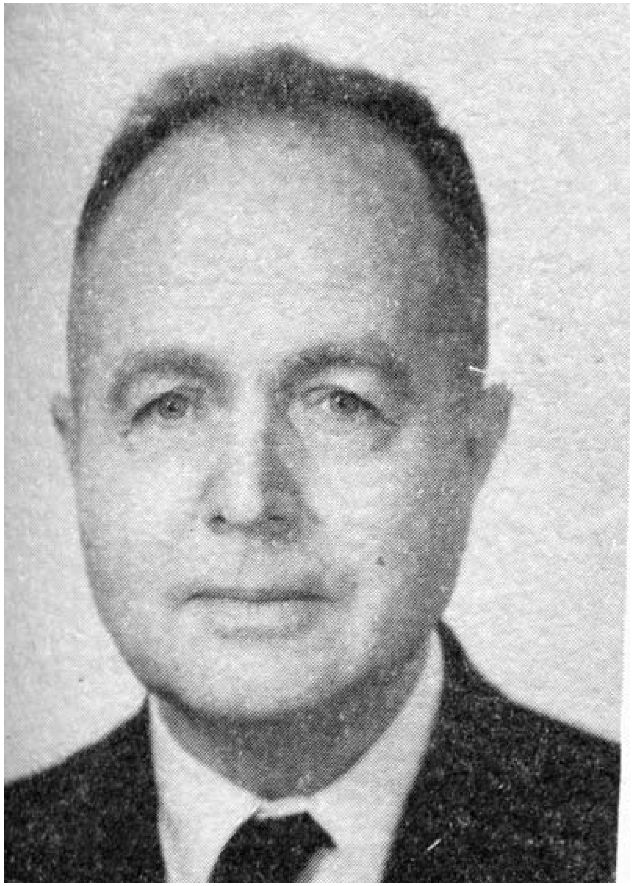
Impacts of Changing Land Use on Subsurface Water Resources in Semiarid Regions



Bridget R. Scanlon

Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin

John Manning Birdsall
1902-1975



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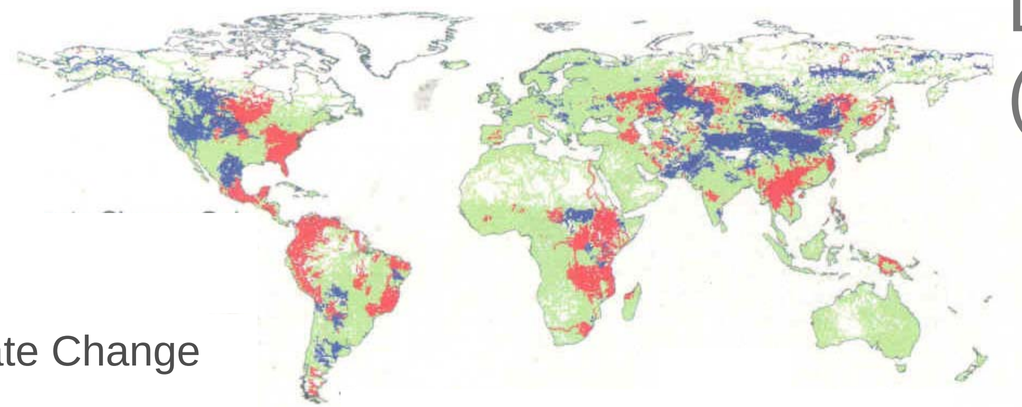
Acknowledgments and Collaborators

- Funding sources:
  - Geological Society of America
  - Jackson School of Geosciences
  - Bureau of Economic Geology
  - Bureau of Reclamation
  - Department of Energy
  - National Science Foundation
  - Texas Commission on Environmental Quality
  - Texas Water Development Board
- Collaborators:
  - Robert Reedy, Andrew Tachovsky, Dani Kurtzman, Gil Strassberg, Kelley Keese (Bureau of Economic Geology)
  - Jirka Simunek, UC Riverside
  - Brett Bruce, Kevin Dennehy, Jason Gurdak, Pete McMahon, Dave Stonestrom (USGS)

Basic Questions
Impacts of Changing Land Use on Water Resources

- Why is it important?
- What impacts does changing land use have on water resources and how can we quantify these impacts?
- Where are similar impacts documented globally?
- How can we use the understanding of impacts to develop sustainable water resources?

Relative Change in Demand per Discharge (1985 – 2025)



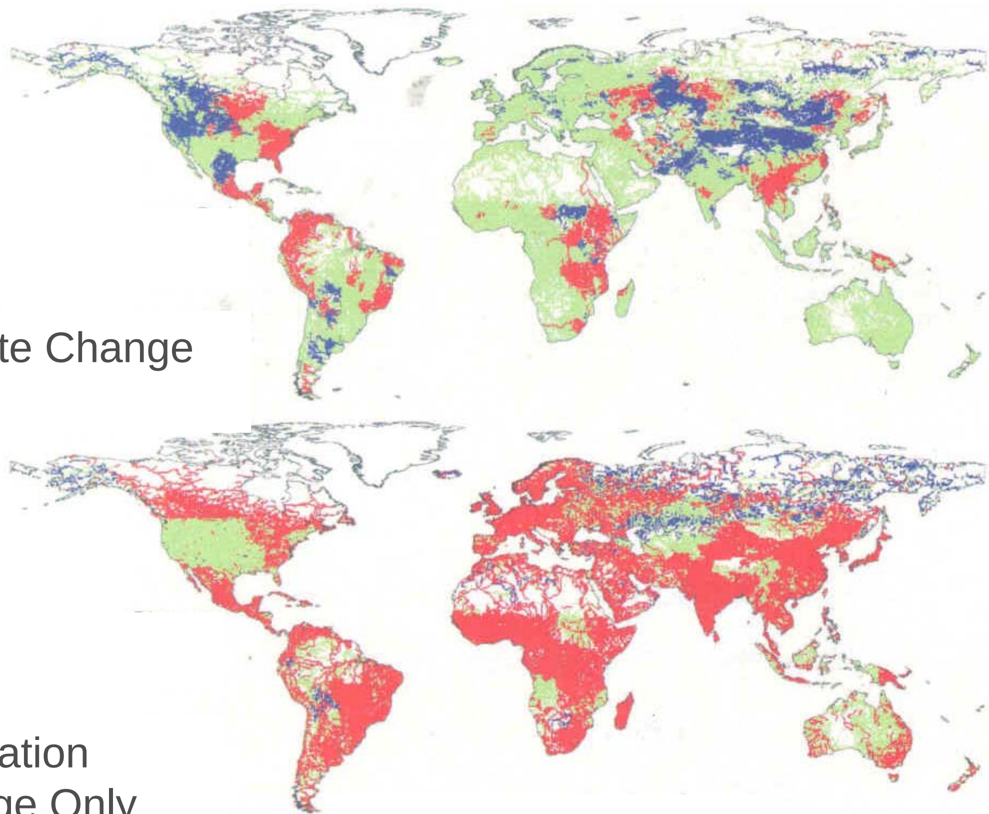
Climate Change Only

$$\frac{\textit{Demand/discharge}_{scenario}}{\textit{Demand/discharge}_{base}}$$

- <0.8
- 0.8-1.2
- >1.2

Vorosmarty et al., 2000

Relative Change in Demand per Discharge 1985-2025



Climate Change Only

Population Change Only

$$\frac{\textit{Demand/discharge}_{scenario}}{\textit{Demand/discharge}_{base}}$$

<0.8

0.8-1.2

>1.2

Vorosmarty et al., 2000

How much water do you consume each day?

How much water do you consume each day?

- Drinking (2 – 5 L/d/p)
- Washing, sanitation, household tasks (50 – 200 L/d/p)

Renault and Wallender, 2000
Molden and Fraiture, 2006

How much water do you consume each day?

- Drinking (2 – 5 L/d/p)
- Washing, sanitation, household tasks (50 – 200 L/d/p)
- Diet:
  - 2,600 L/d/p (vegetarian)
  - 5,400 L/d/p (nonvegetarian)
- Proposed diet: 3000 cal/d/p; water requirements ~ 1 L/cal

Renault and Wallender, 2000
Molden and Fraiture, 2006

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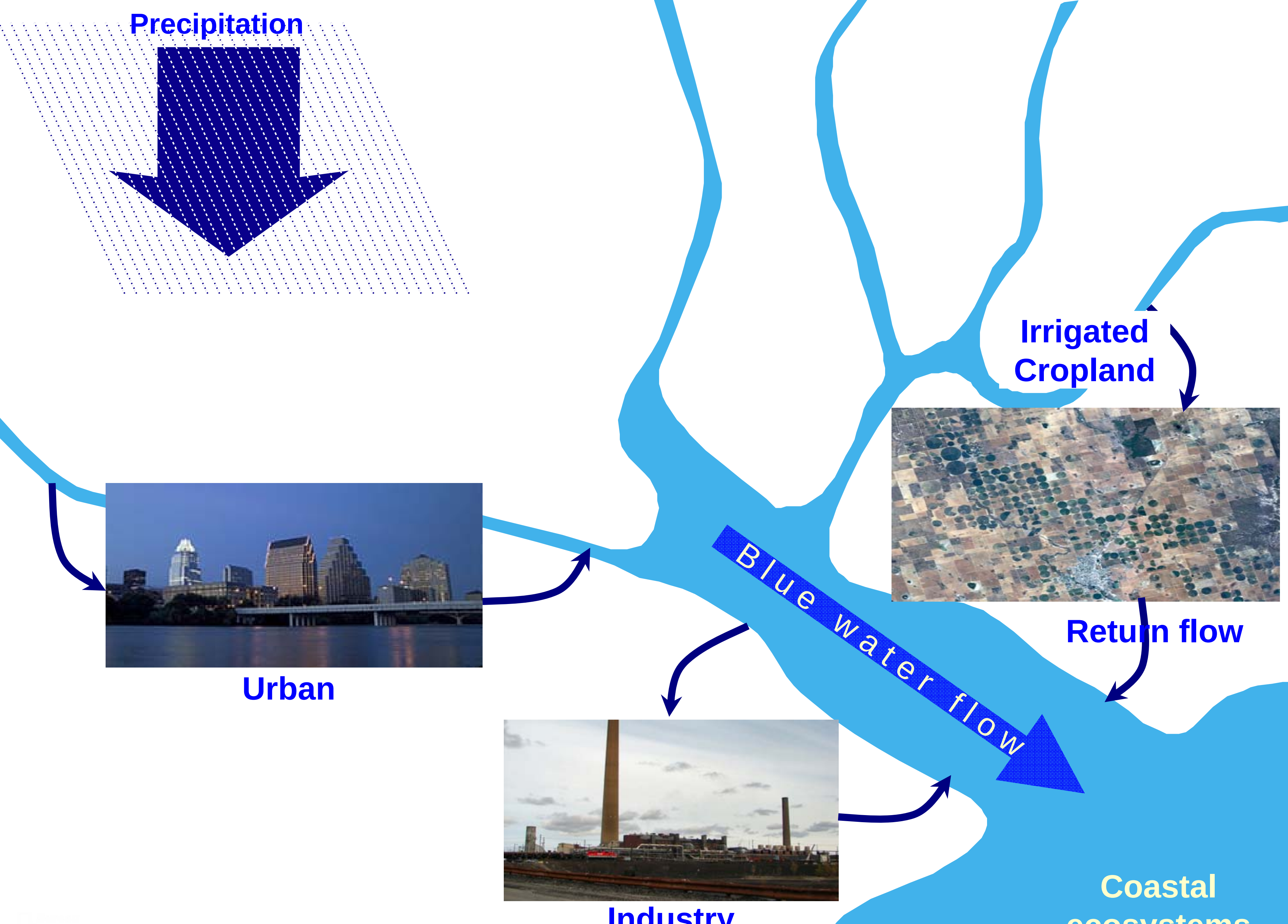
- Proposed diet: 3000 cal/d/p; Water requirements ~ 1 L/cal

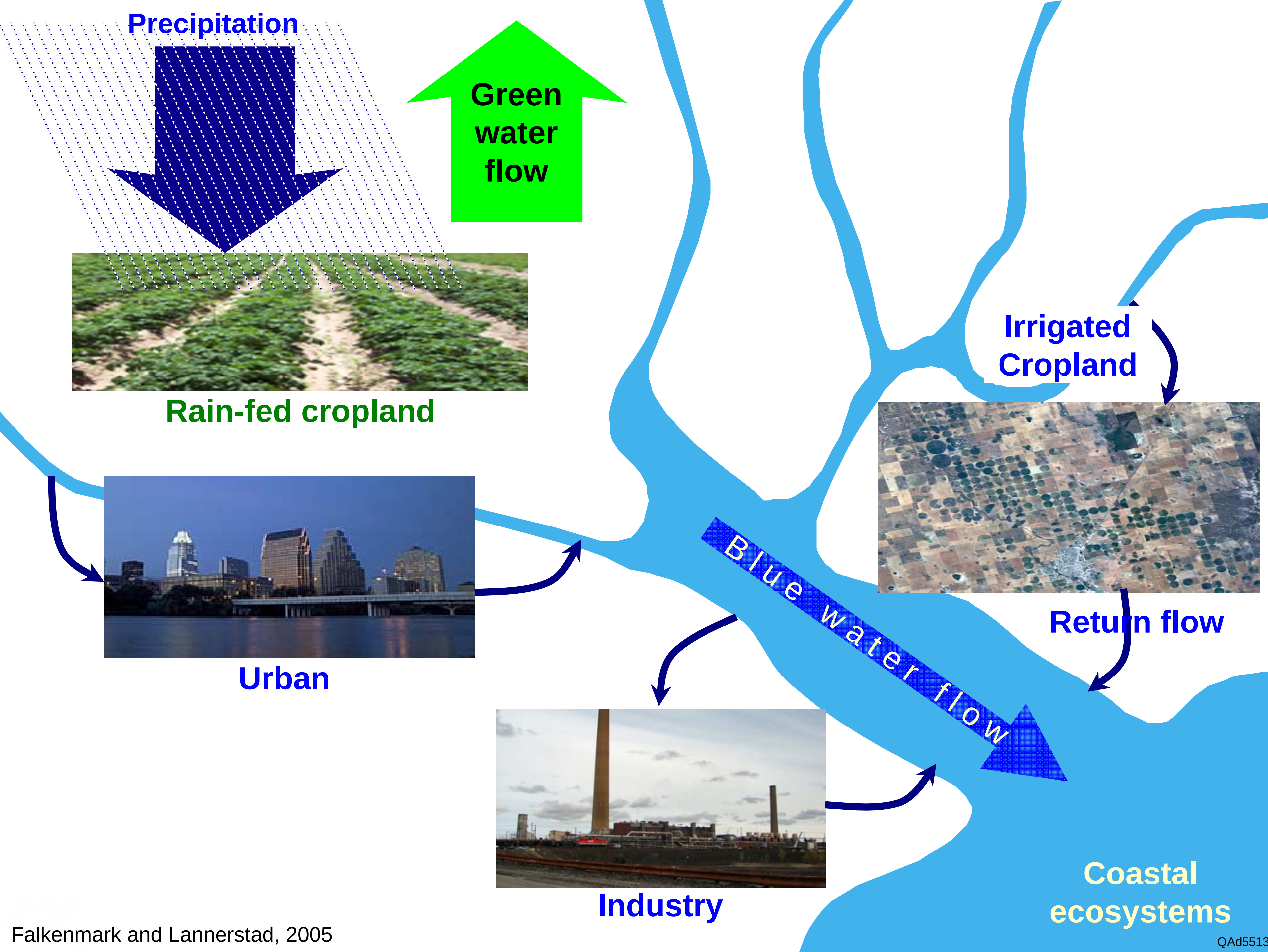
Liters of water required to produce 1 kg of product

• Bovine meat	13,500
• Poultry/Pork	4,300
• Cereals	700 – 1,400
• Fruits	450
• Vegetables	150

Renault and Wallender, 2000
Molden and Fraiture, 2006

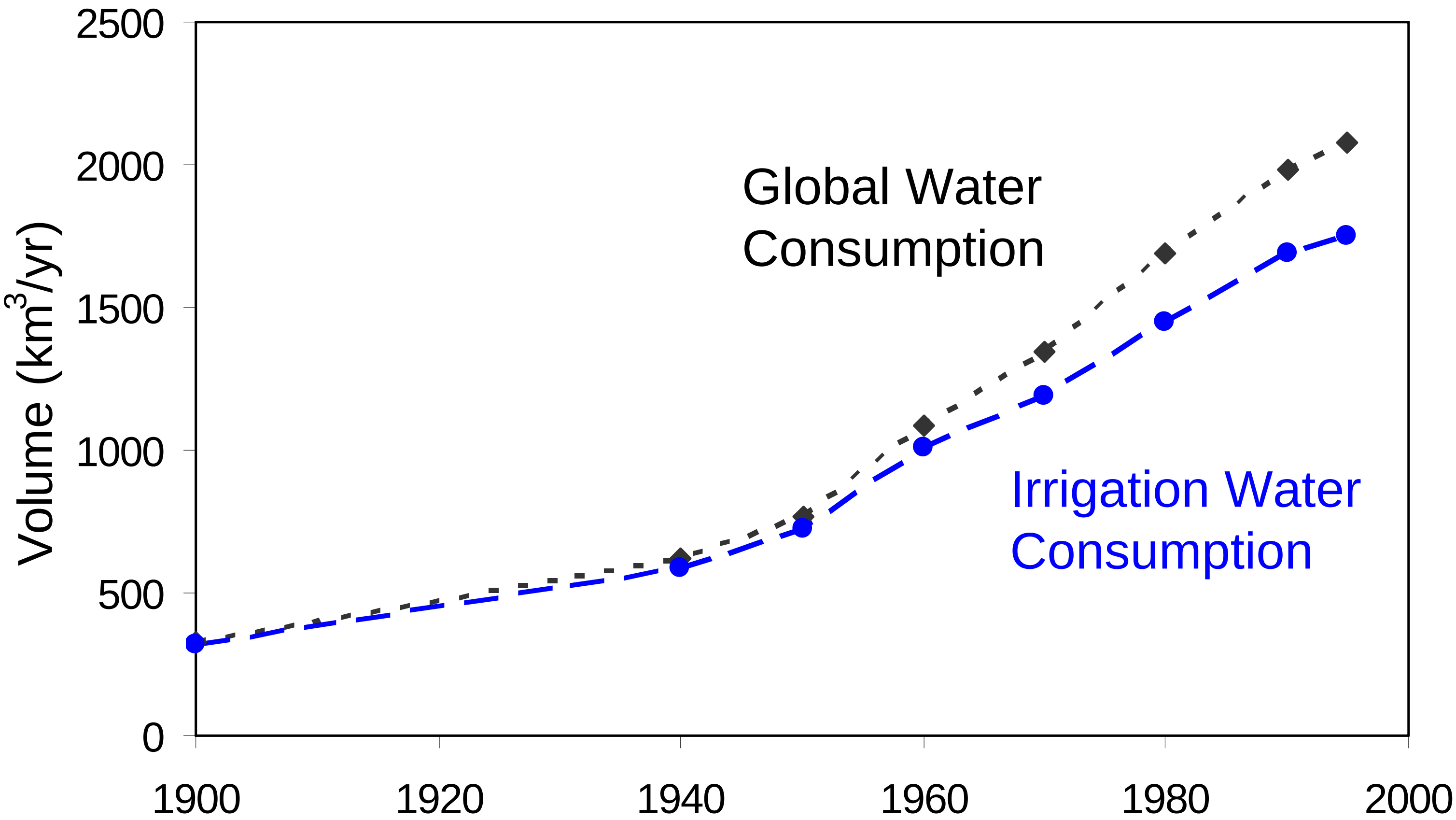


Falkenmark and Lannerstad, 2005



Falkenmark and Lannerstad, 2005

Global and Irrigated Water Consumption



Irrigated agriculture: 20% of cropland, 40% of food production
Rainfed agriculture: 80% of cropland, 60% of food production
Yield from irrigated agriculture = ~2.5 x yield from rainfed agriculture

Shiklomanov, 2000

Basic Questions
Impacts of Changing Land Use on Water Resources

- Why is it important?
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- Where are similar impacts documented globally?
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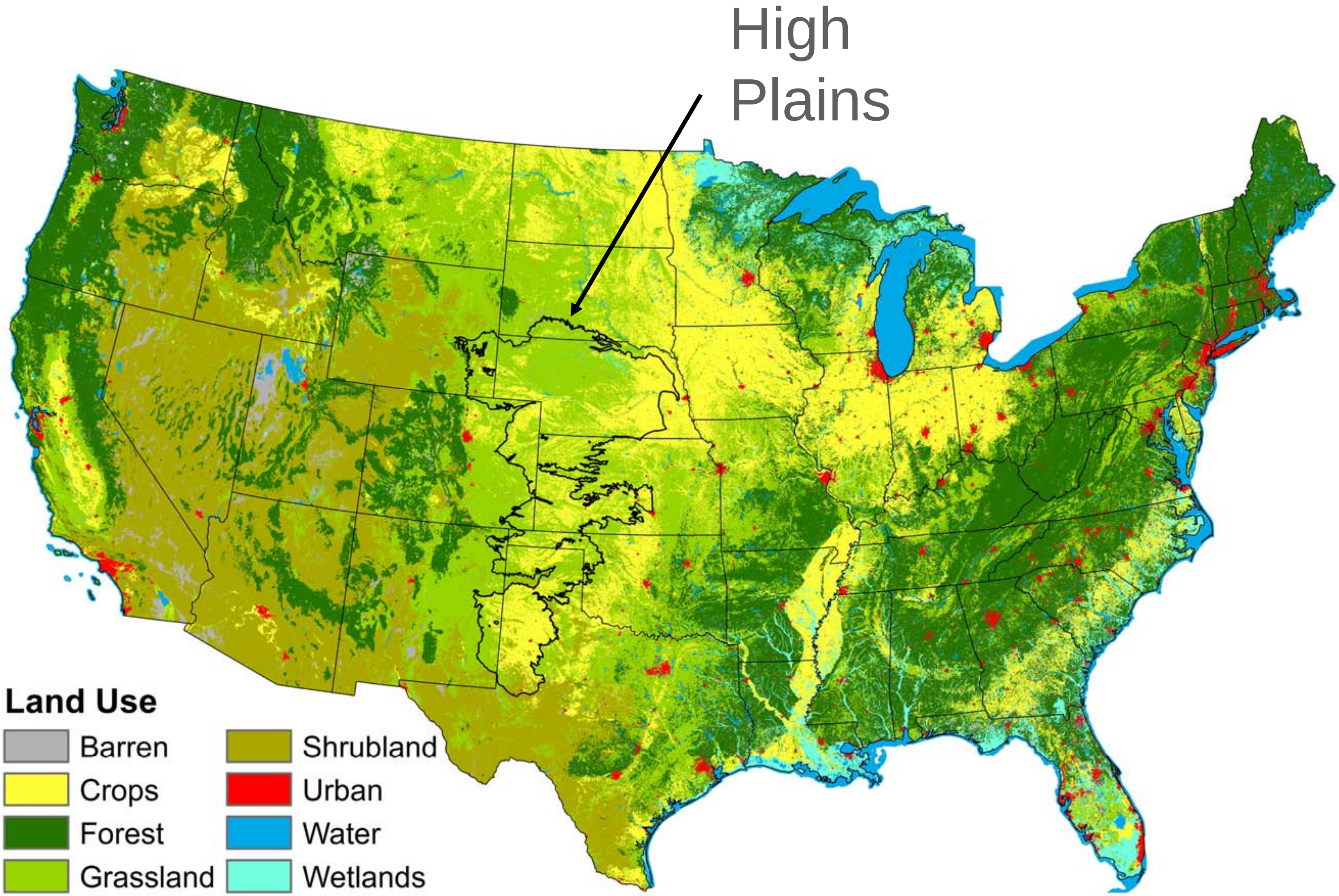
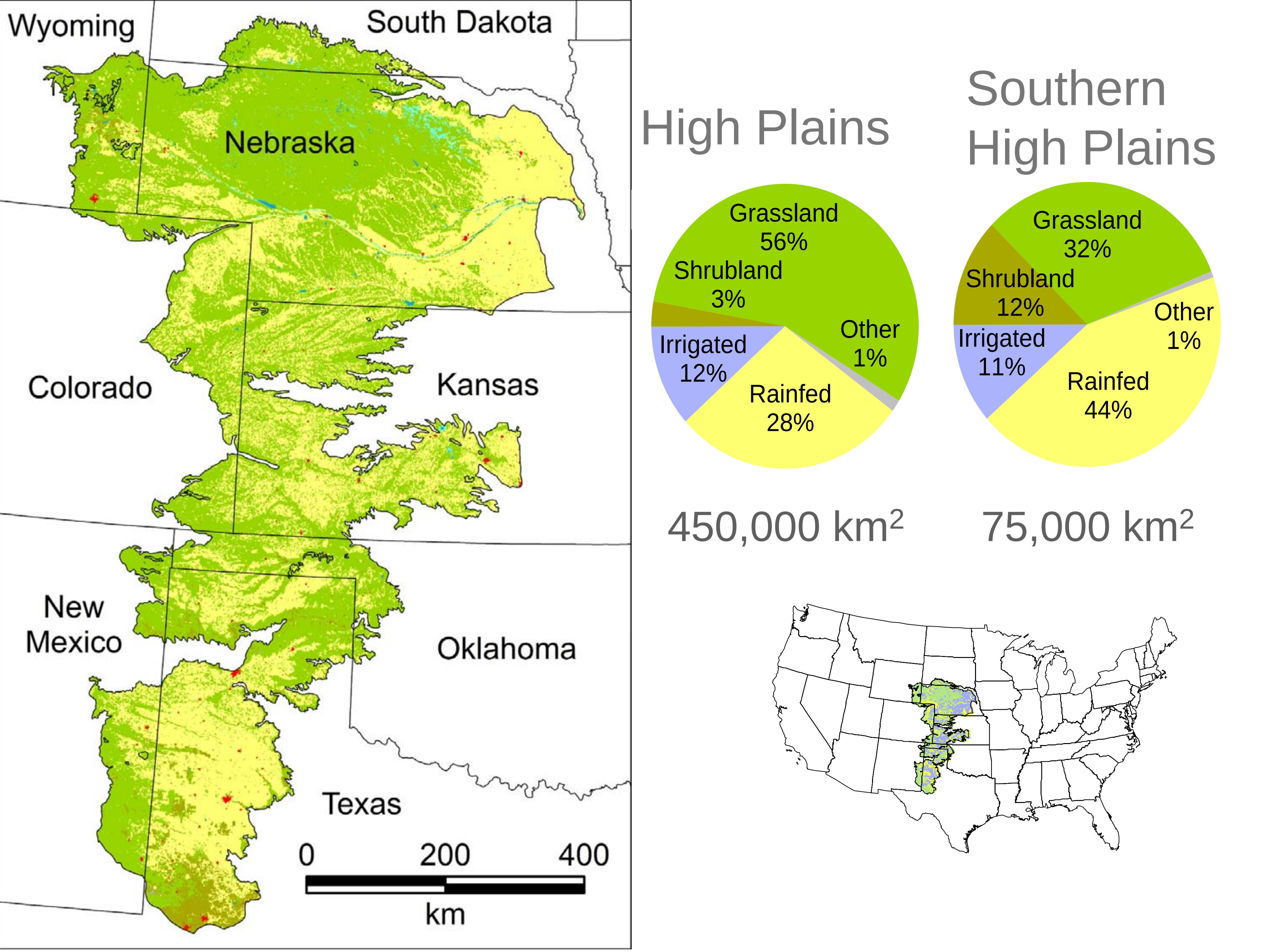
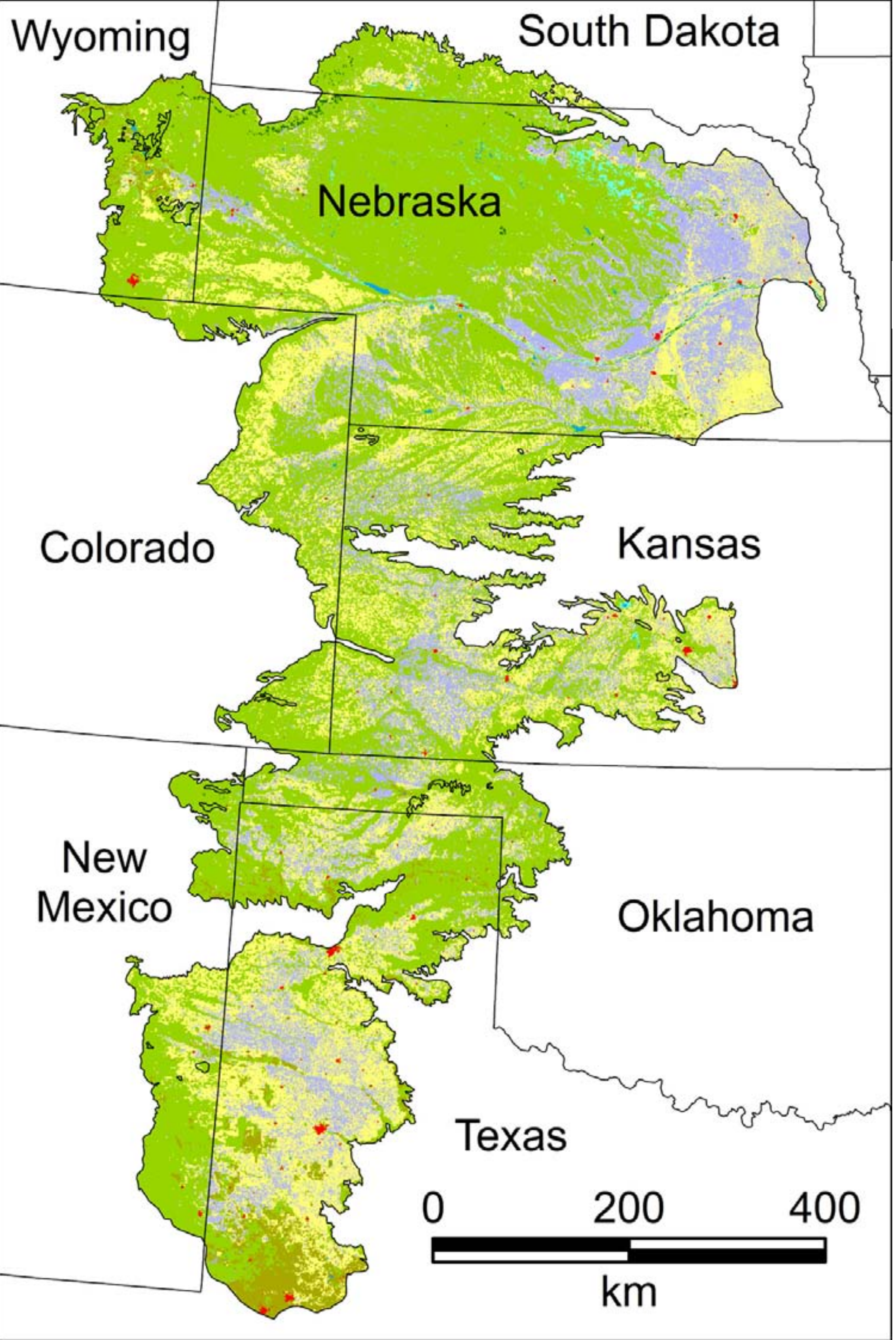
Land-Cover Types in the US (1992)




Wyoming
South Dakota
Nebraska
Colorado
Kansas
New Mexico
Oklahoma
Texas
0
200
400
km
High Plains
Grassland 56%
Shrubland 3%
Irrigated 12%
Rainfed 28%
Other 1%
450,000 km2
Southern High Plains
Grassland 32%
Shrubland 12%
Irrigated 11%
Rainfed 44%
Other 1%
75,000 km2


Boman, Texas Tech Univ

Irrigated Cropland



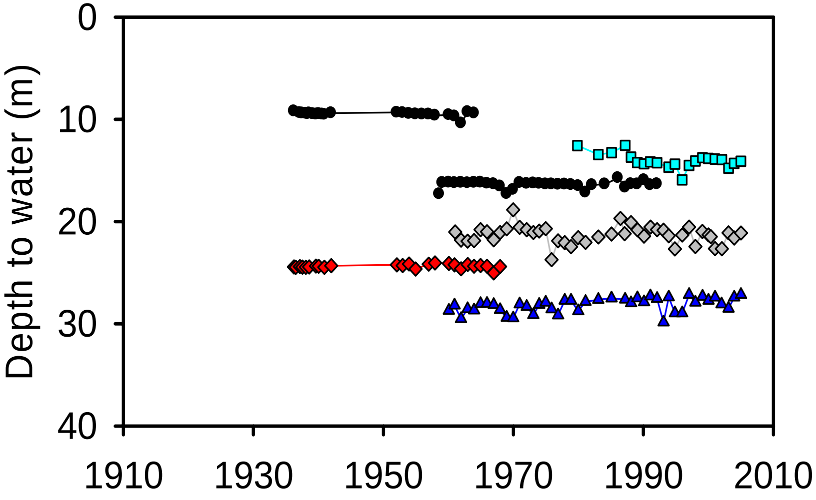
Qi et al., 2002

Impacts of Land-Use Change on Groundwater

- Impact on groundwater quantity
  - groundwater level monitoring
  - GRACE satellite

Natural Ecosystems

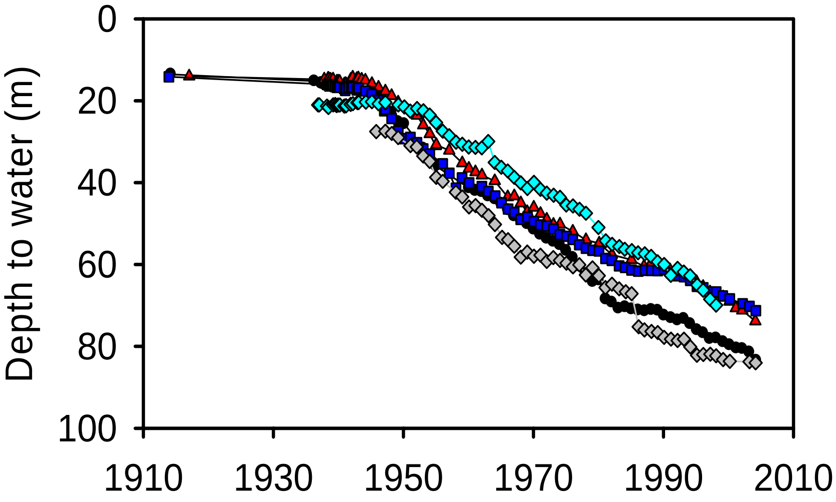
Impacts of Land-Use Changes on Groundwater Levels

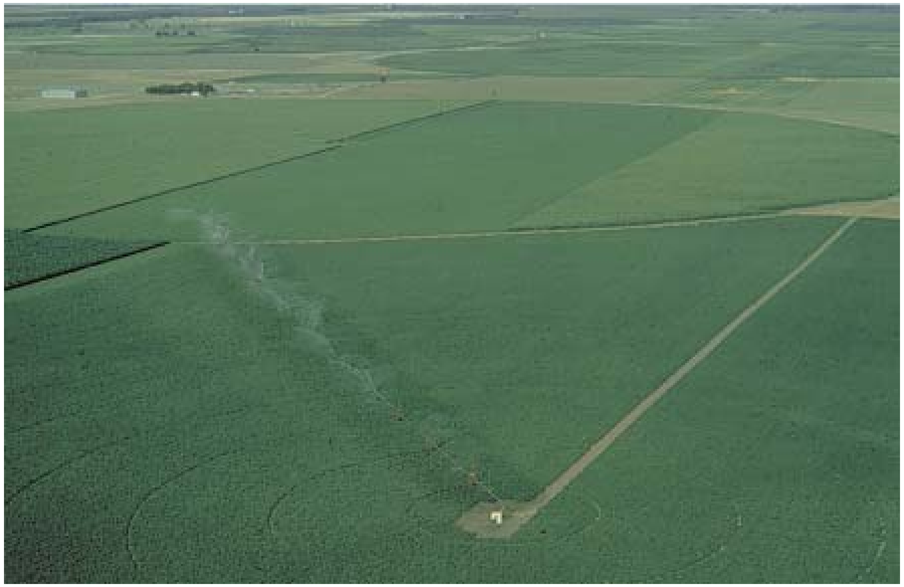


Impacts of Land-Use Changes on Groundwater Levels

Natural Ecosystem

Irrigated Agriculture

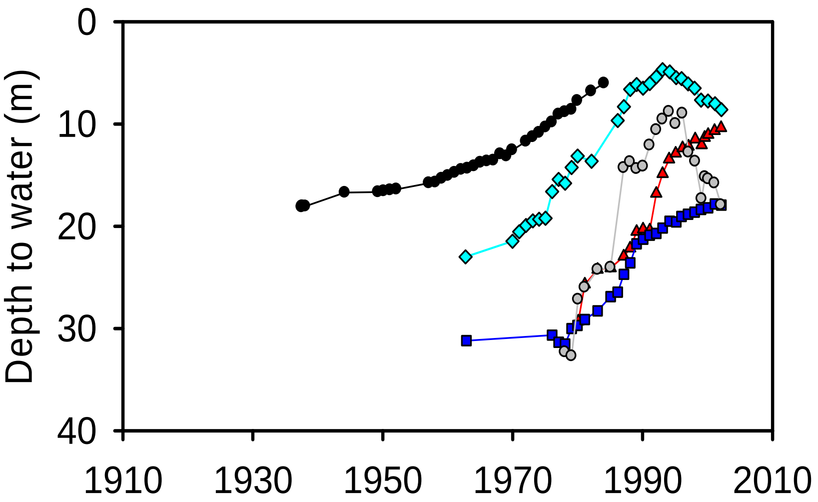




Natural Ecosystem

Irrigated Agriculture

Rainfed Agriculture

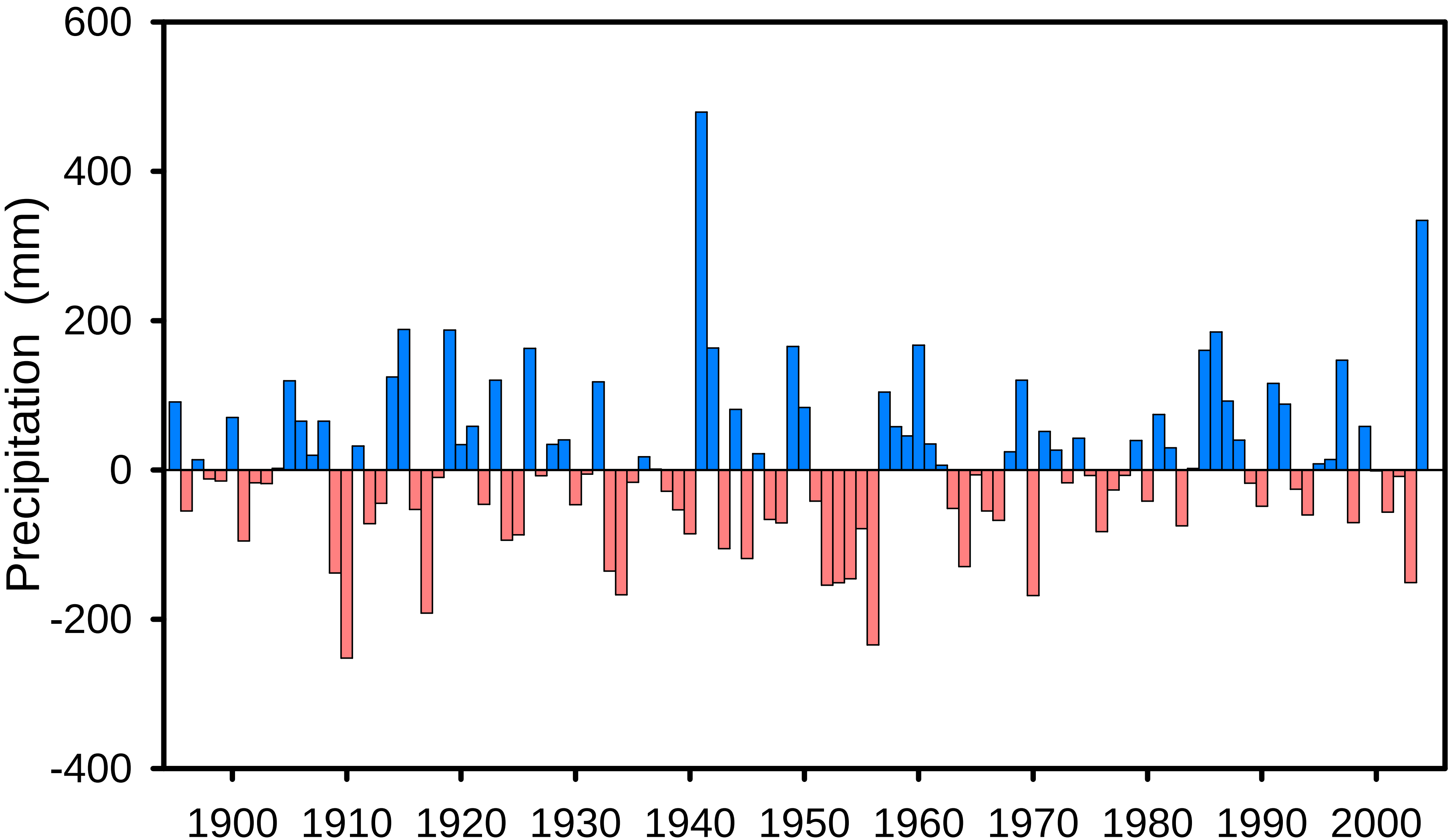


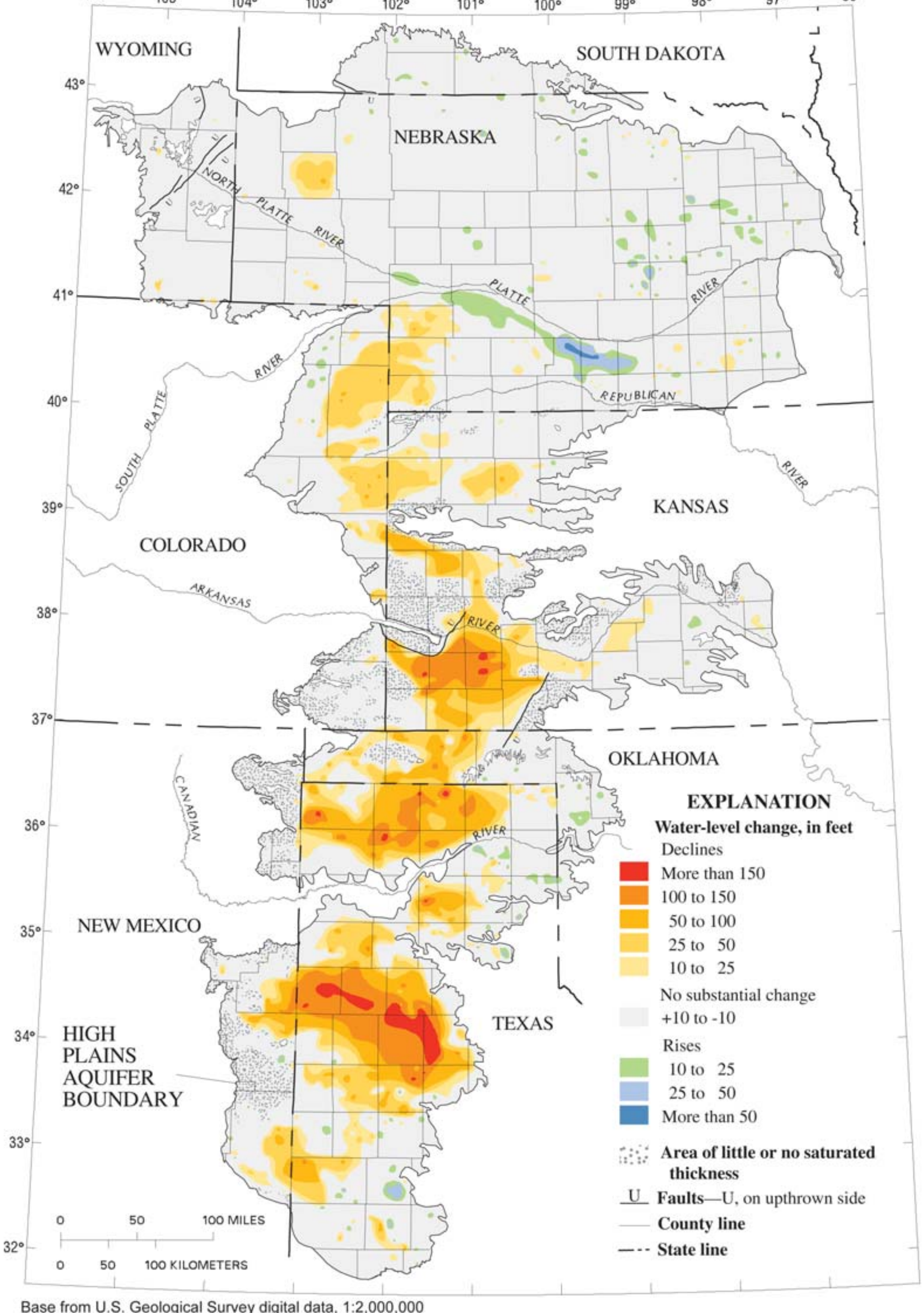
Causes of Increased Recharge Beneath Rainfed Agriculture

$$D \uparrow \text{ or } R\uparrow = P \uparrow - ET \downarrow - R_0 \downarrow$$

where D is drainage, R is recharge, P is precipitation, ET is evapotranspiration, and R_0 is runoff.

Precipitation in the Southern High Plains





Impact of Land Use Change on Groundwater Levels

Declines

- > 150 ft
- 100 to 150
- 50 to 100
- 25 to 50
- 10 to 25

No change

- -10 to 10

Rises

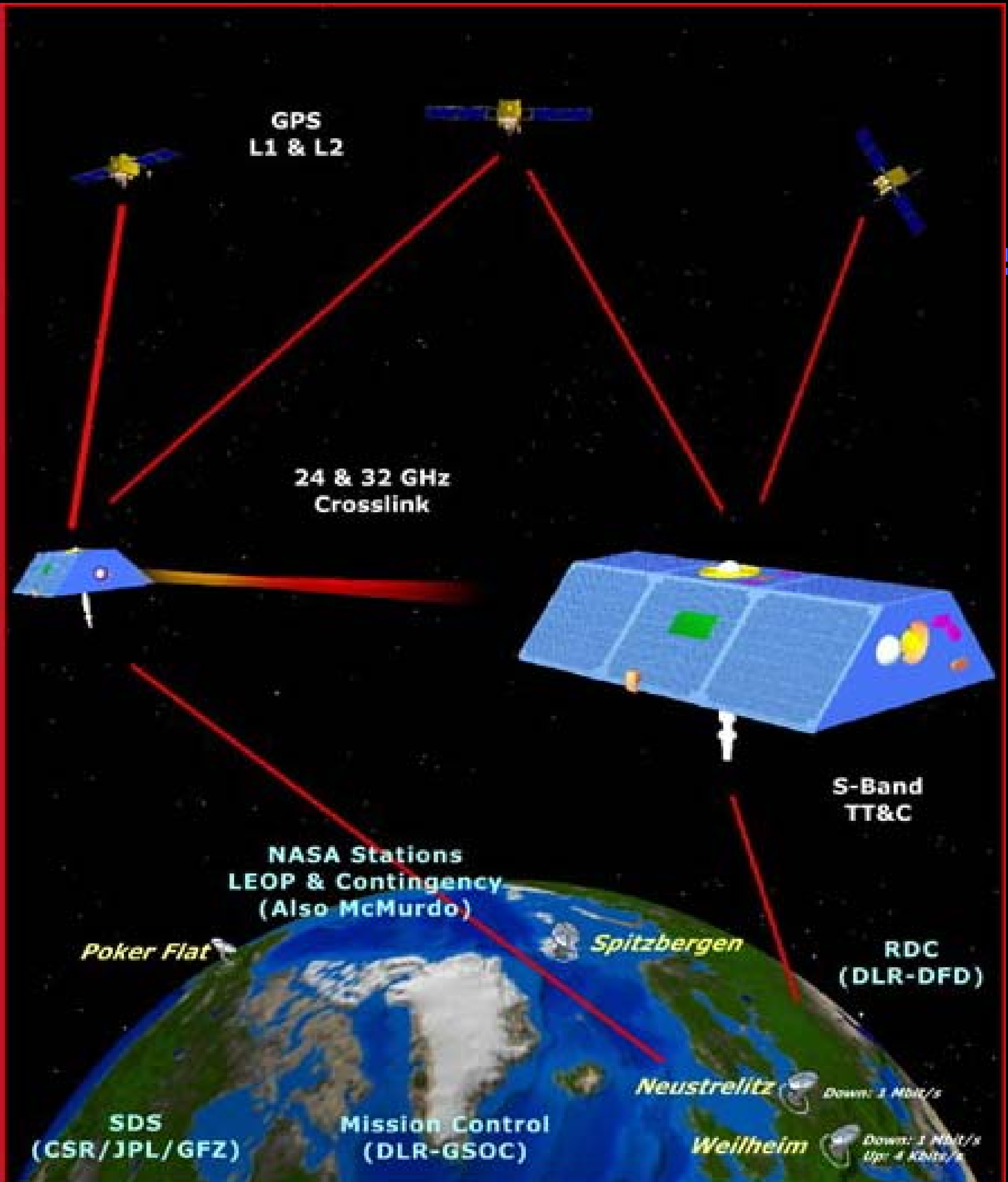
- 10 to 25
- 25 to 50
- 50 to 100

9,200 wells

Average decline: 3.8 m (12.6 ft)

Decline Texas: 10.7 m (35 ft)

McGuire, 2004



GRACE
Gravity Recovery and Climate Expt.

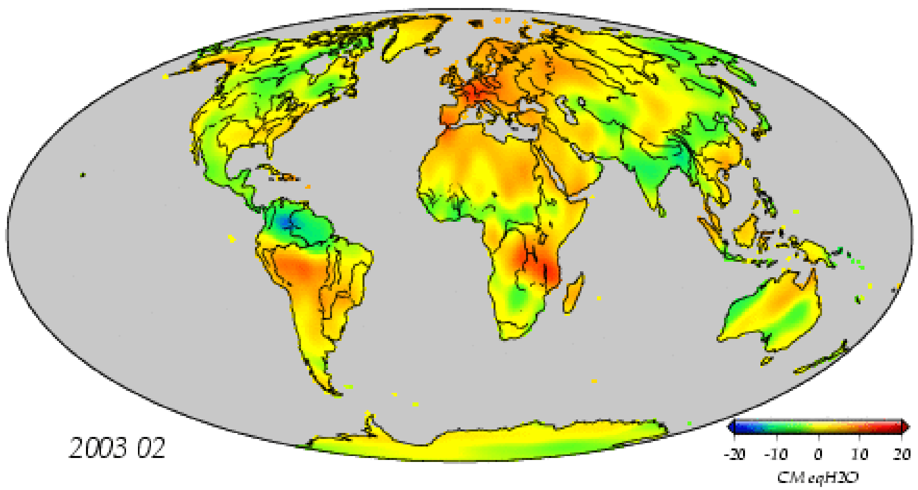
Launched March 2002

Spatial resolution: ~ 200,000 km^2

Terrestrial water storage

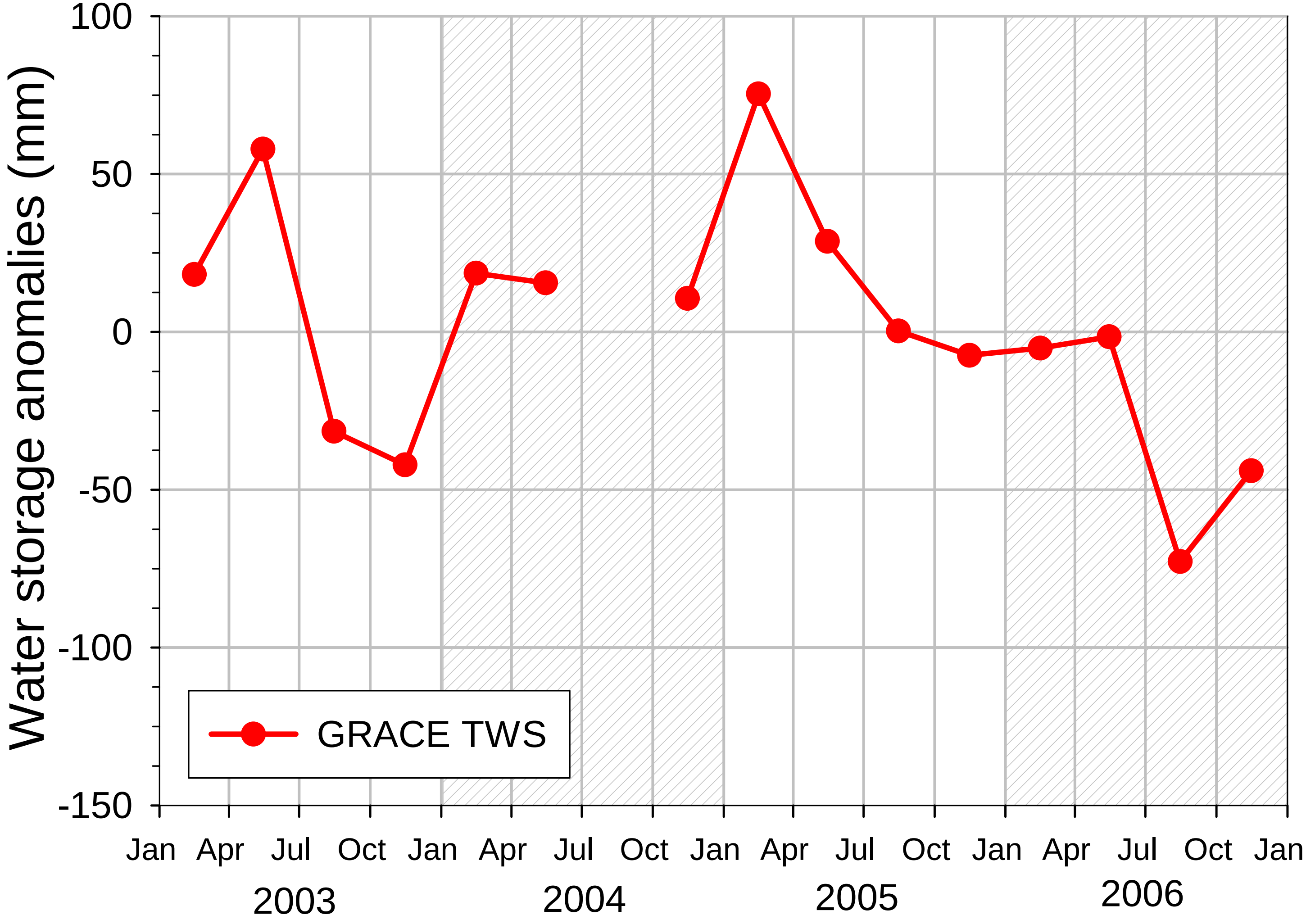
From Gravity to Mass

- Satellites detect changes in Earth's gravity field by monitoring changes in distances between the satellites to within 10 μm
- Observed monthly changes in gravity are attributed to changes in water distribution in the atmosphere, surface water, soil water, and groundwater



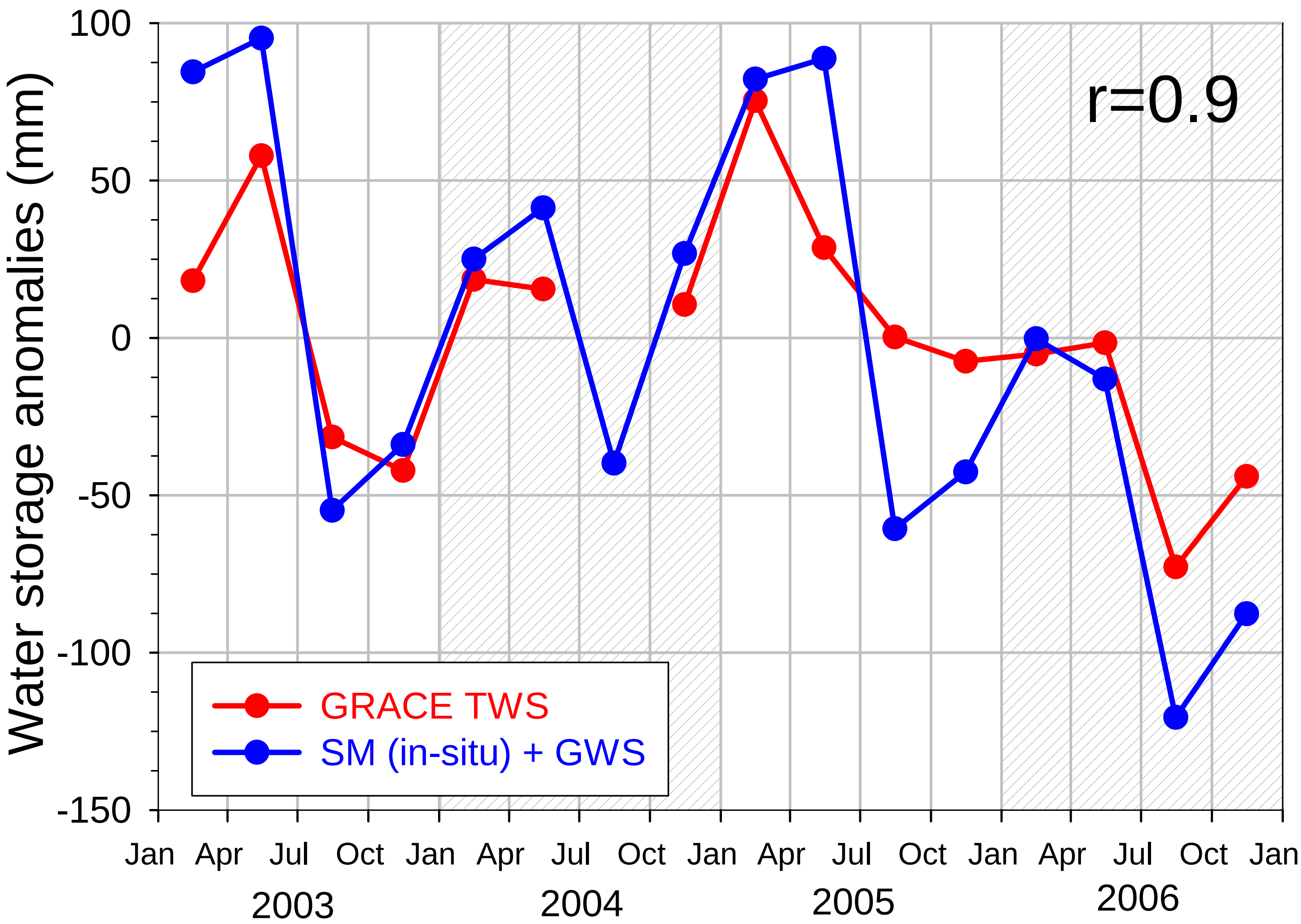
http://gracetellus.jpl.nasa.gov/

GRACE Seasonal Terrestrial Water Storage



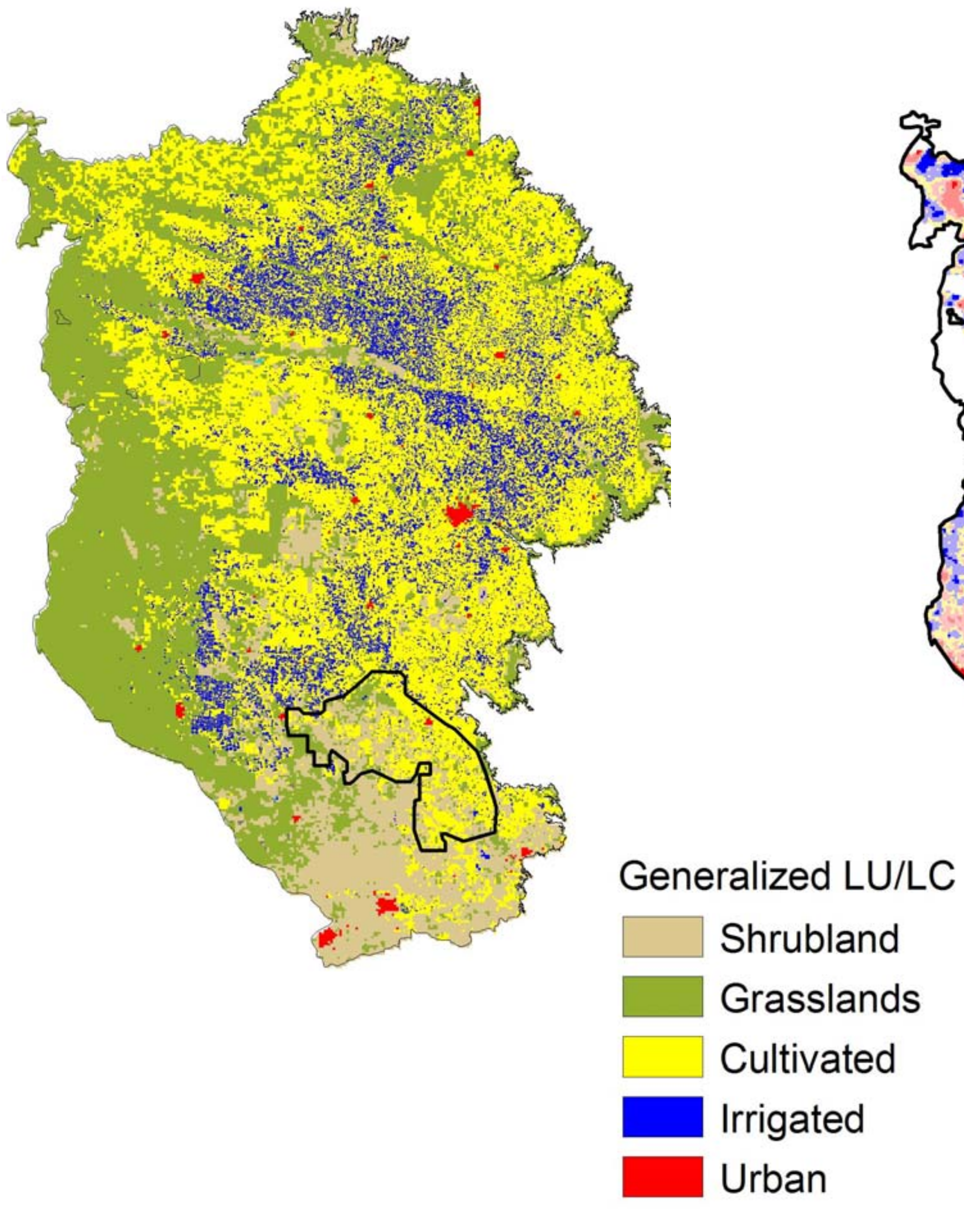
Strassberg et al., 2006

Comparison of GRACE Seasonal Terrestrial Water Storage with Measured Data

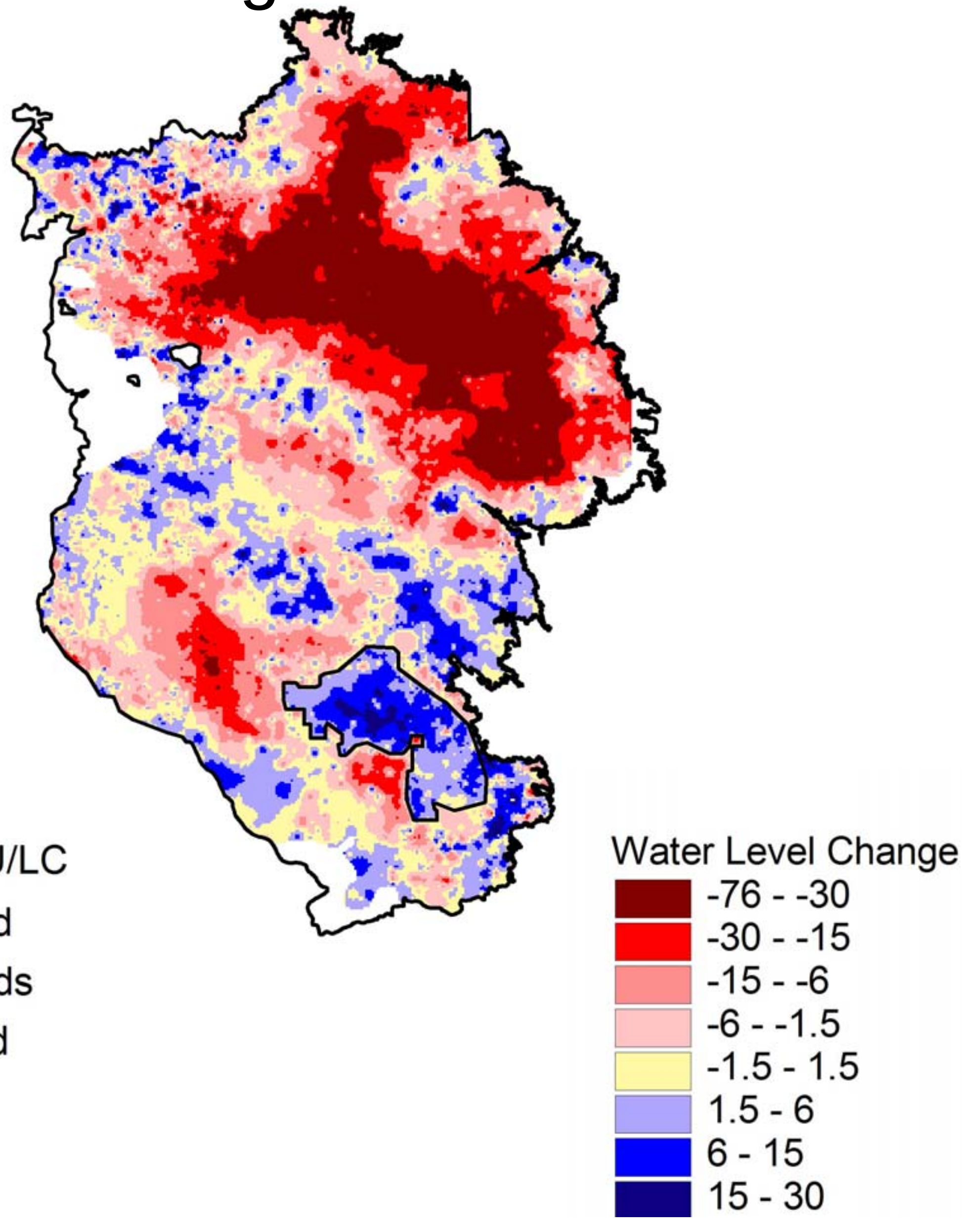


Strassberg et al., 2006

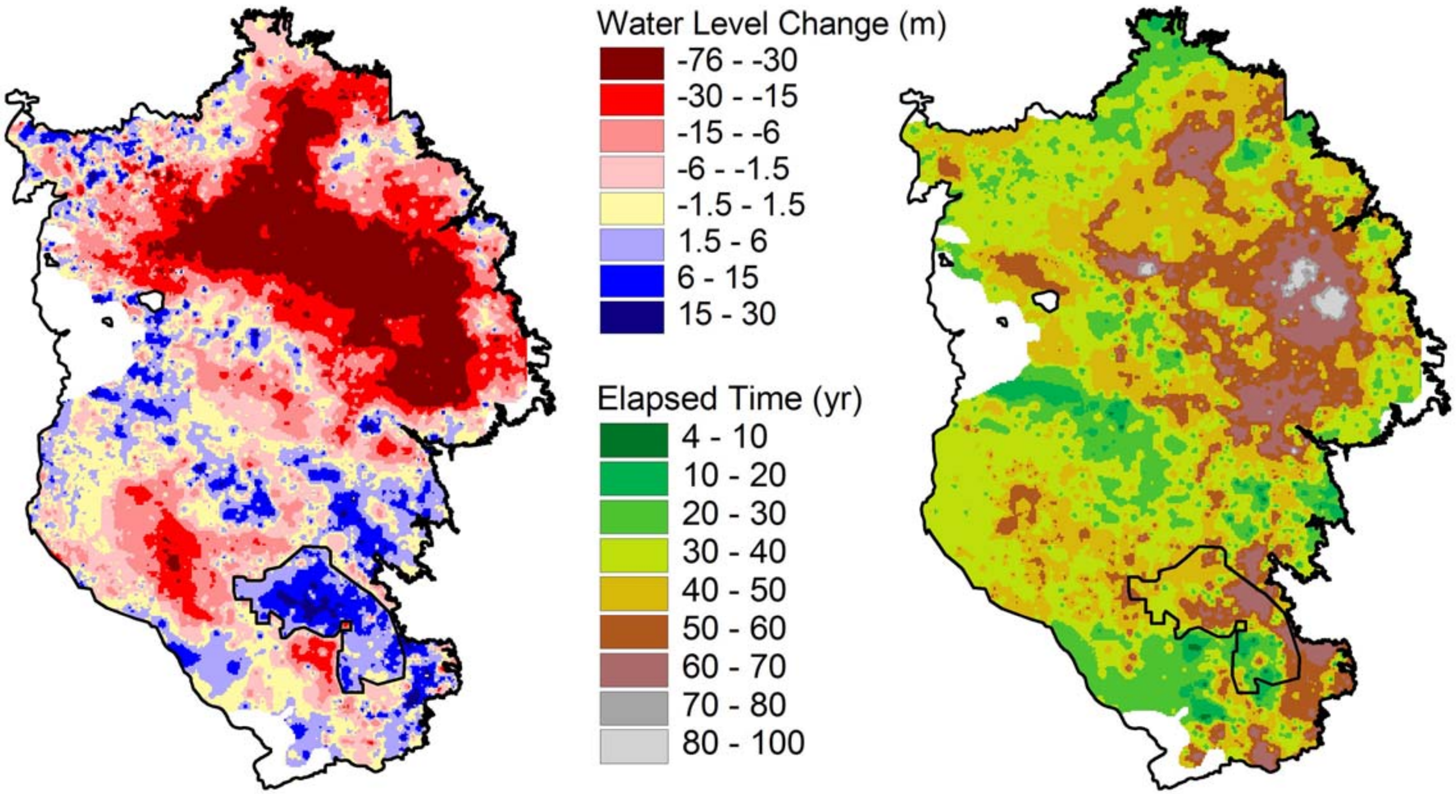
Land Use (1992)



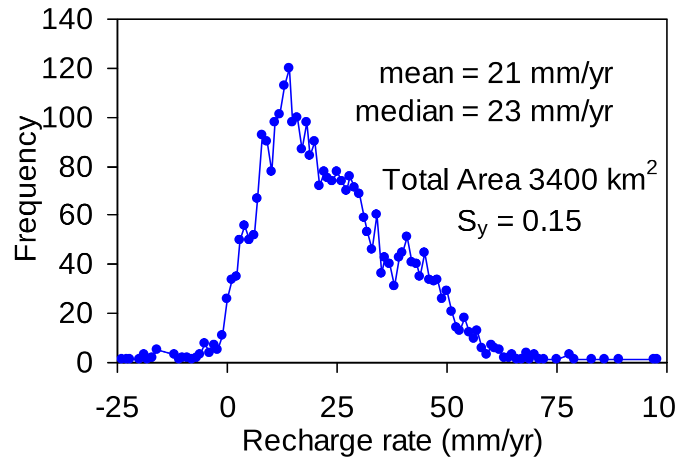
Groundwater Level Change



Recharge Estimation from Water Level Rises in Rainfed Agriculture



Recharge =
Specific Yield $\Delta h/\Delta t$



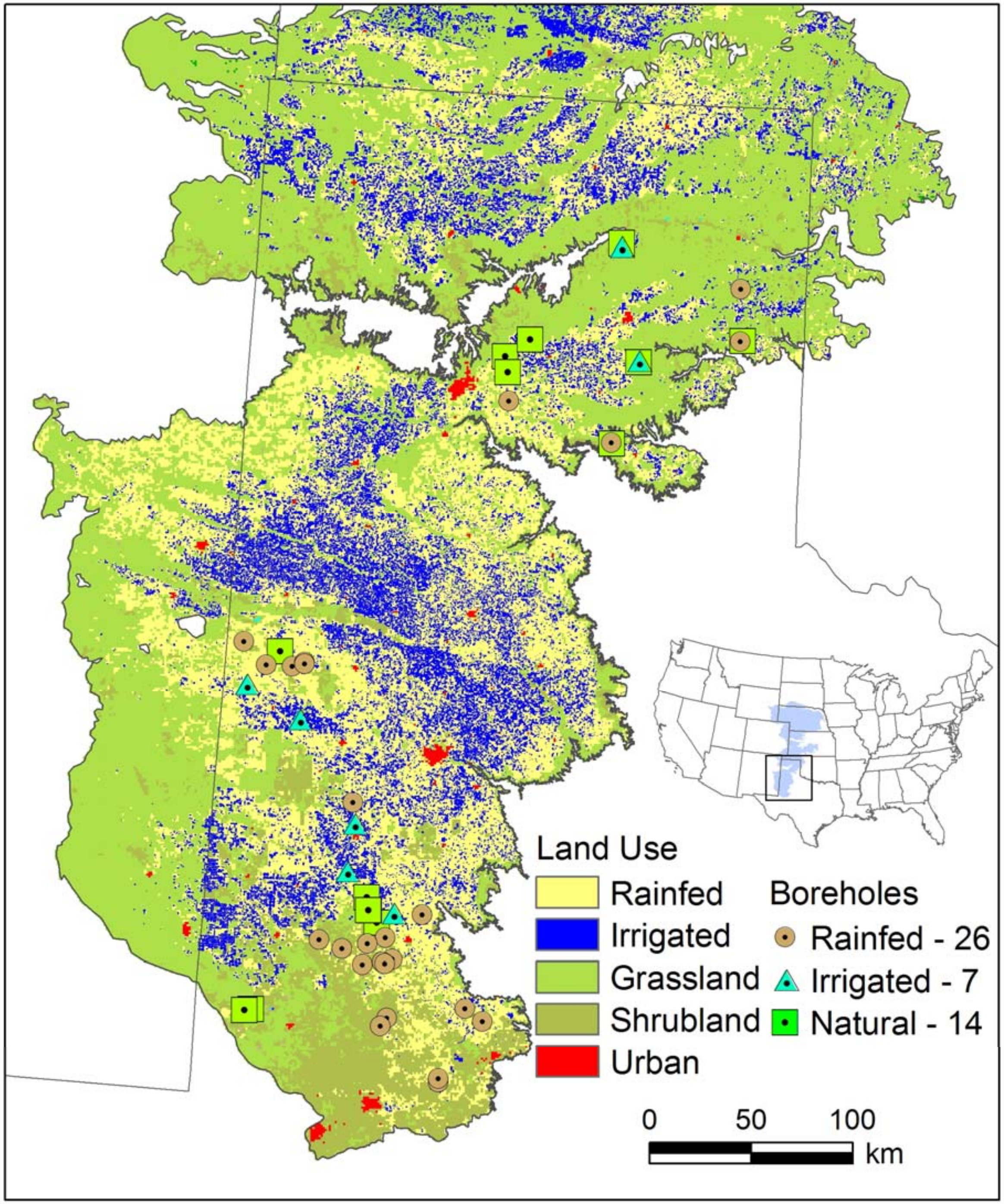
Impacts of Land-Use Change on Groundwater

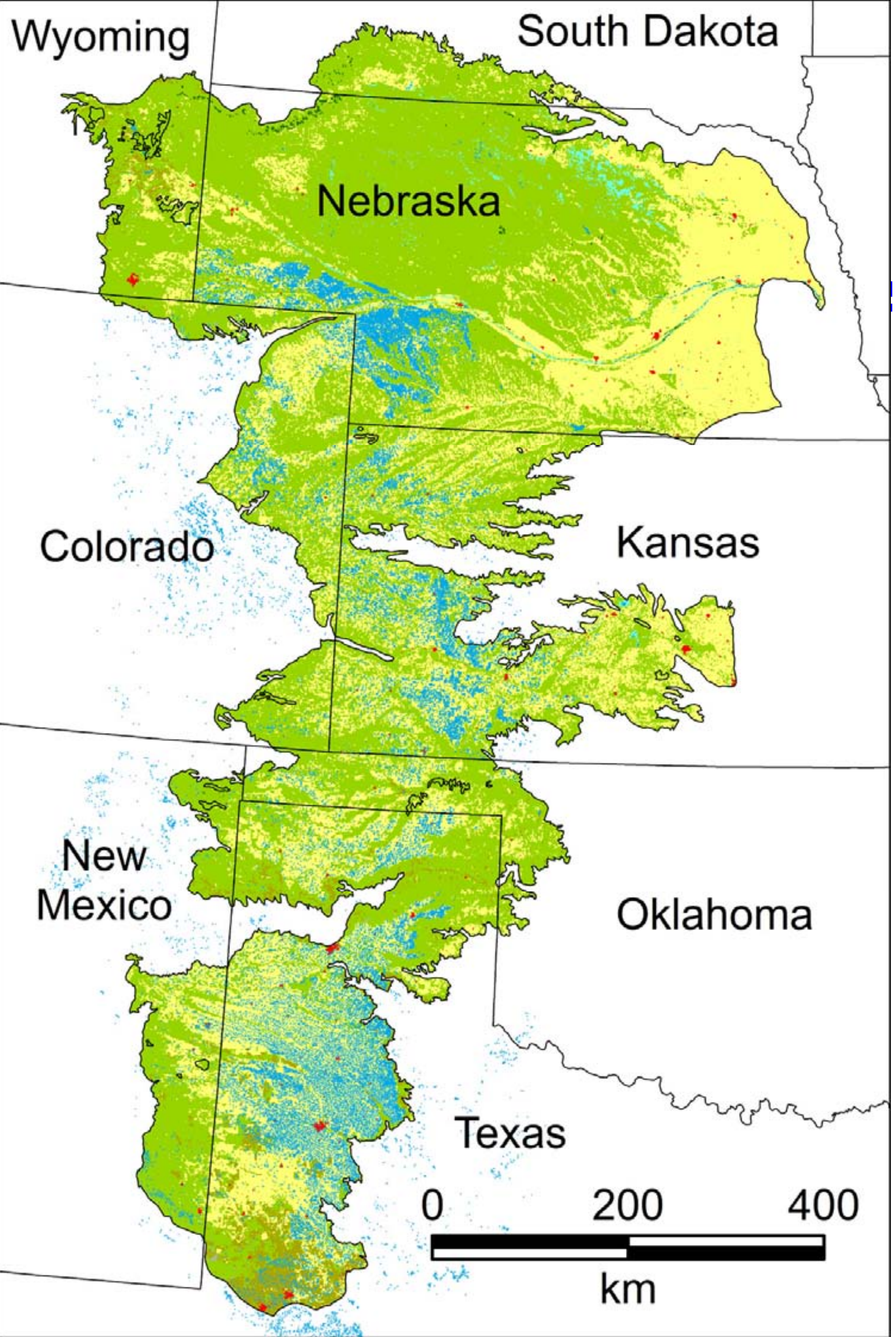
- Natural ecosystems: no change in groundwater storage
- Irrigated agriculture:
  - ~ 4 m decrease in WT over High Plains, 1950 -2003
  - ~ 40 m decrease in WT over 10,000 km^2 area in southern HP, 1950 – 2003
  - Seasonal WT fluctuations can be monitored by GRACE satellite
- Rainfed agriculture
  - ~ 7 m increase in WT over 3,400 km^2 area in southern HP = recharge rate of 23 mm/yr

Unsaturated Zone as Archive of Land-Use and Climate-Change Impacts on Water Resources

- Natural ecosystems:
  - Playa focused recharge
  - Long-term (≤ 10,000 yr) drying in interplaya settings
- Rainfed agriculture:
  - Increased drainage/recharge
  - Salt mobilization

Unsaturated Zone Boreholes High Plains



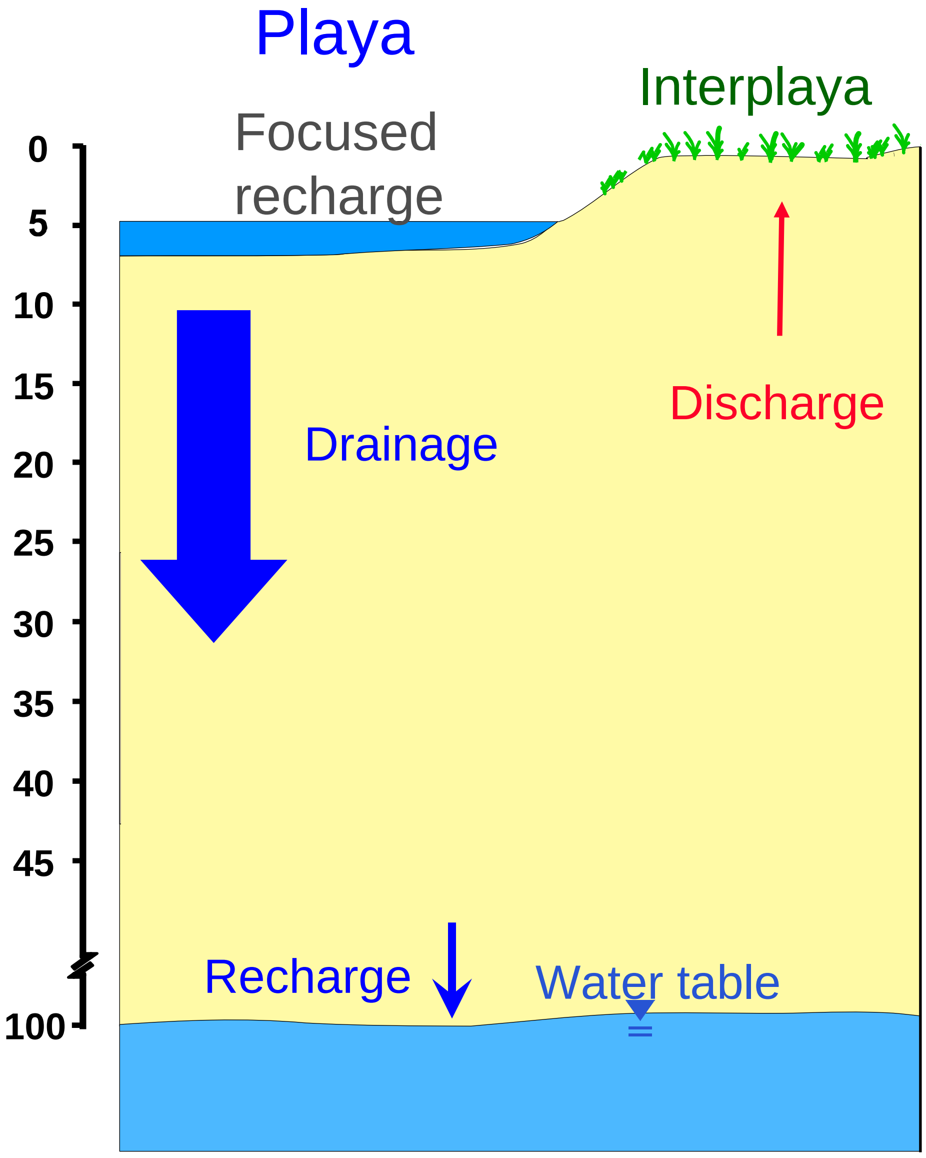


Playa Distribution

High Plains ~ 50,000 playas

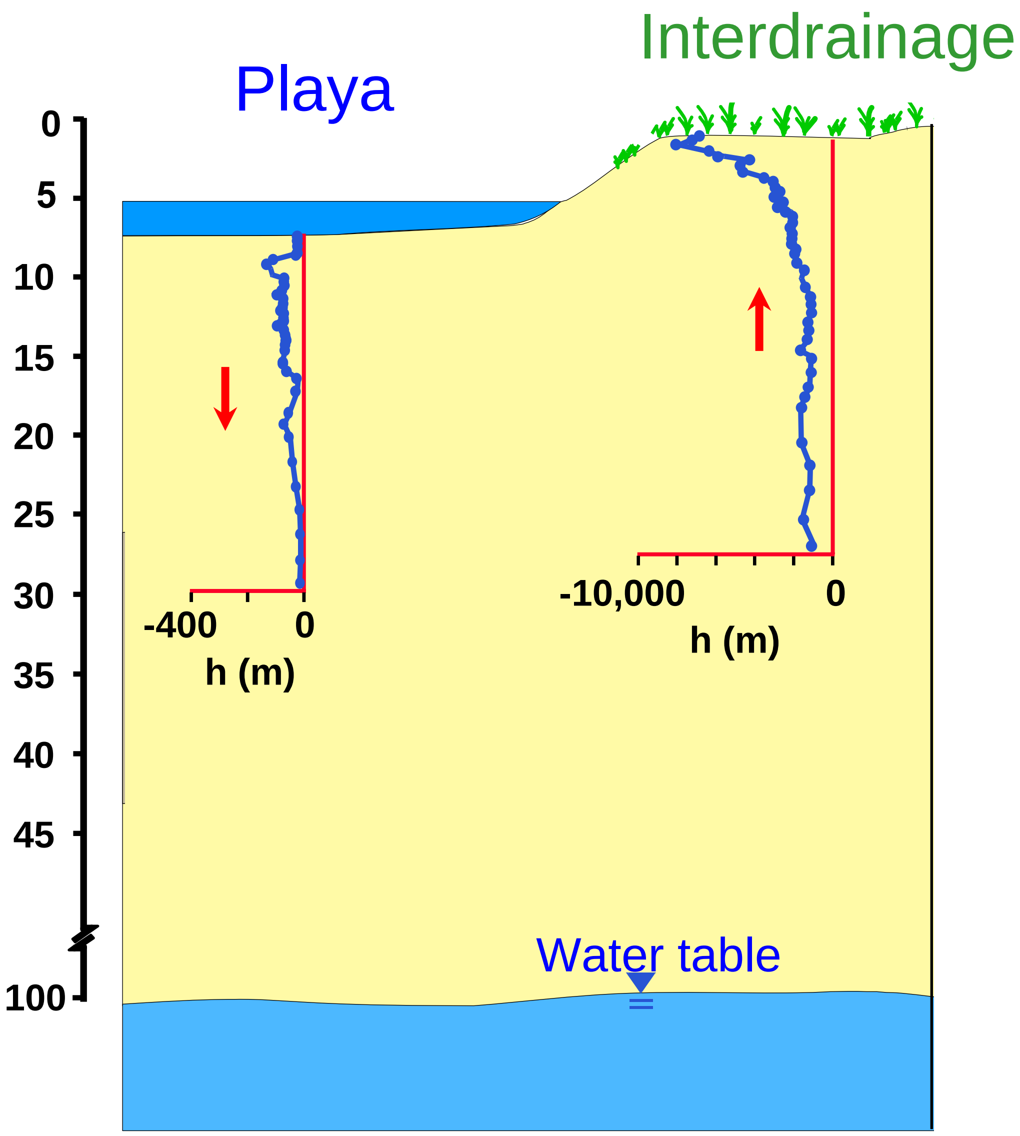
Southern High Plains:
~ 16,000 playas

Conceptual Model of Unsaturated Flow



Wood and Sanford, 1995; GW
Scanlon et al., 1997, WRR

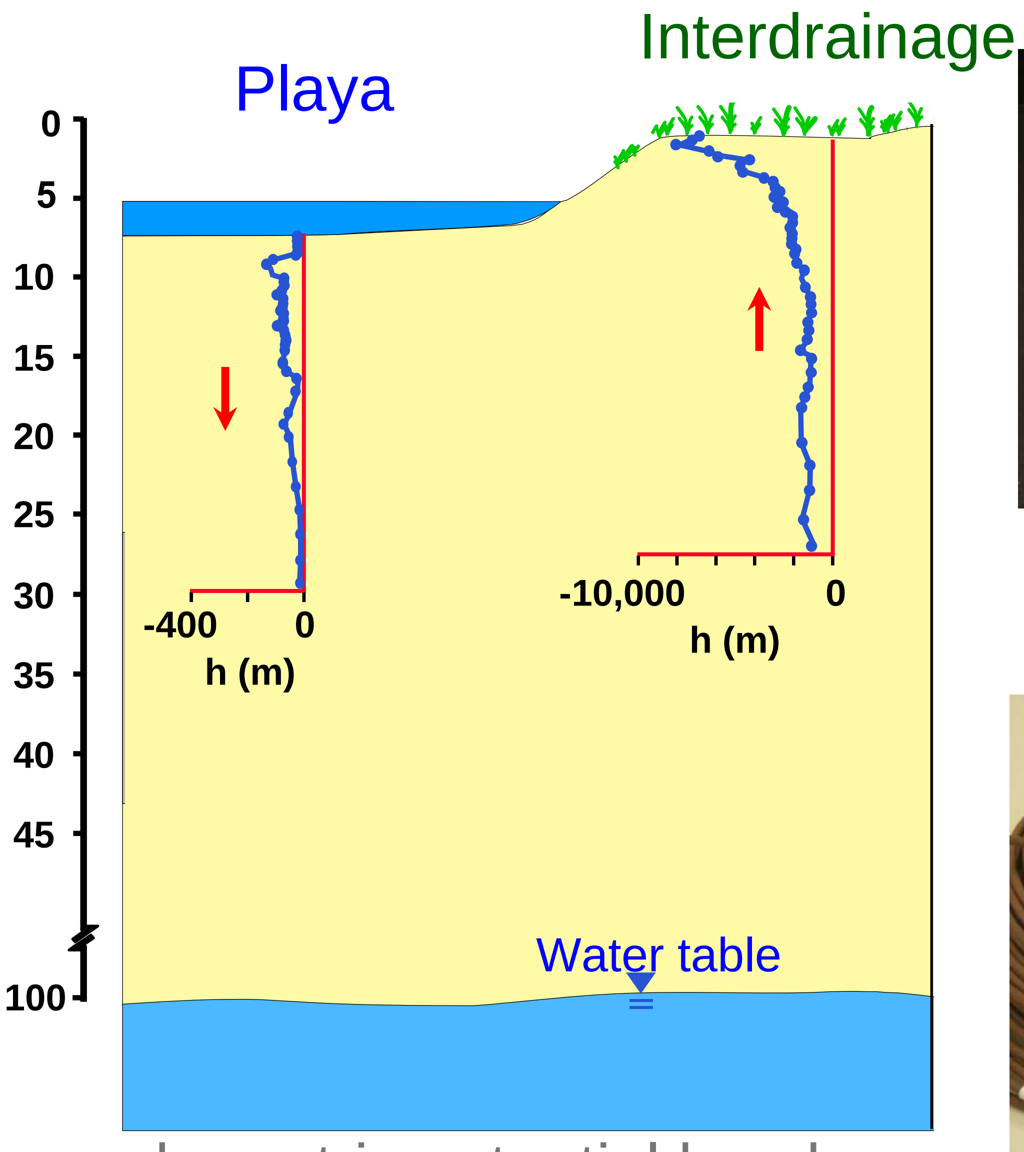
Flow Directions Determined from Potential Head Data



h: matric potential head

QAd2331Bx

Flow Directions Determined from Potential Head Data



h: matric potential head

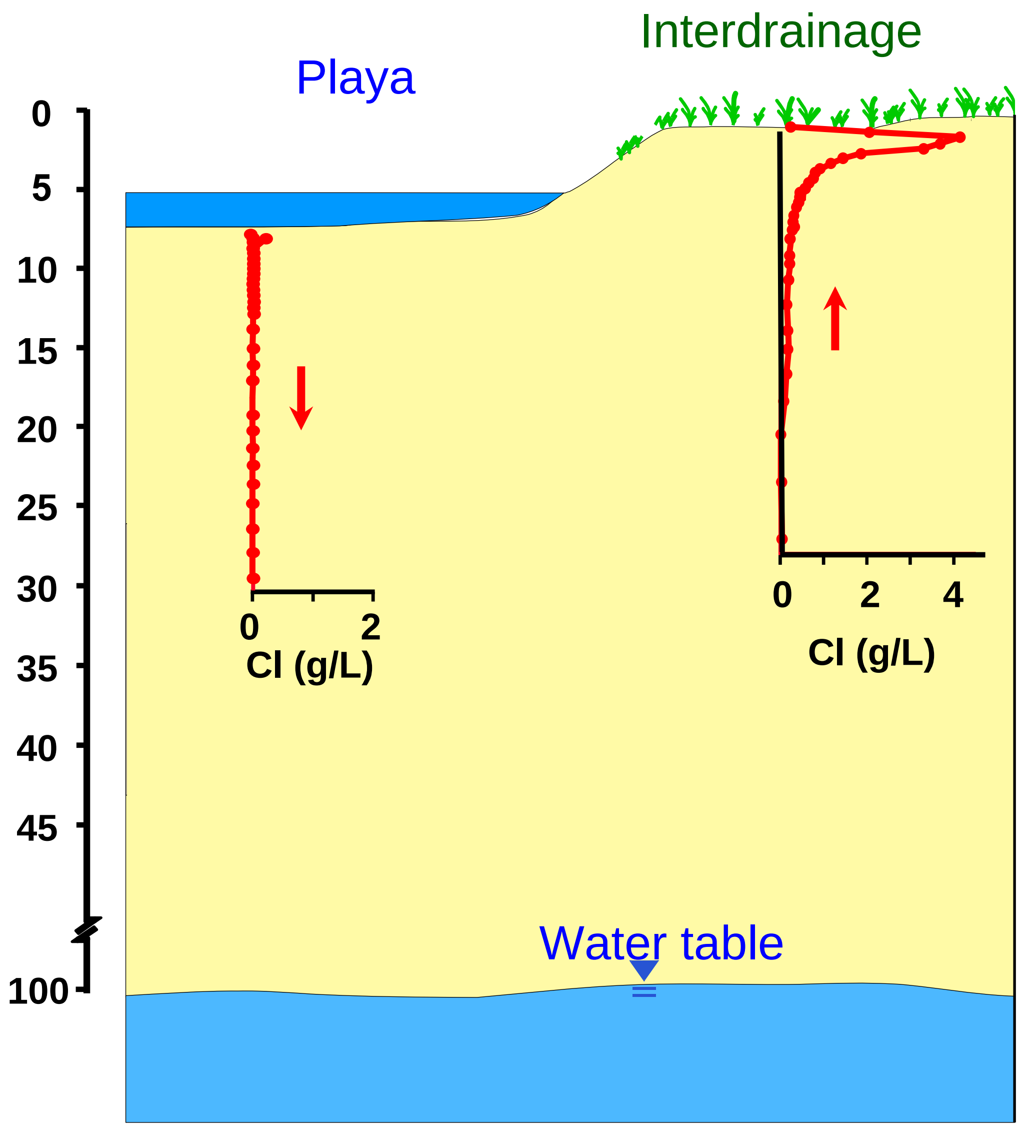
WP-4 Dew Point Potentiameter
(0 to -30,000 m; ± 10 m)

Heat Dissipation Sensor
(0.1 to -35,000 m; ± 1 m)

QAd2331Bx


CRC

Chloride as a Qualitative Indicator of Water Movement



Chloride from precipitation

Chloride in soil water is inversely related to water flux

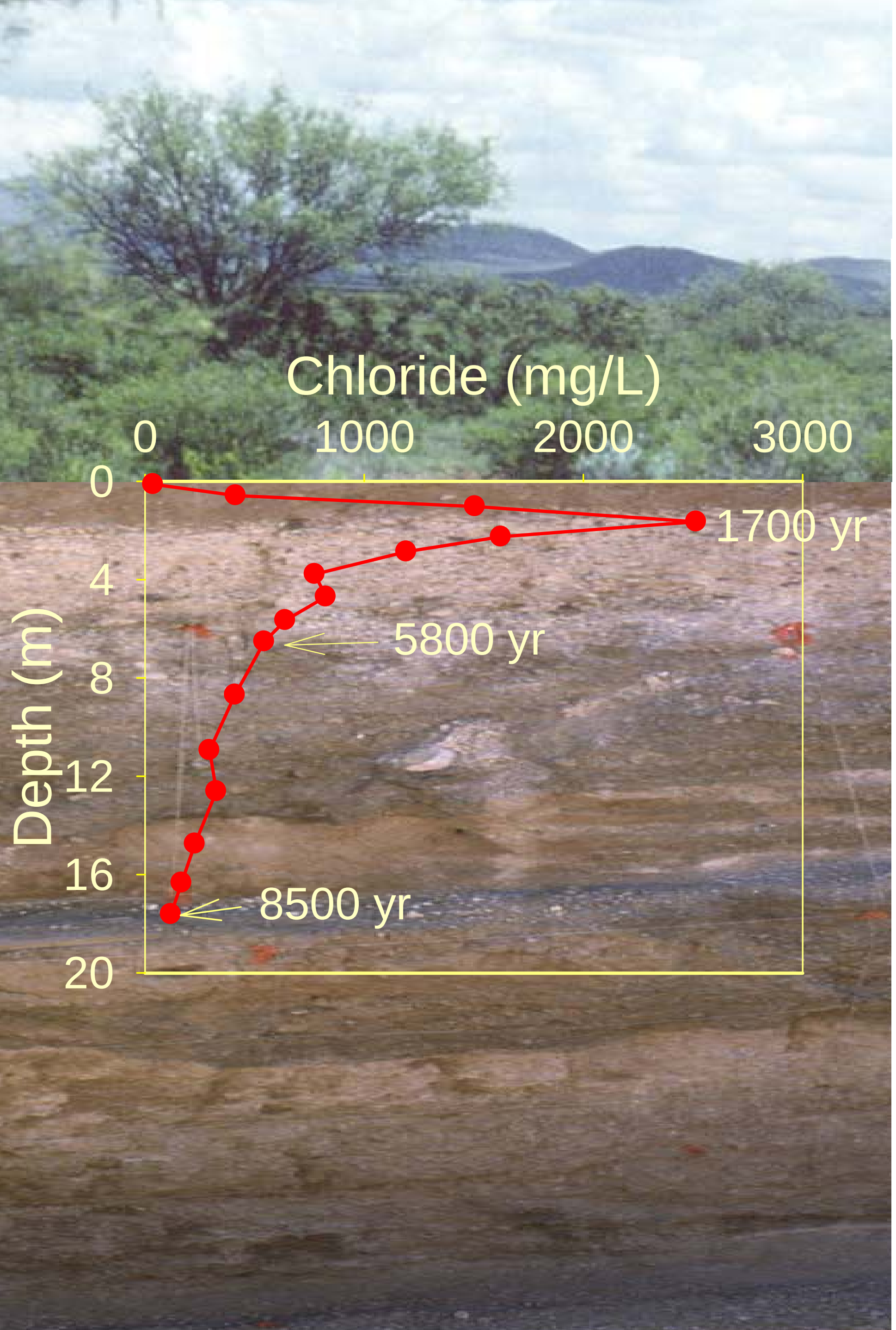
low Cl --- high water flux

high Cl --- low water flux

Plants exclude Cl during evapotranspiration

QAd2331Cx

Chloride as a Tracer of Water Movement



Chloride for Age Dating Soil Pore Water

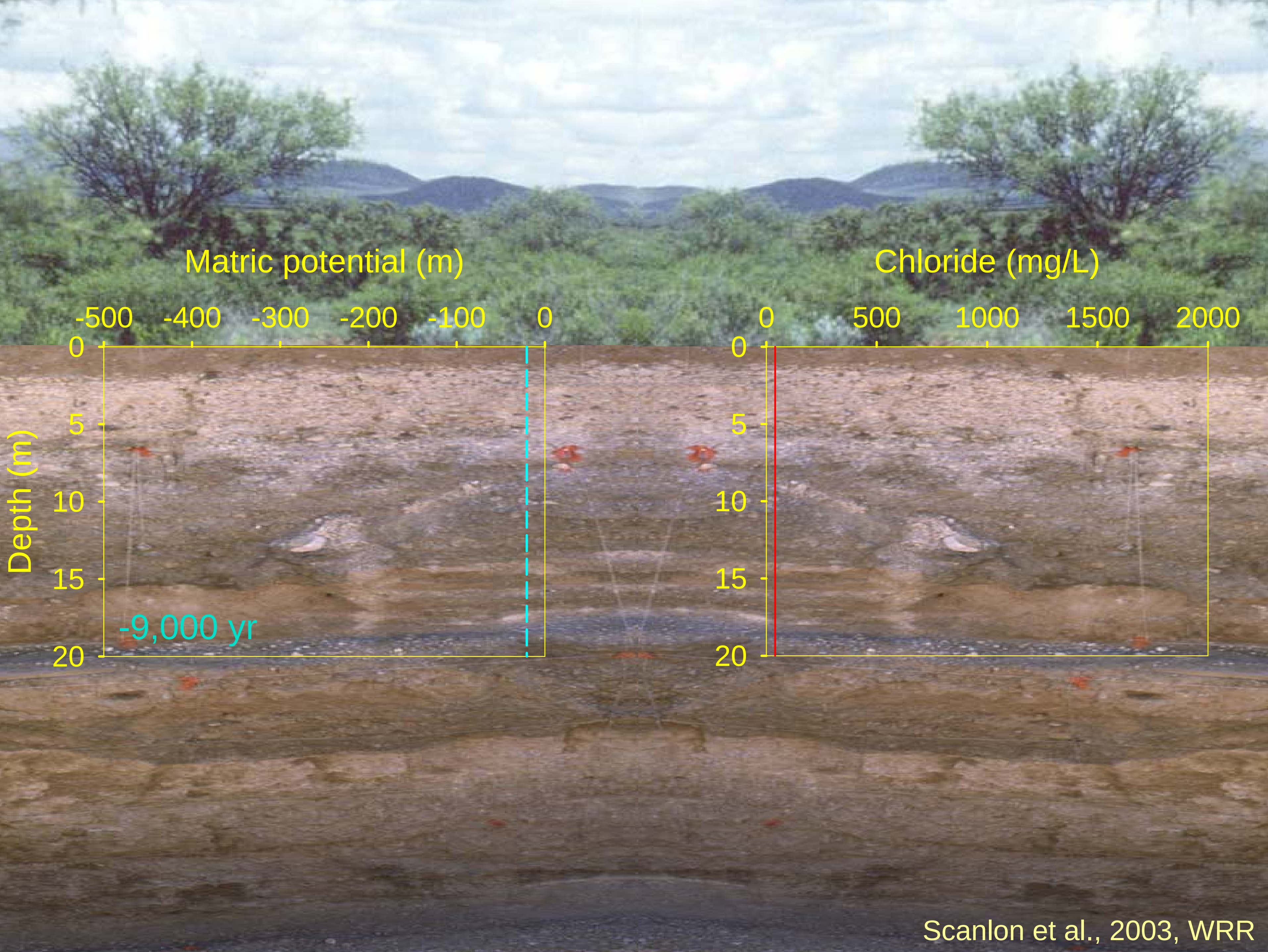
$$Age = \frac{mass\ of\ chloride}{chloride\ input}$$

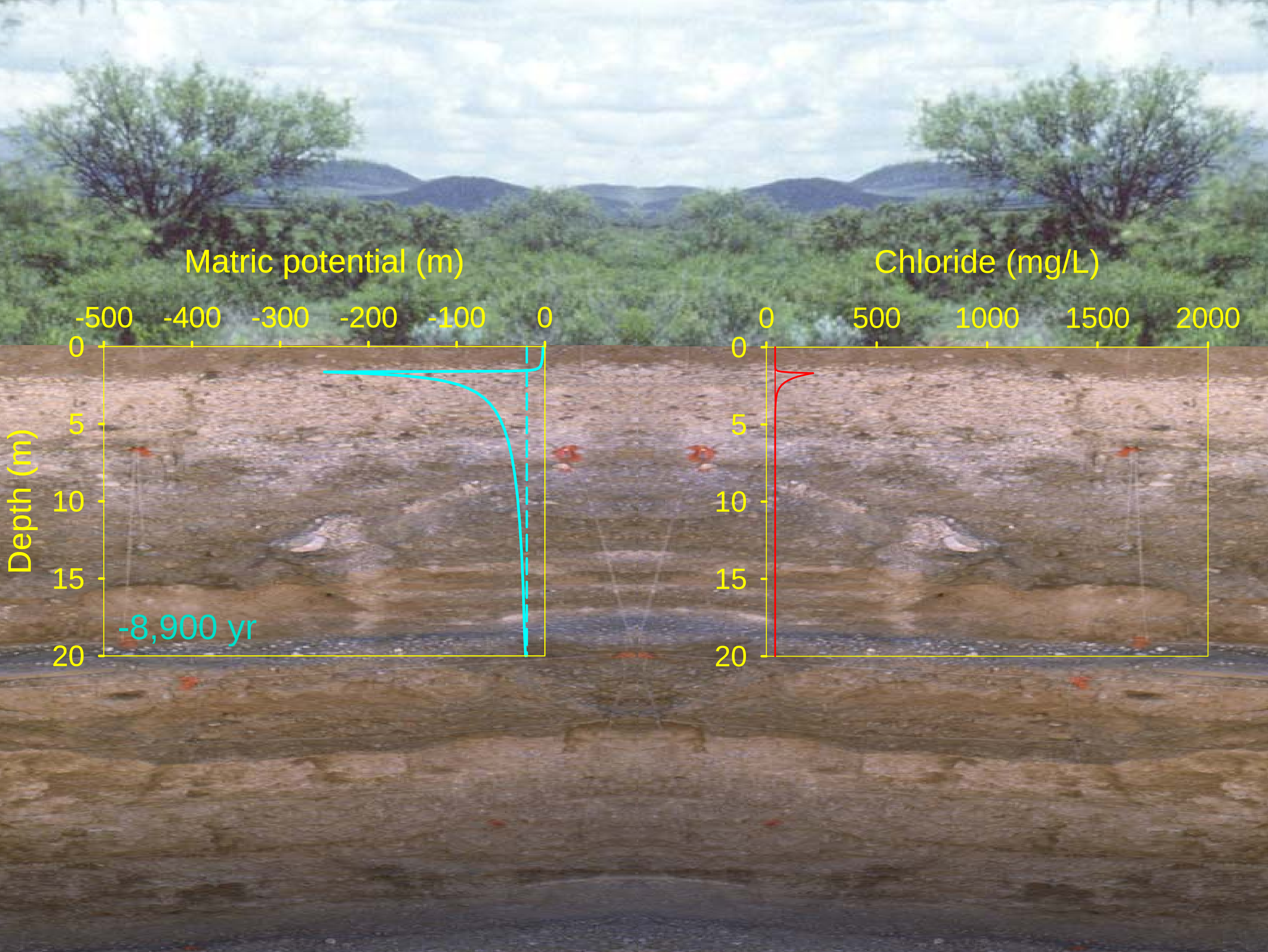
$$t = \frac{\int_0^z \theta Cl_{uz}\, dz}{P \times Cl_p}$$

P = 500 mm/yr

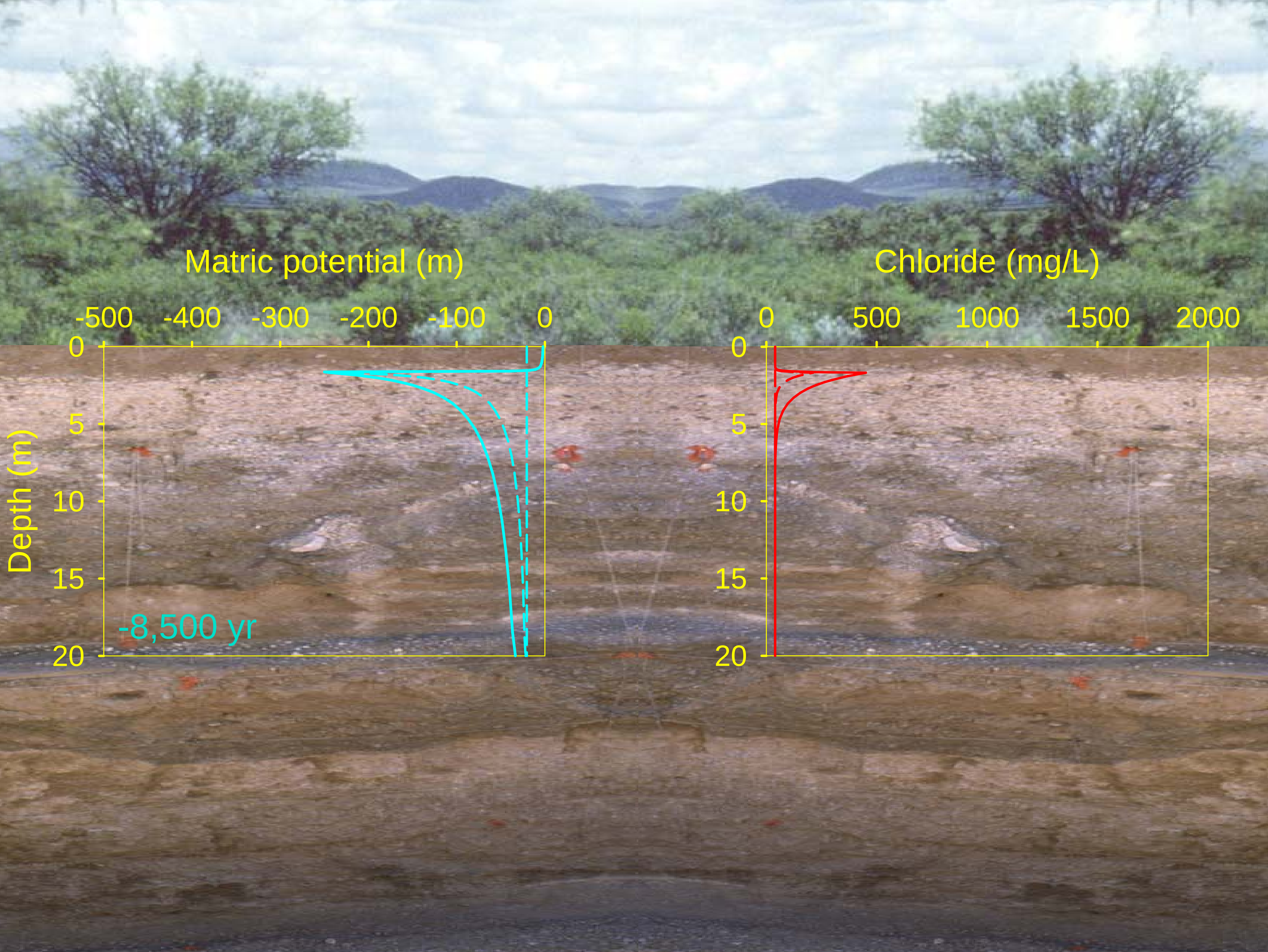
Cl_p = 0.3 mg/L

Cl_p from National Atmospheric Deposition Program (NADP)

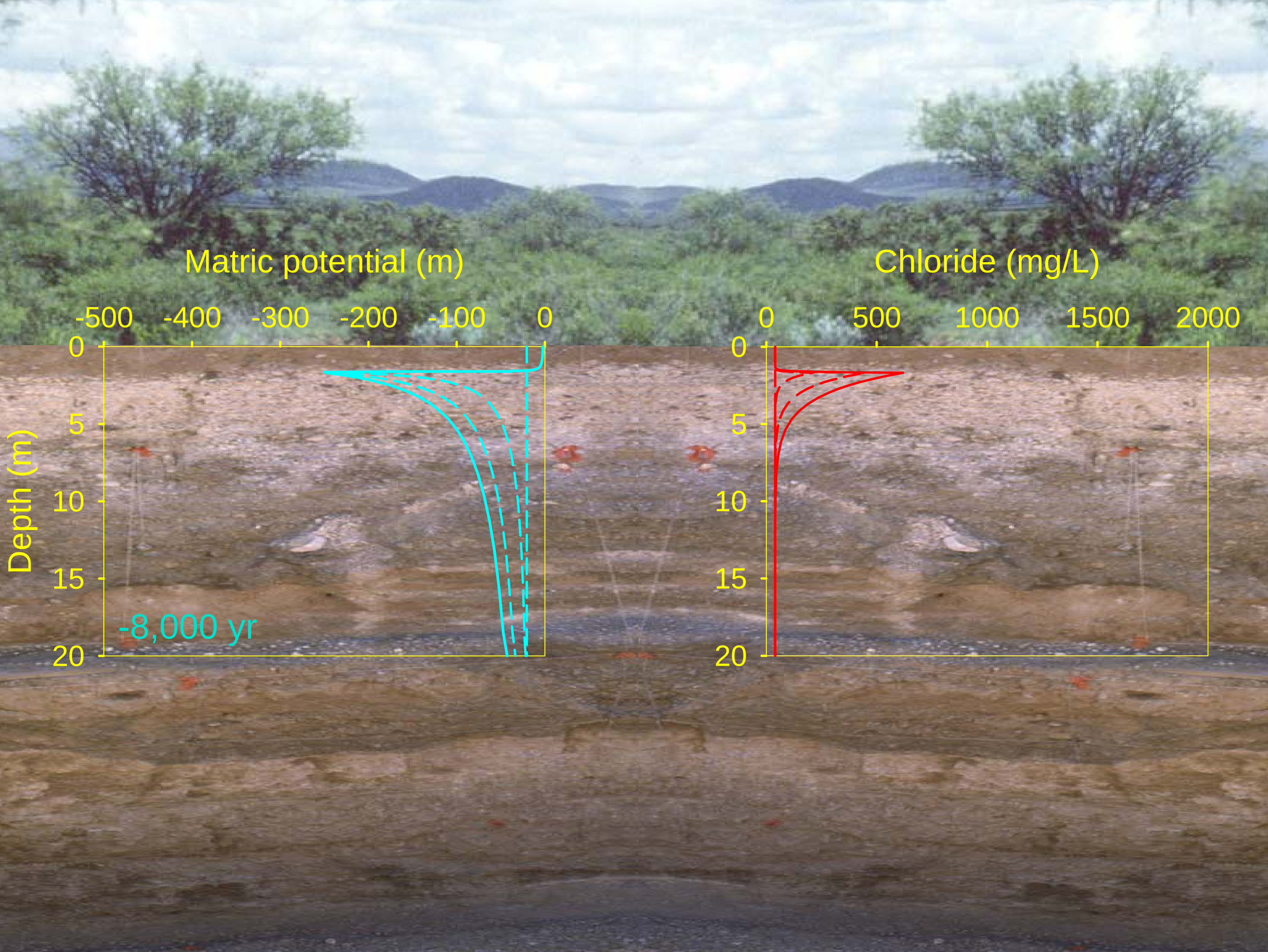

Matric potential (m)
Chloride (mg/L)
-500
-400
-300
-200
-100
0
0
500
1000
1500
2000
Depth (m)
0
5
10
15
20
0
5
10
15
20
-9,000 yr
Scanlon et al., 2003, WRR



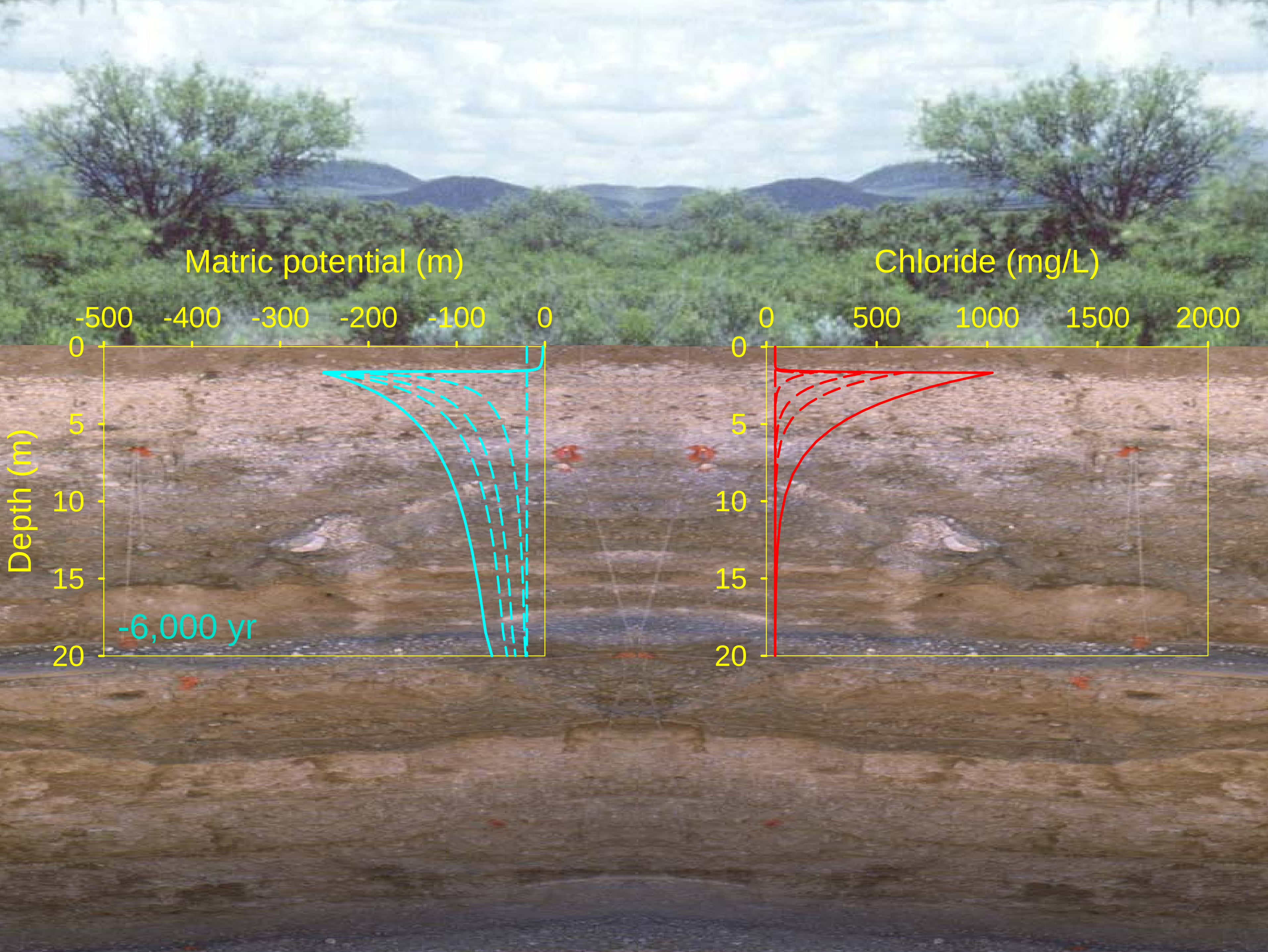
Matric potential (m)
-500
-400
-300
-200
-100
0
Chloride (mg/L)
0
500
1000
1500
2000
Depth (m)
0
5
10
15
20
-8,900 yr

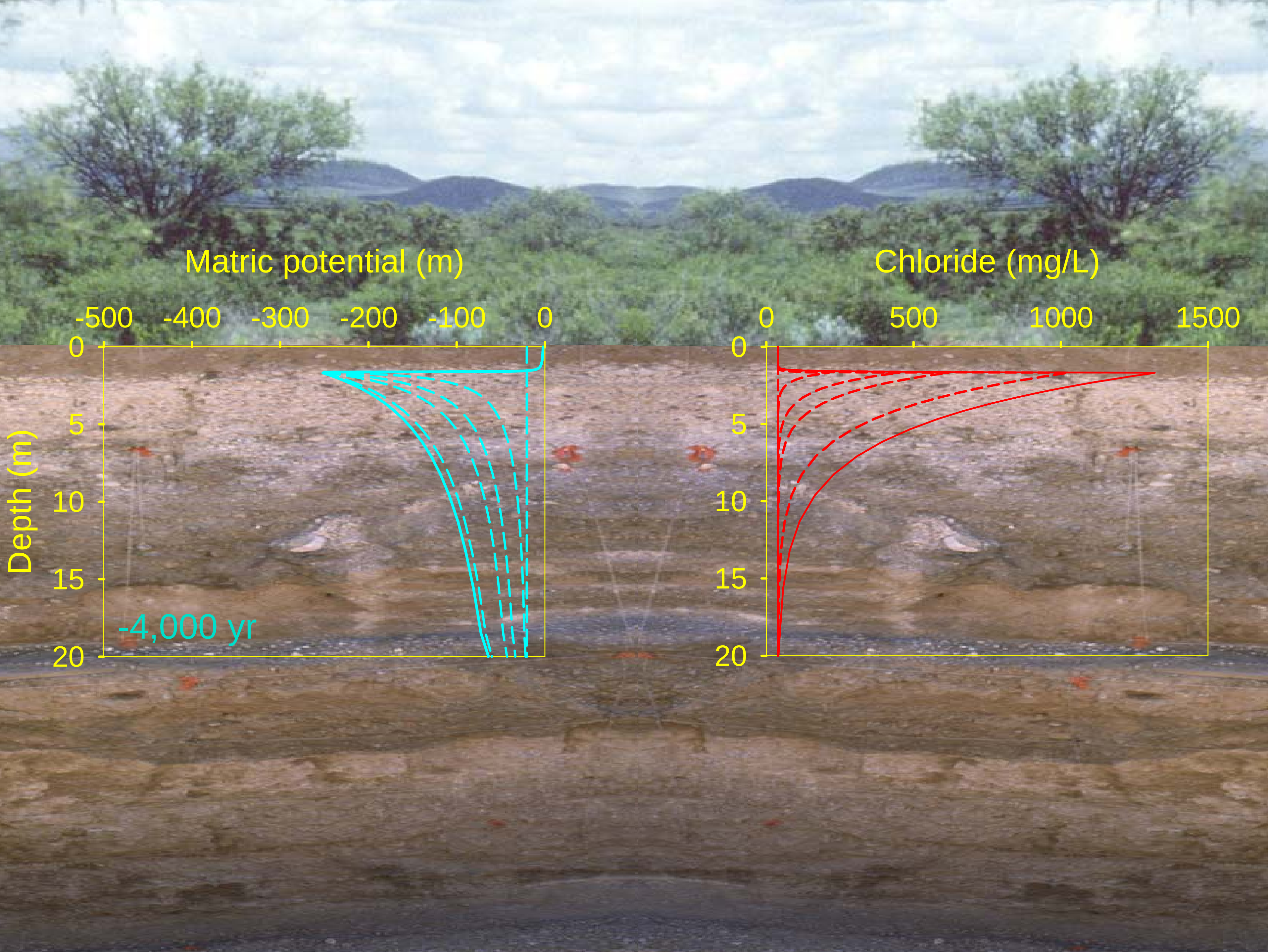


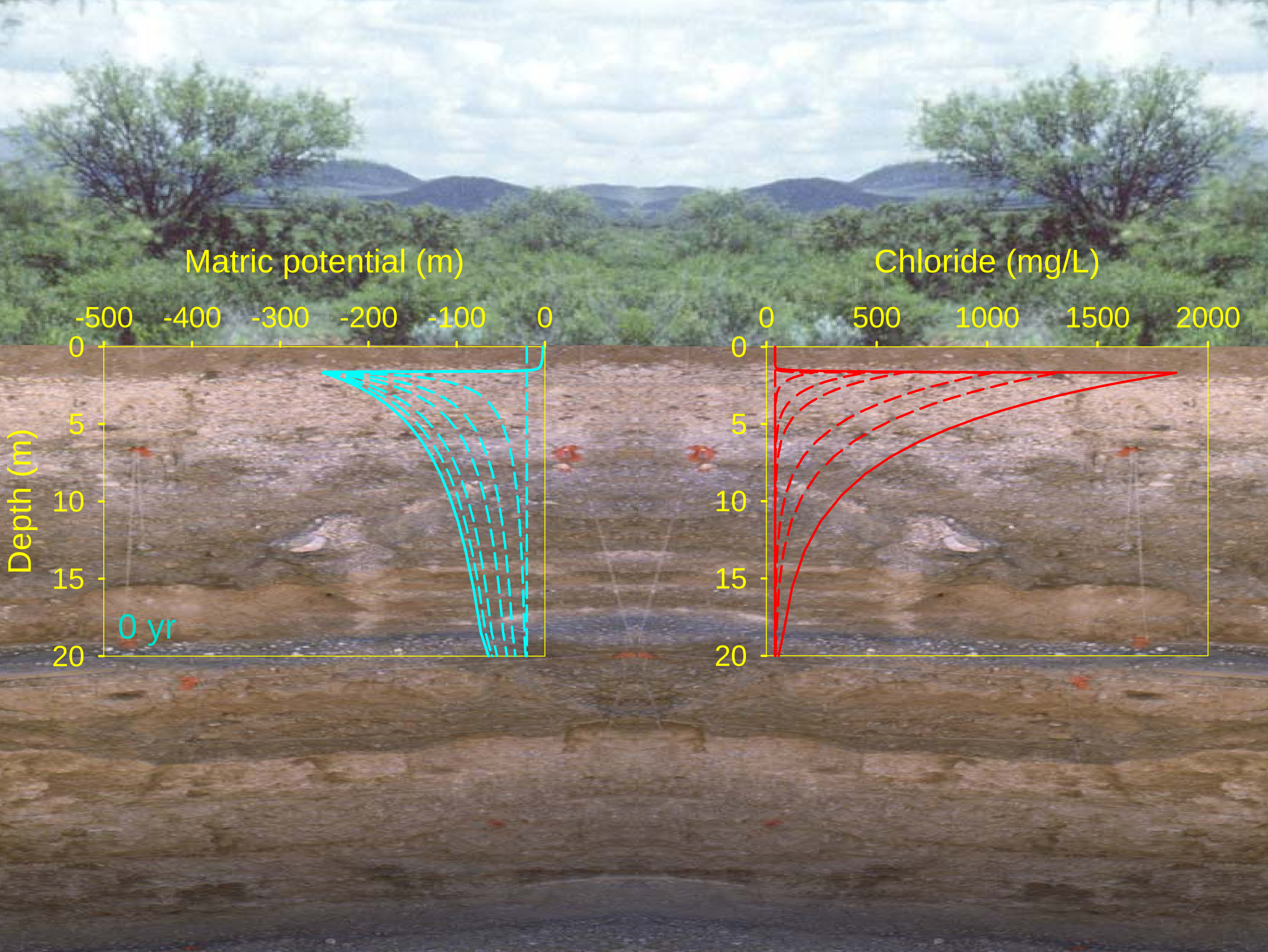
Matric potential (m)
-500
-400
-300
-200
-100
0
Chloride (mg/L)
0
500
1000
1500
2000
Depth (m)
0
5
10
15
20
-8,500 yr



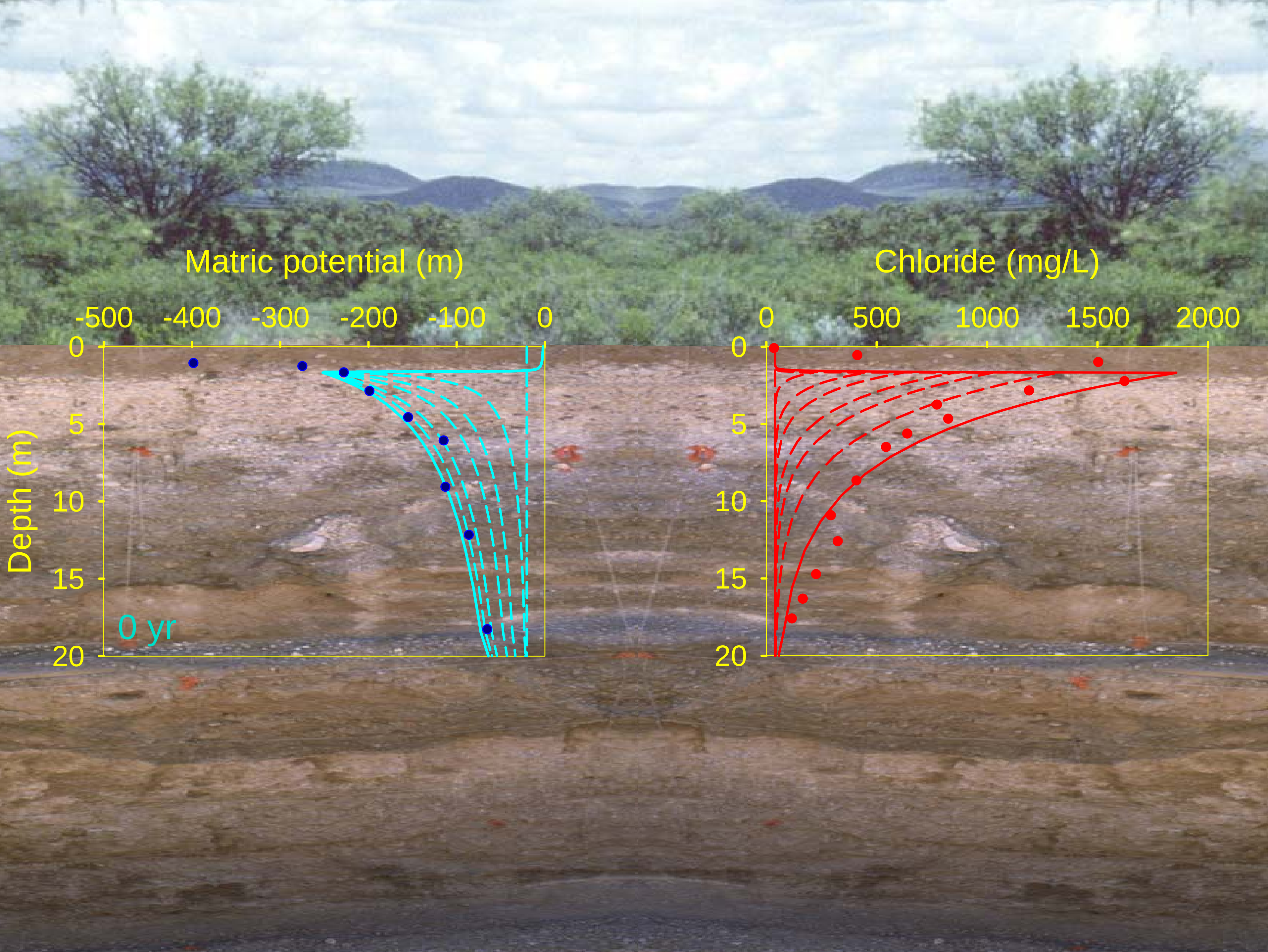
Matric potential (m)
-500
-400
-300
-200
-100
0
Depth (m)
0
5
10
15
20
-8,000 yr
Chloride (mg/L)
0
500
1000
1500
2000
0
5
10
15
20


Matric potential (m)
-500
-400
-300
-200
-100
0
Depth (m)
0
5
10
15
20
-6,000 yr
Chloride (mg/L)
0
500
1000
1500
2000
0
5
10
15
20

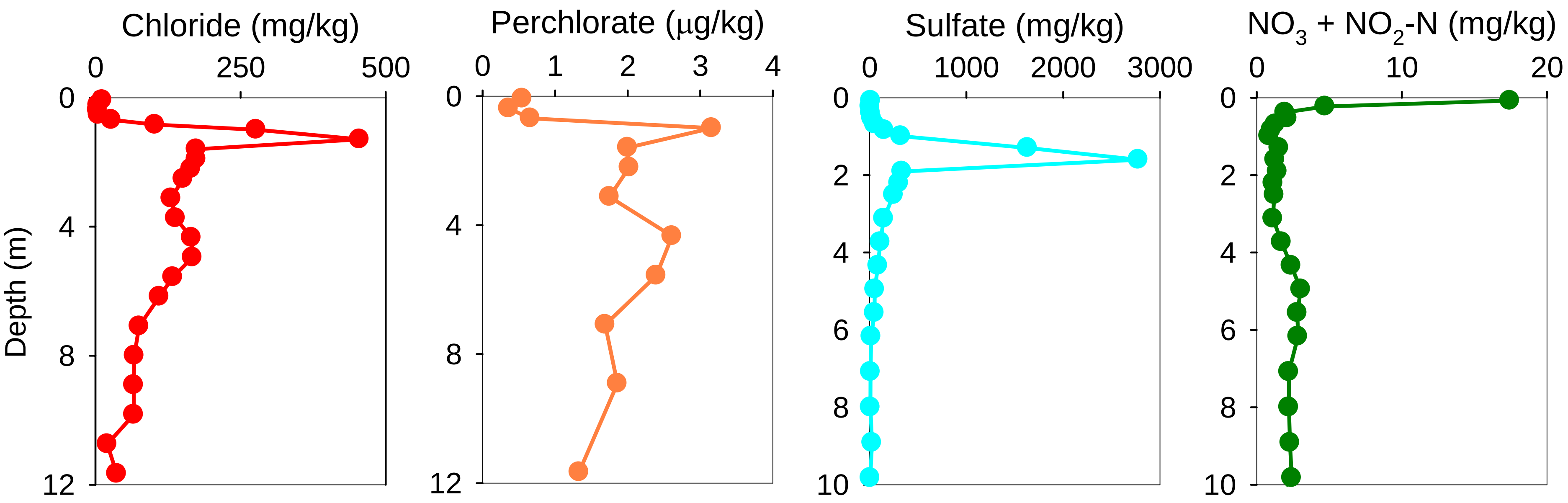

Matric potential (m)
-500 -400 -300 -200 -100 0
Depth (m)
0 5 10 15 20
-4,000 yr
Chloride (mg/L)
0 500 1000 1500
0 5 10 15 20



Matric potential (m)
-500
-400
-300
-200
-100
0
Depth (m)
0
5
10
15
20
0 yr
Chloride (mg/L)
0
500
1000
1500
2000
0
5
10
15
20

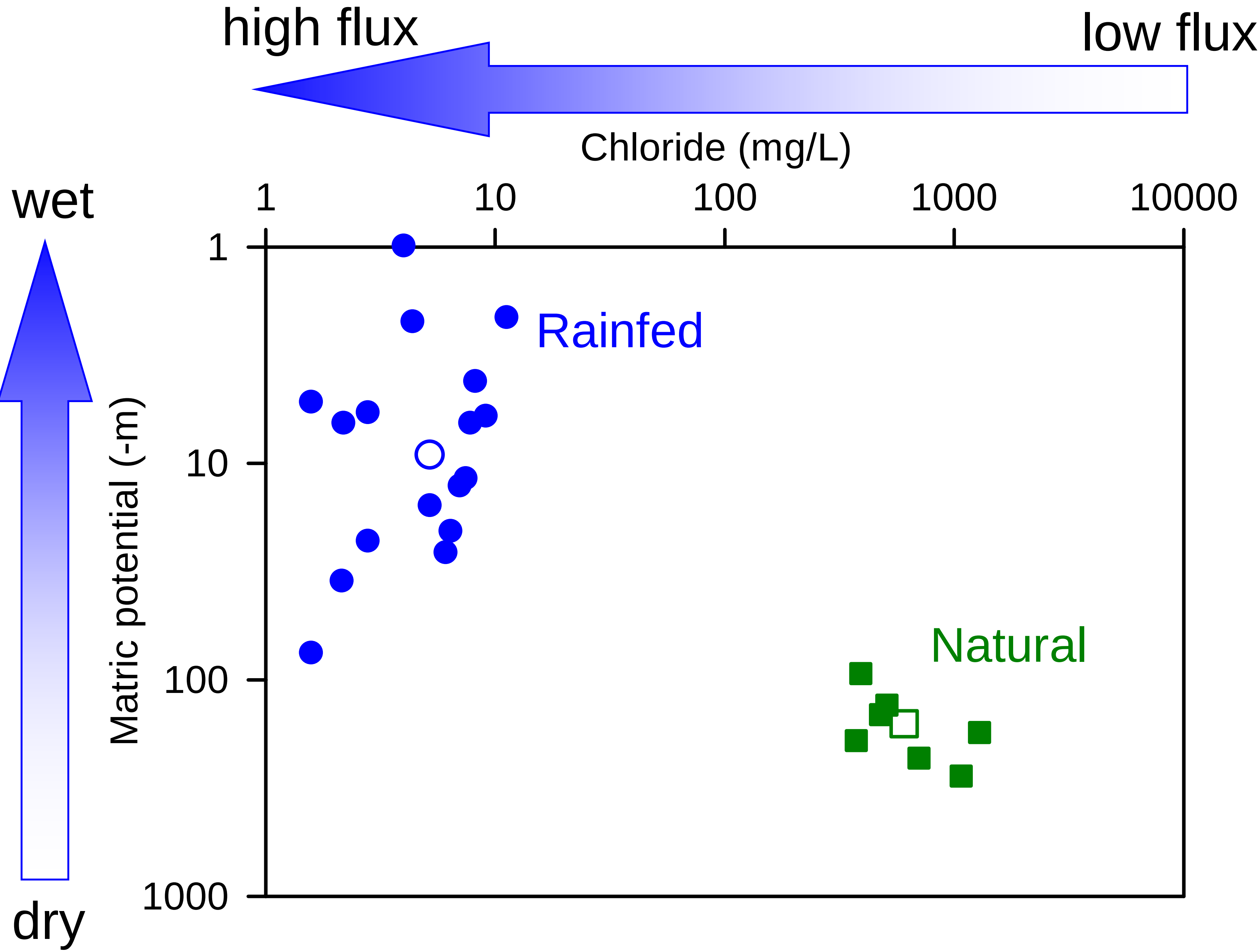

Matric potential (m)
-500
-400
-300
-200
-100
0
Depth (m)
0
5
10
15
20
0 yr
Chloride (mg/L)
0
500
1000
1500
2000
0
5
10
15
20

Salt Reservoirs Beneath Natural Ecosystems



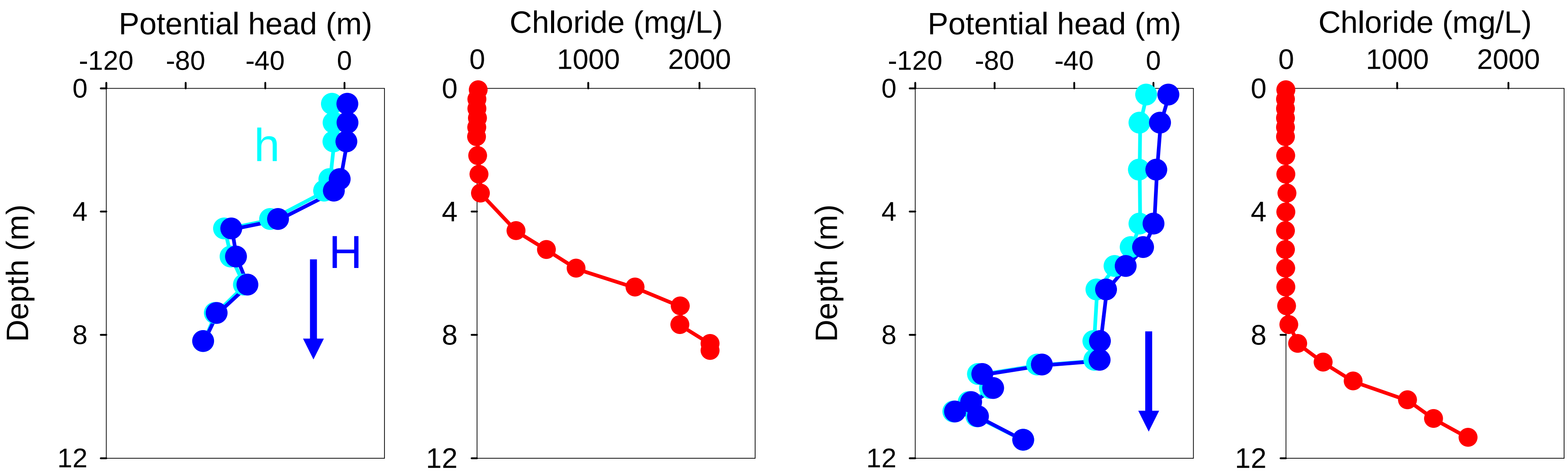
Natural Ecosystems

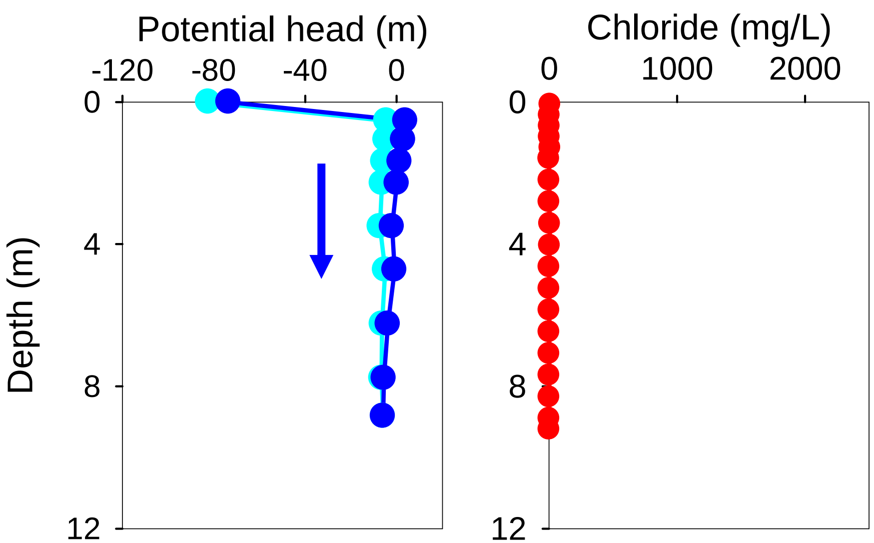
- Recharge focused beneath playas
- Little or no recharge in interplaya settings during the Holocene (~ 10,000 – 15,000 yr)
- Buildup of salts caused by drying of profiles



Scanlon et al., 2005, GCB

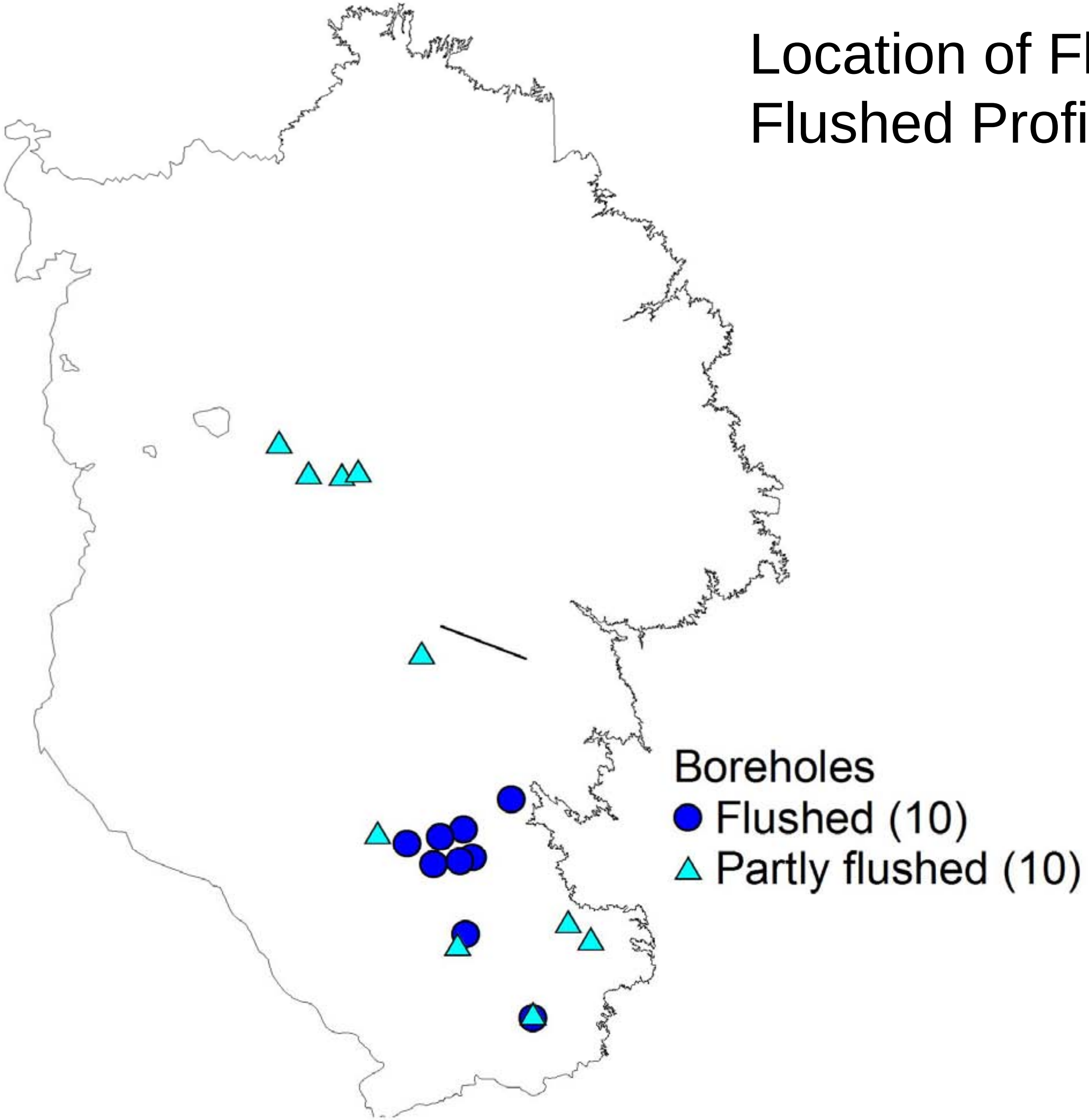
Impact of Rainfed Agriculture



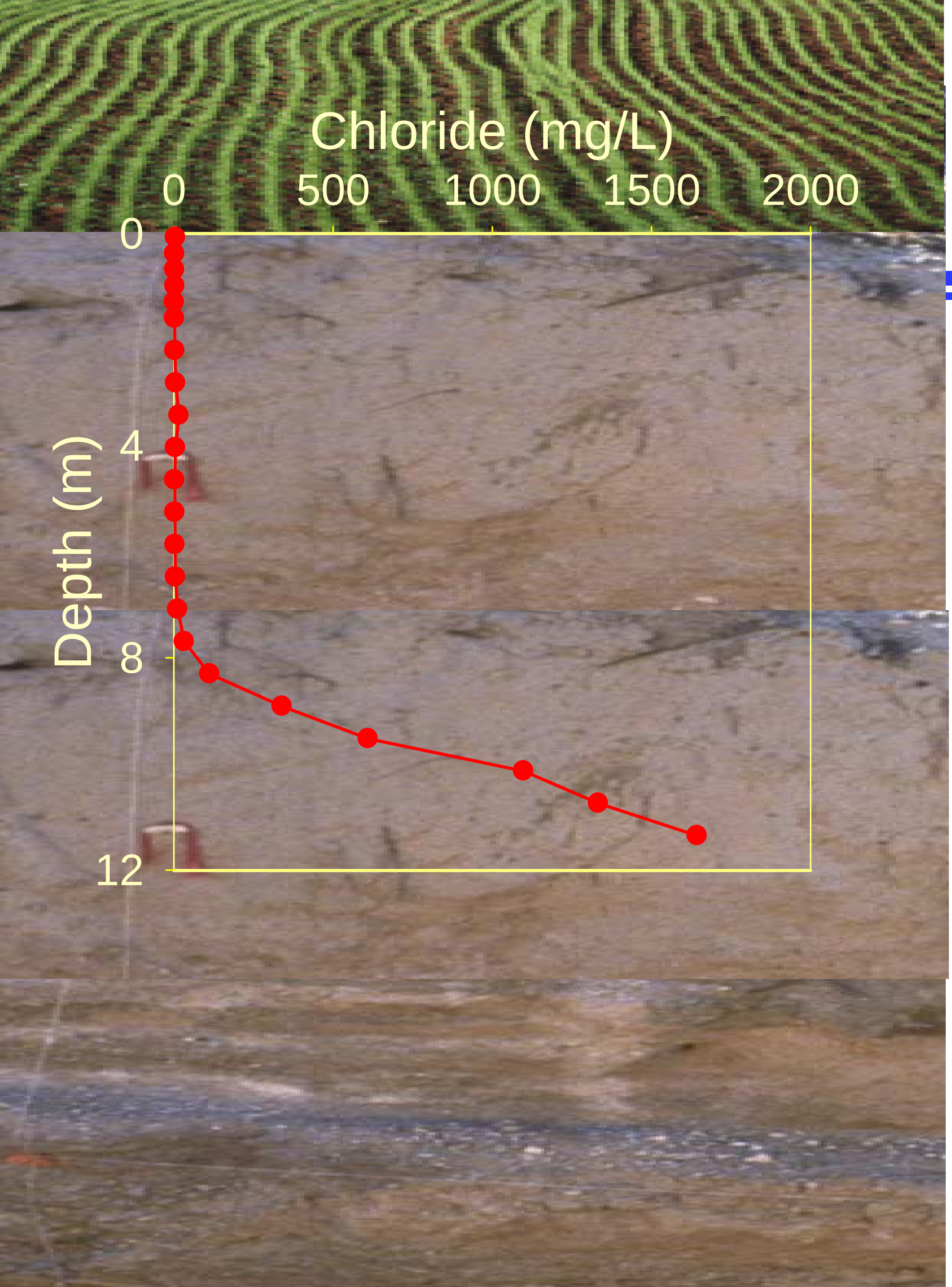


Downward head gradients
Low Cl….flushed zone
drainage/recharge

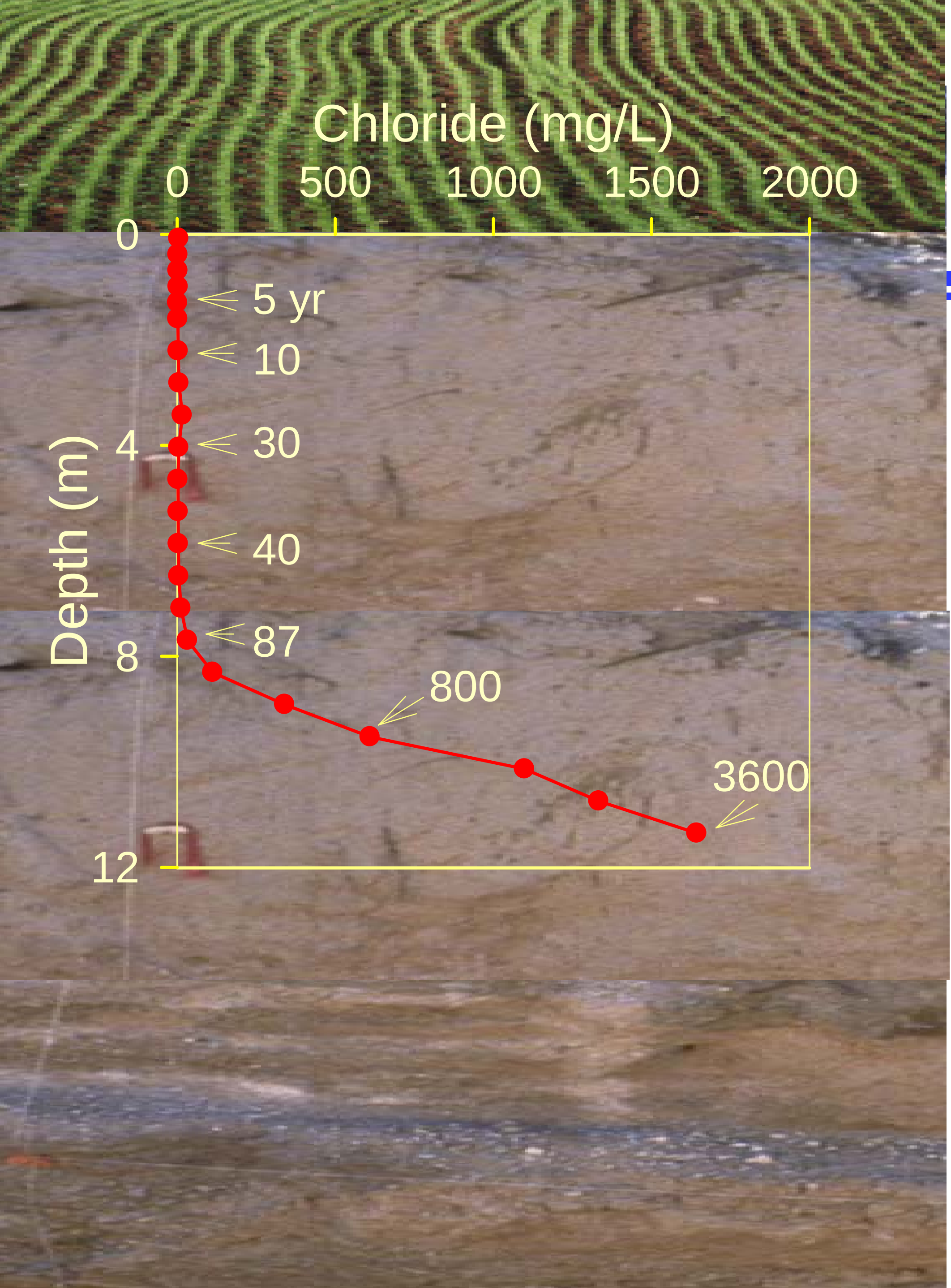
Location of Flushed and Partly Flushed Profiles



Chloride Profile beneath Rainfed Agriculture



Quantitative Chloride Mass Balance (CMB)



$$Age = \frac{mass\ of\ chloride}{chloride\ input}$$

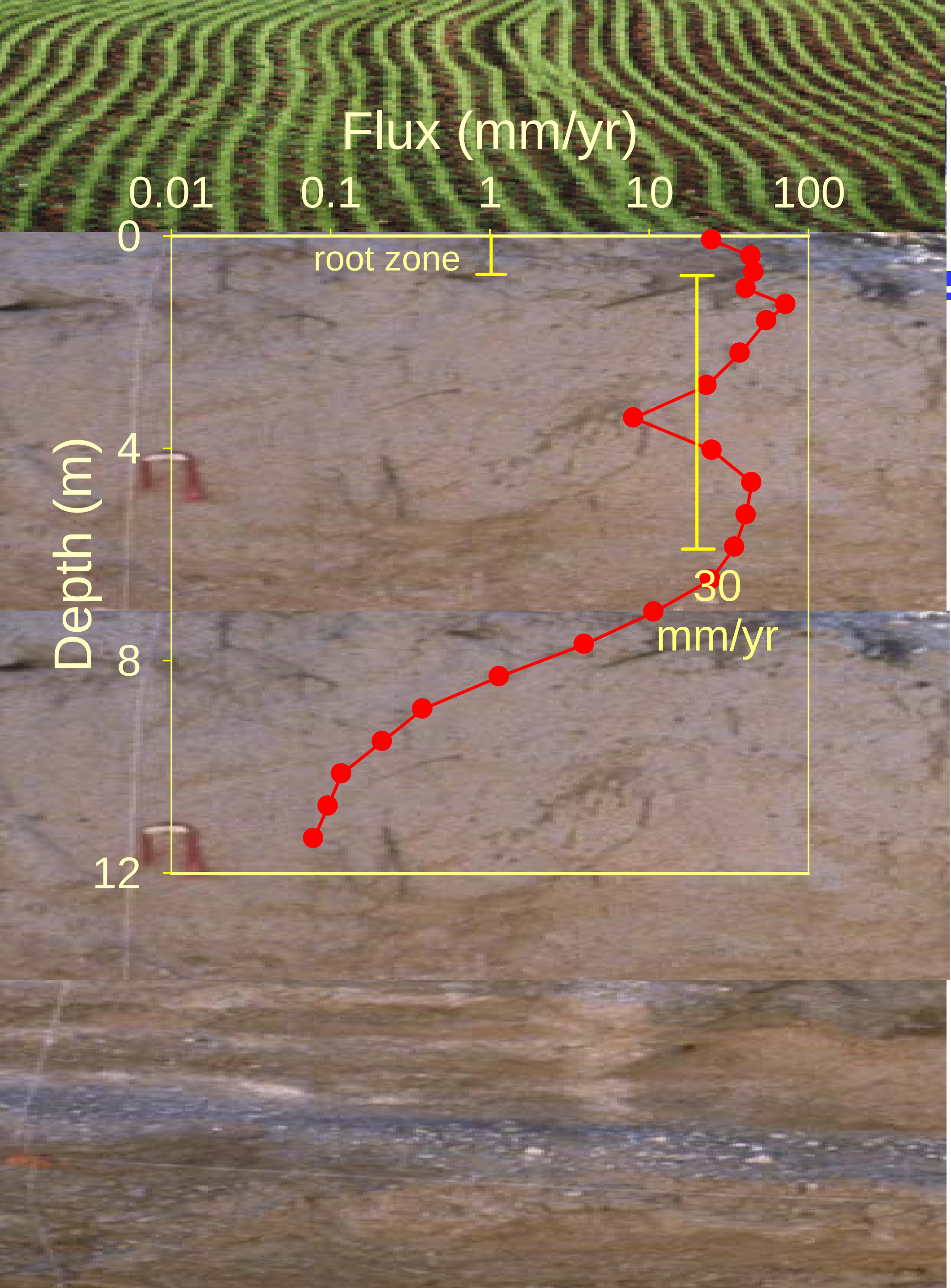
$$t = \frac{\int_0^z \theta Cl_{uz} dz}{PCl_p}$$

$$P = 450\,mm/yr$$

$$Cl_p = 0.3mg/L$$

Scanlon et al., 2007, WRR

Quantitative Chloride Mass Balance (CMB)



$$P \times Cl_p = D \times Cl_{sw}$$

$$D = \frac{P \times Cl_p}{Cl_{sw}}$$

$$D = drainage\,(mm/yr)$$

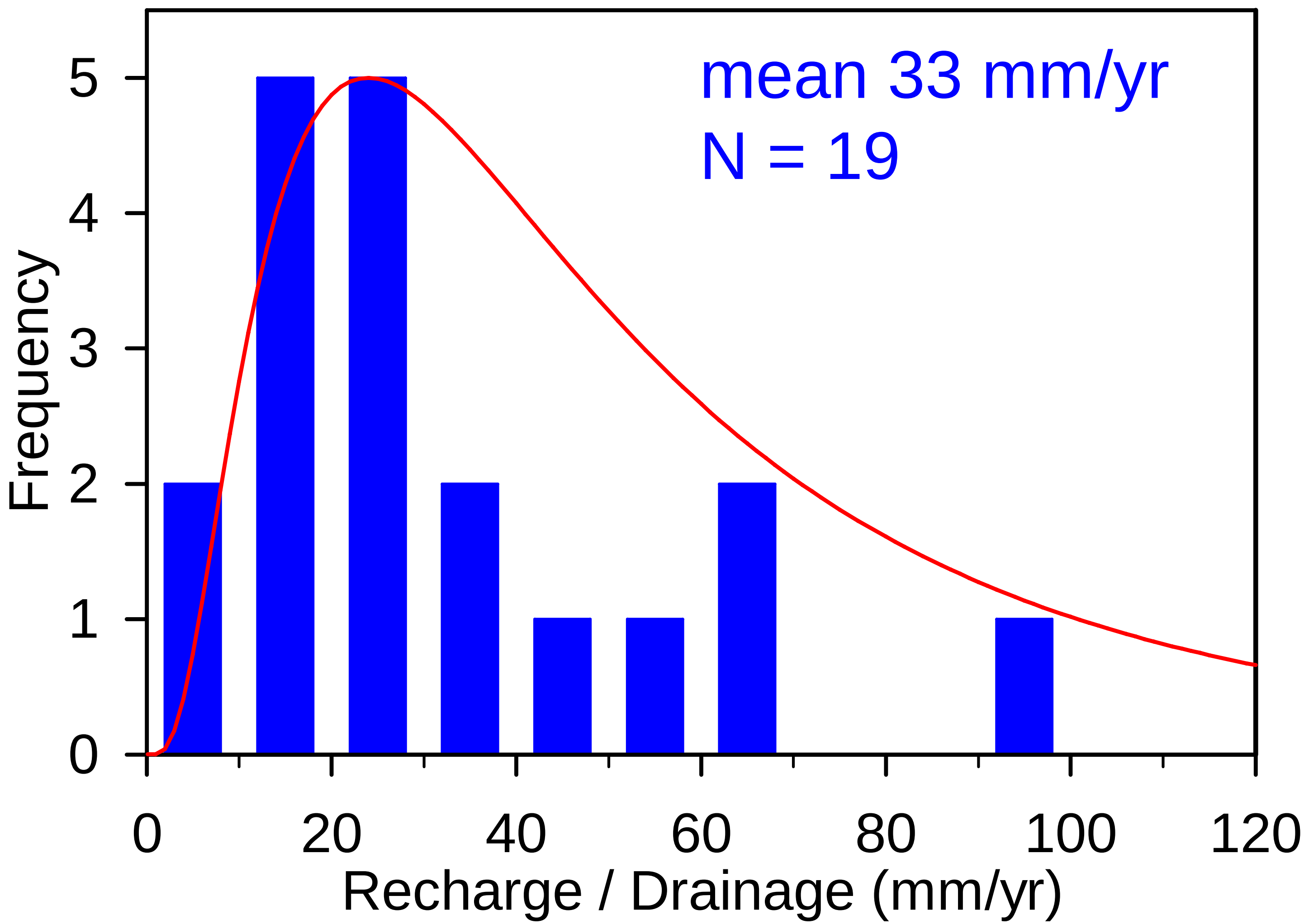
$$P = 450\ mm/yr$$

$$Cl_P = 0.3\ mg/L$$

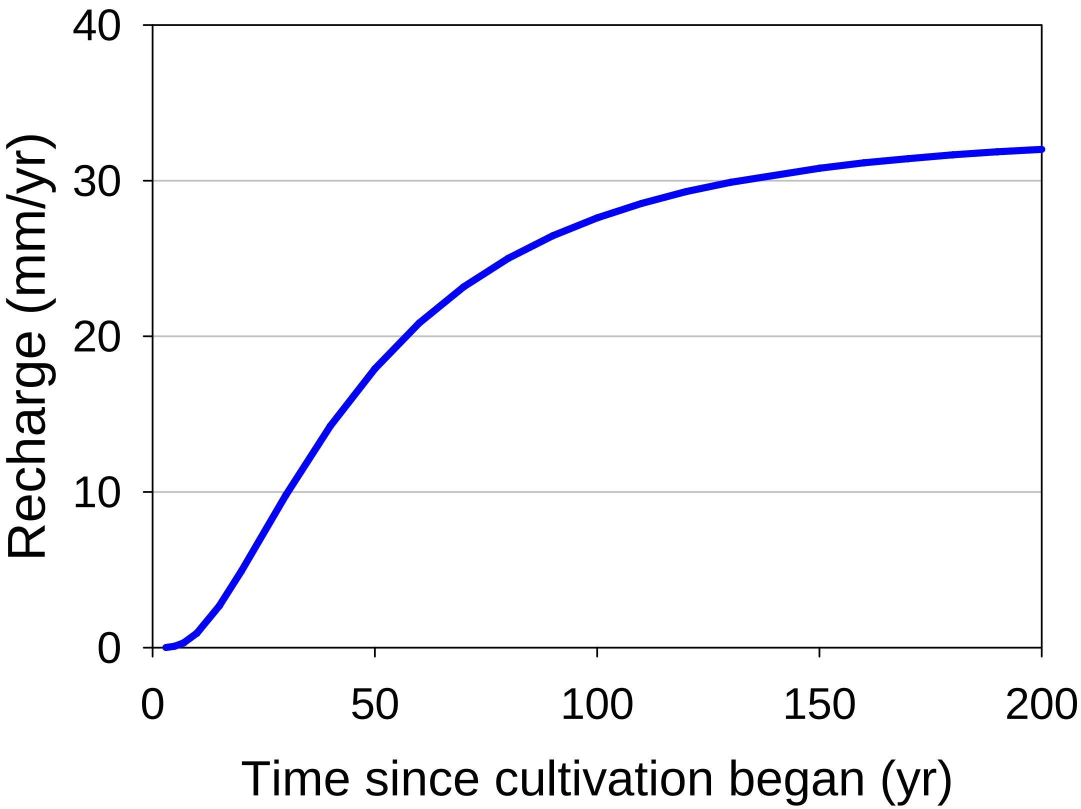
$$Cl_{sw} \leq 34\,mg/L$$

Drainage/recharge
19 profiles
Median = 24 mm/yr
= 5% of precip.

Distribution of Recharge Beneath Rainfed Agriculture (southern High Plains)

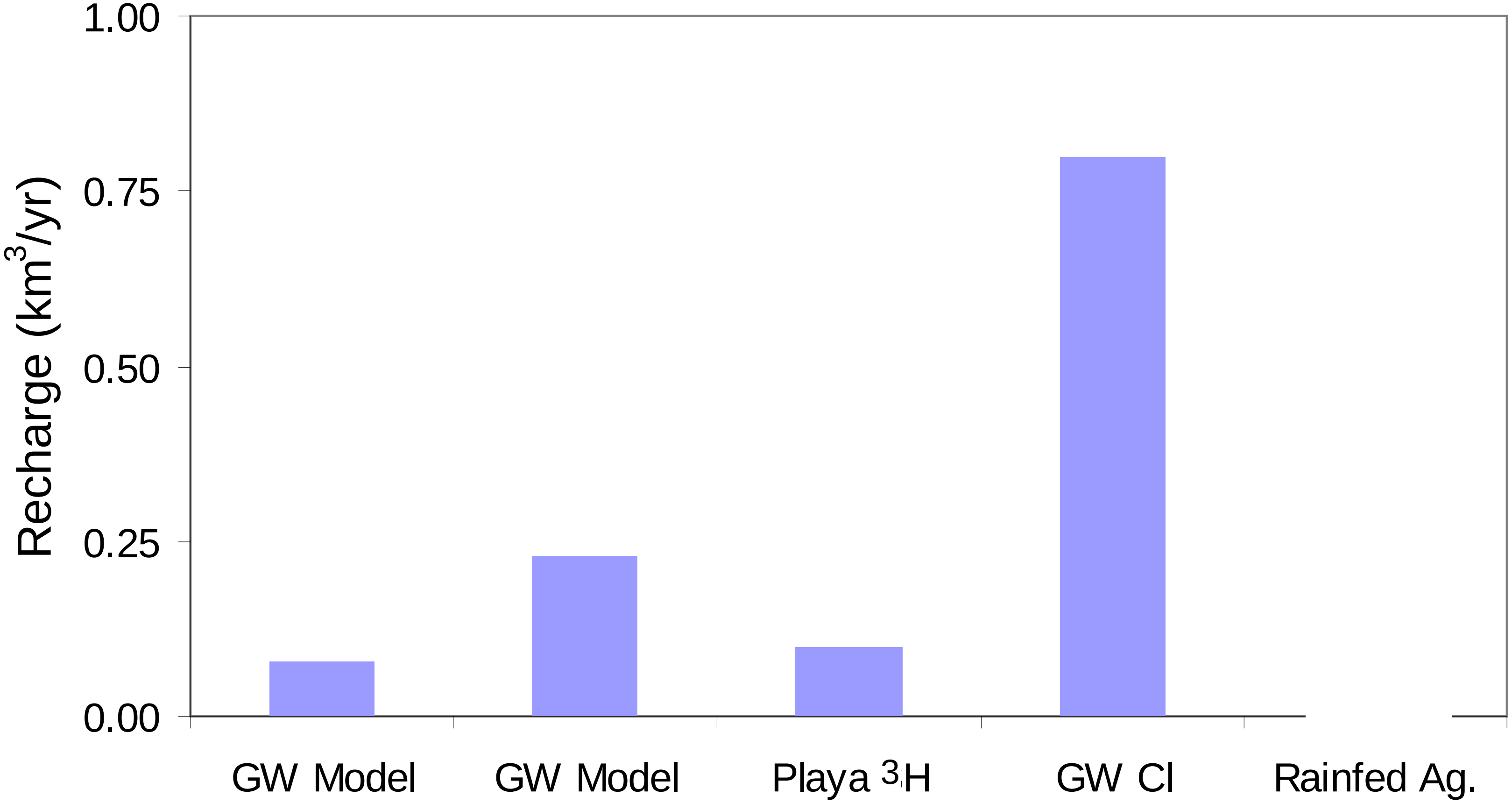


Time Lag Between Drainage and Recharge



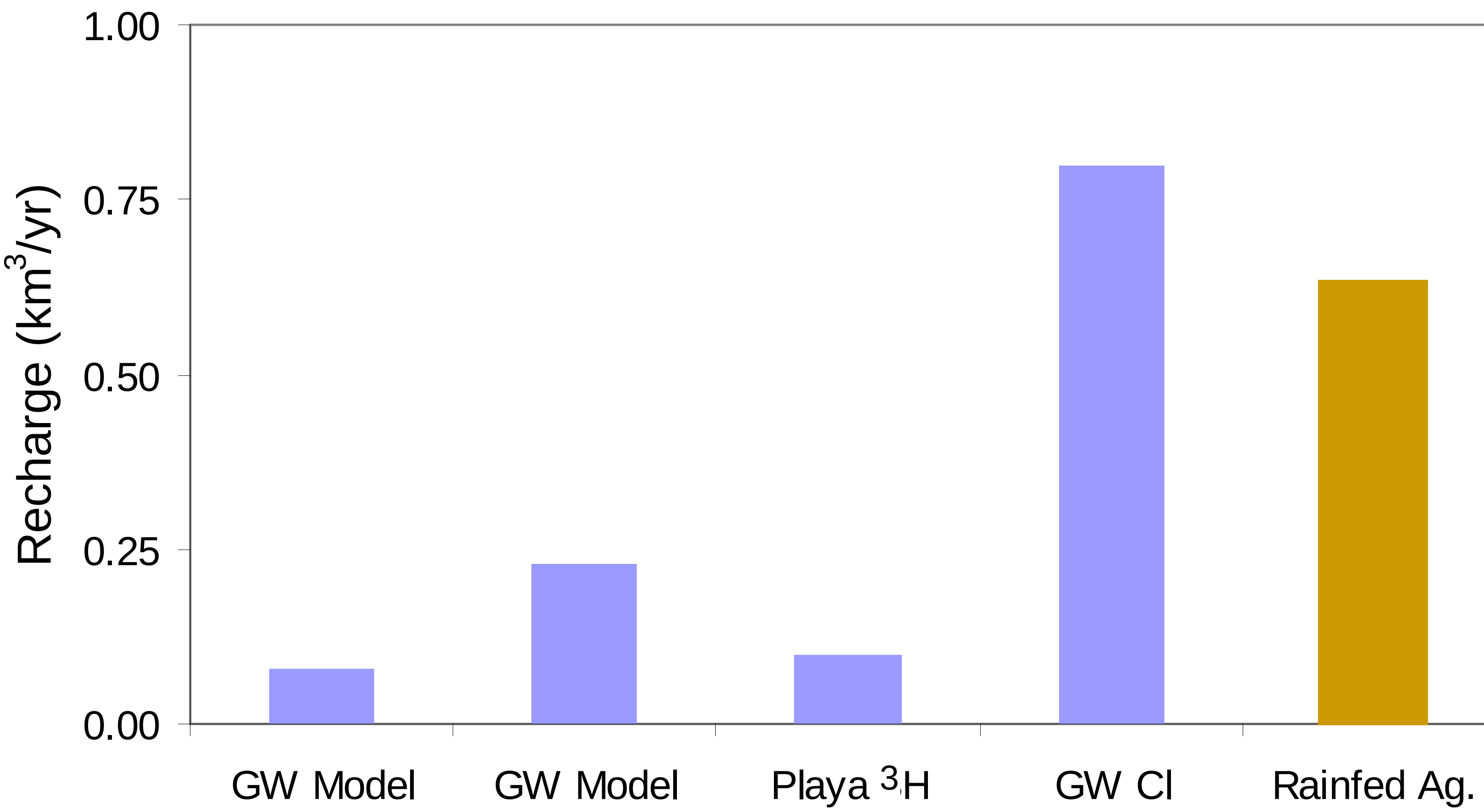
Average water table depth in southern High Plains = 30 m

Impact of Cultivation on Regional Recharge

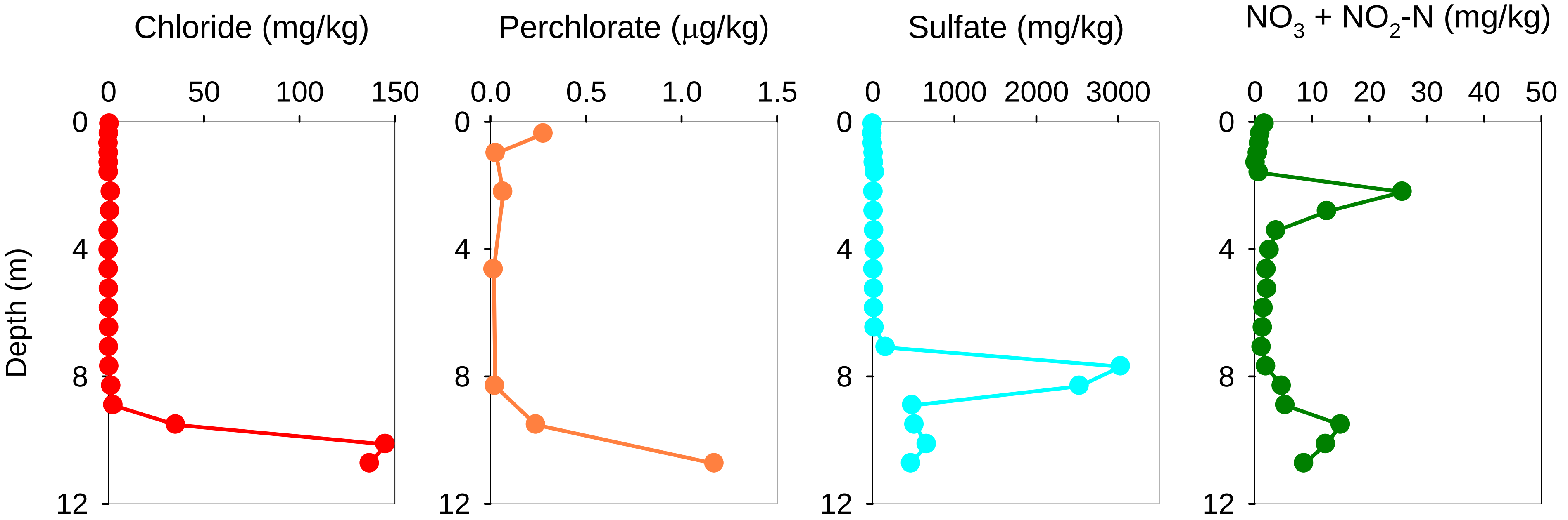


Area of southern High Plains 75,000 km^2

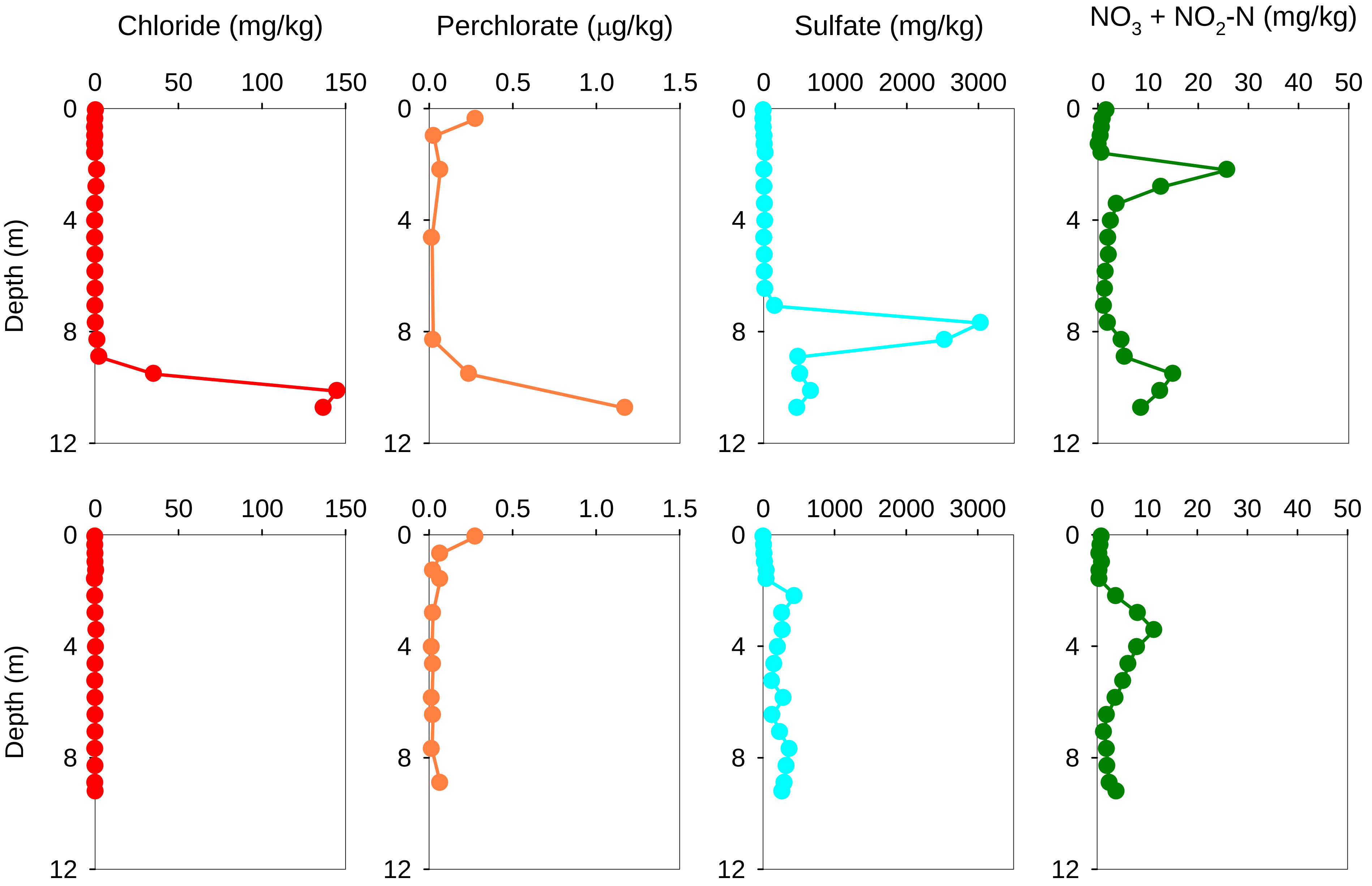
Impact of Cultivation on Regional Recharge



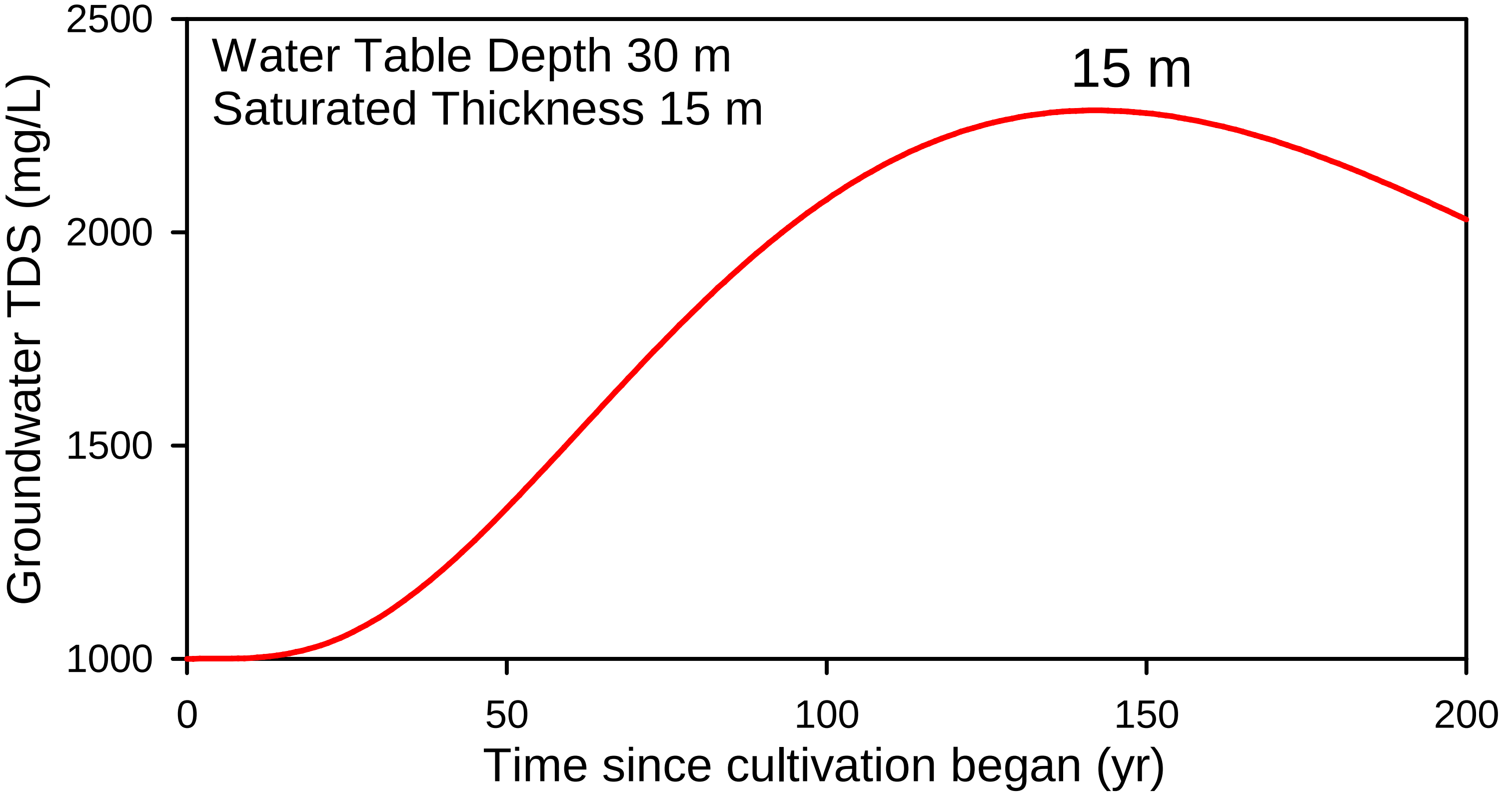
Salt Mobilization Caused by Rainfed Agriculture



Salt Mobilization Caused by Rainfed Agriculture



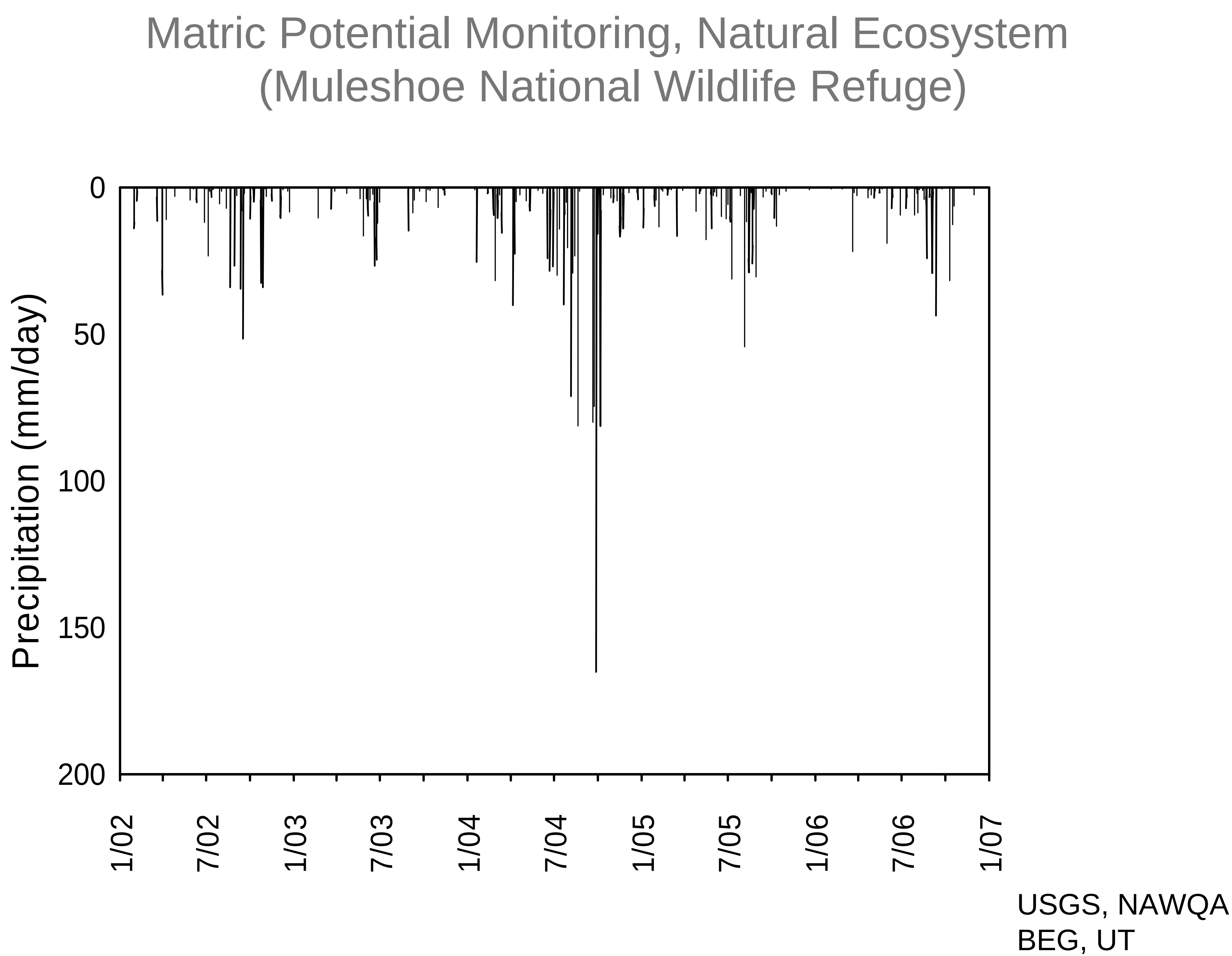
Impact of Increased Recharge on Groundwater Salinity

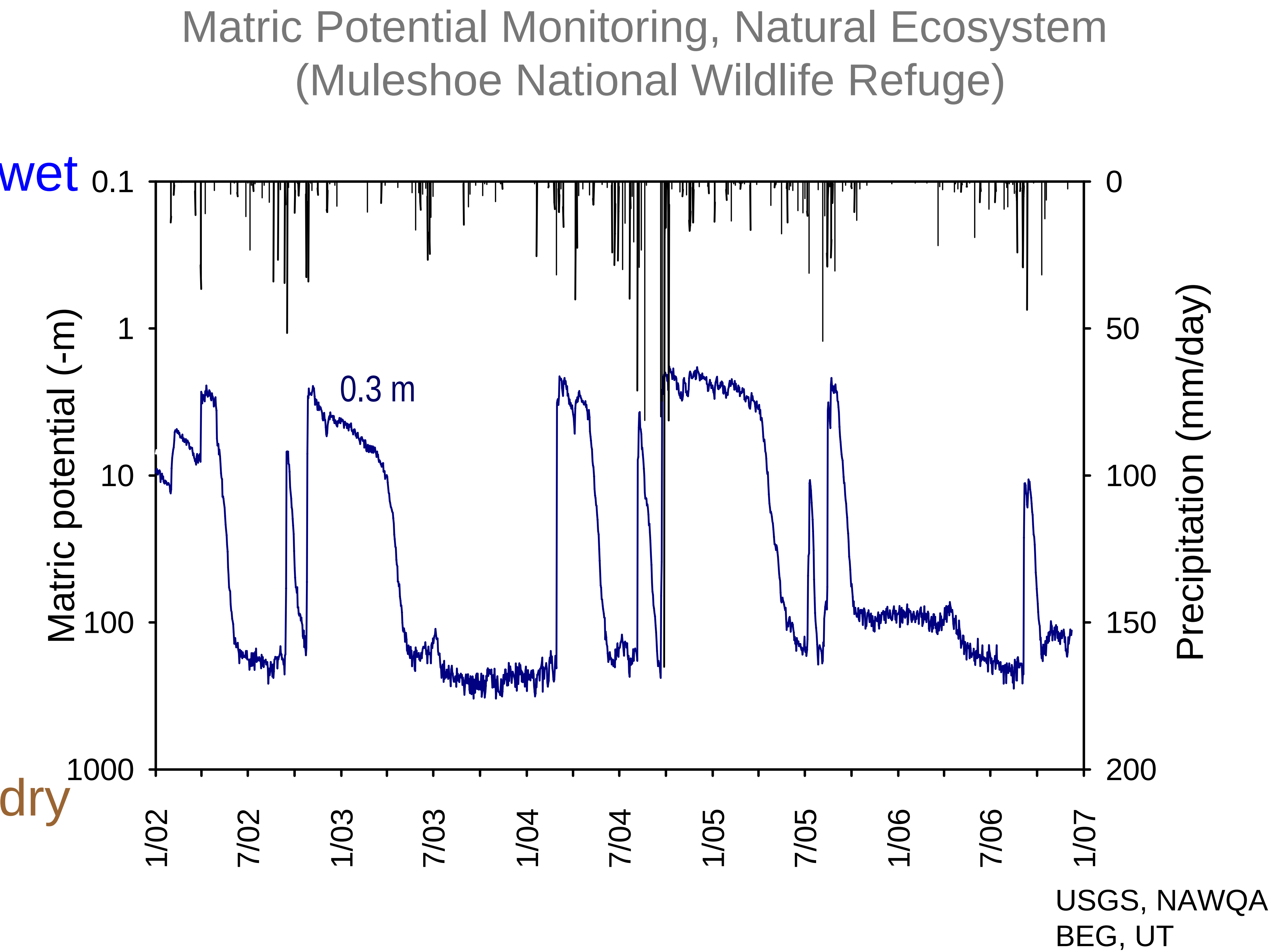


Causes of Differences in Recharge beneath Natural and Agricultural Ecosystems

- Perennial natural vegetation versus annual crops
- Cropland in southern High Plains is fallow from late November to early June
- Roots in perennial native vegetation are much deeper than those in cropland and can remove episodic deep drainage

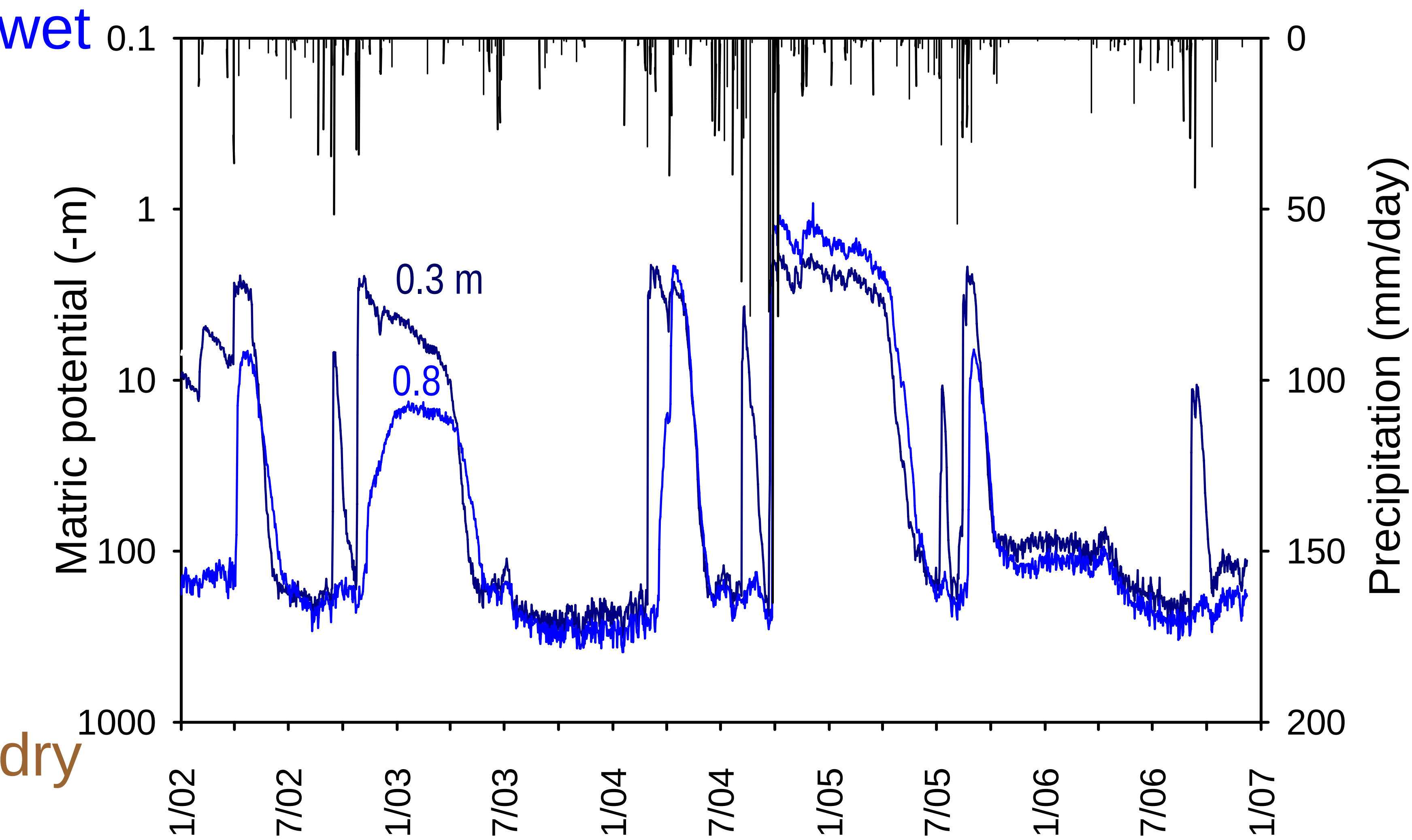
Heat Dissipation Sensor Monitoring Station


Matric Potential Monitoring, Natural Ecosystem
(Muleshoe National Wildlife Refuge)
Precipitation (mm/day)
0
50
100
150
200
1/02
7/02
1/03
7/03
1/04
7/04
1/05
7/05
1/06
7/06
1/07
USGS, NAWQA
BEG, UT



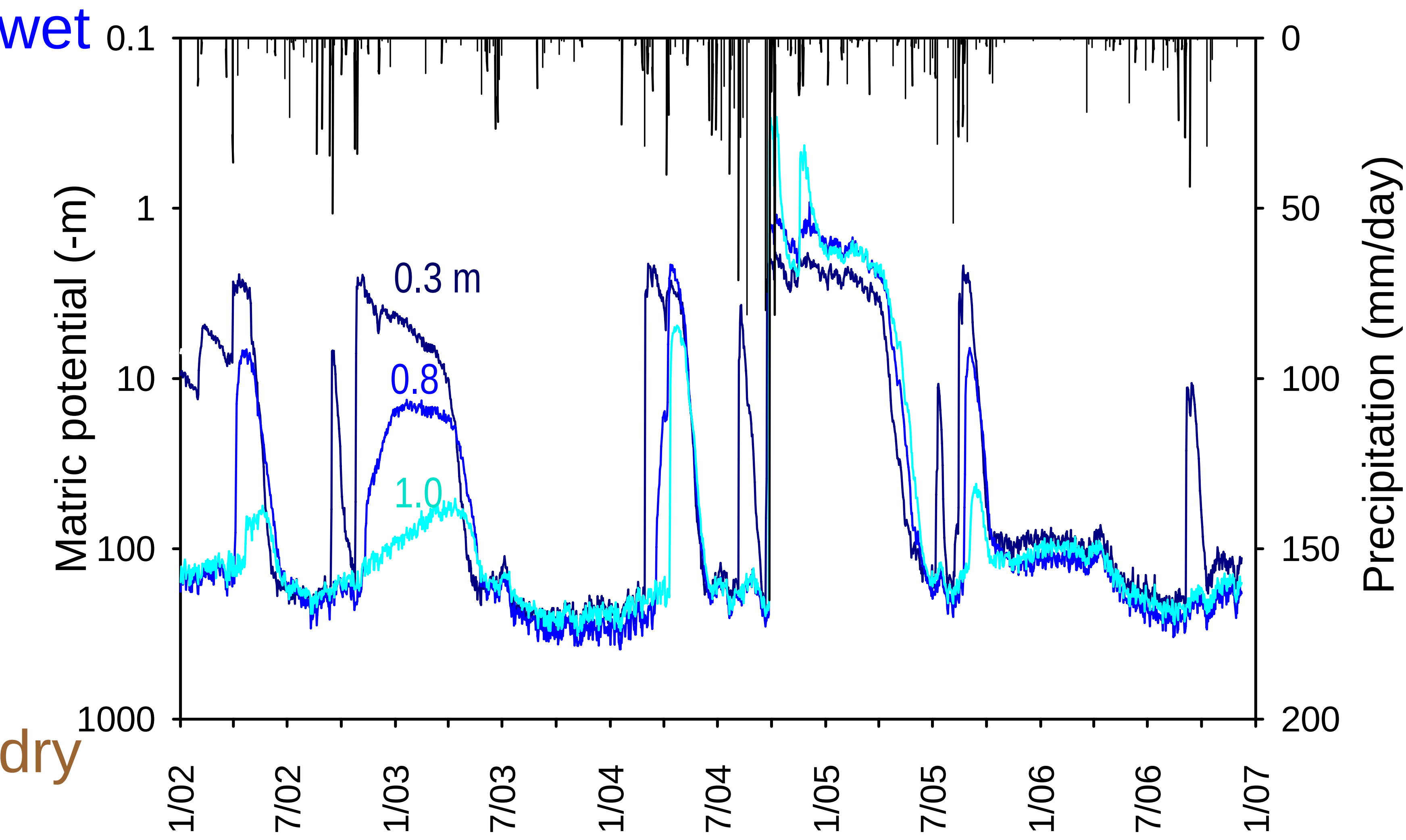
Matric Potential Monitoring, Natural Ecosystem
(Muleshoe National Wildlife Refuge)
wet
dry
0.1
1
10
100
1000
Matric potential (-m)
0
50
100
150
200
Precipitation (mm/day)
0.3 m
1/02
7/02
1/03
7/03
1/04
7/04
1/05
7/05
1/06
7/06
1/07
USGS, NAWQA
BEG, UT

Matric Potential Monitoring, Natural Ecosystem (Muleshoe National Wildlife Refuge)



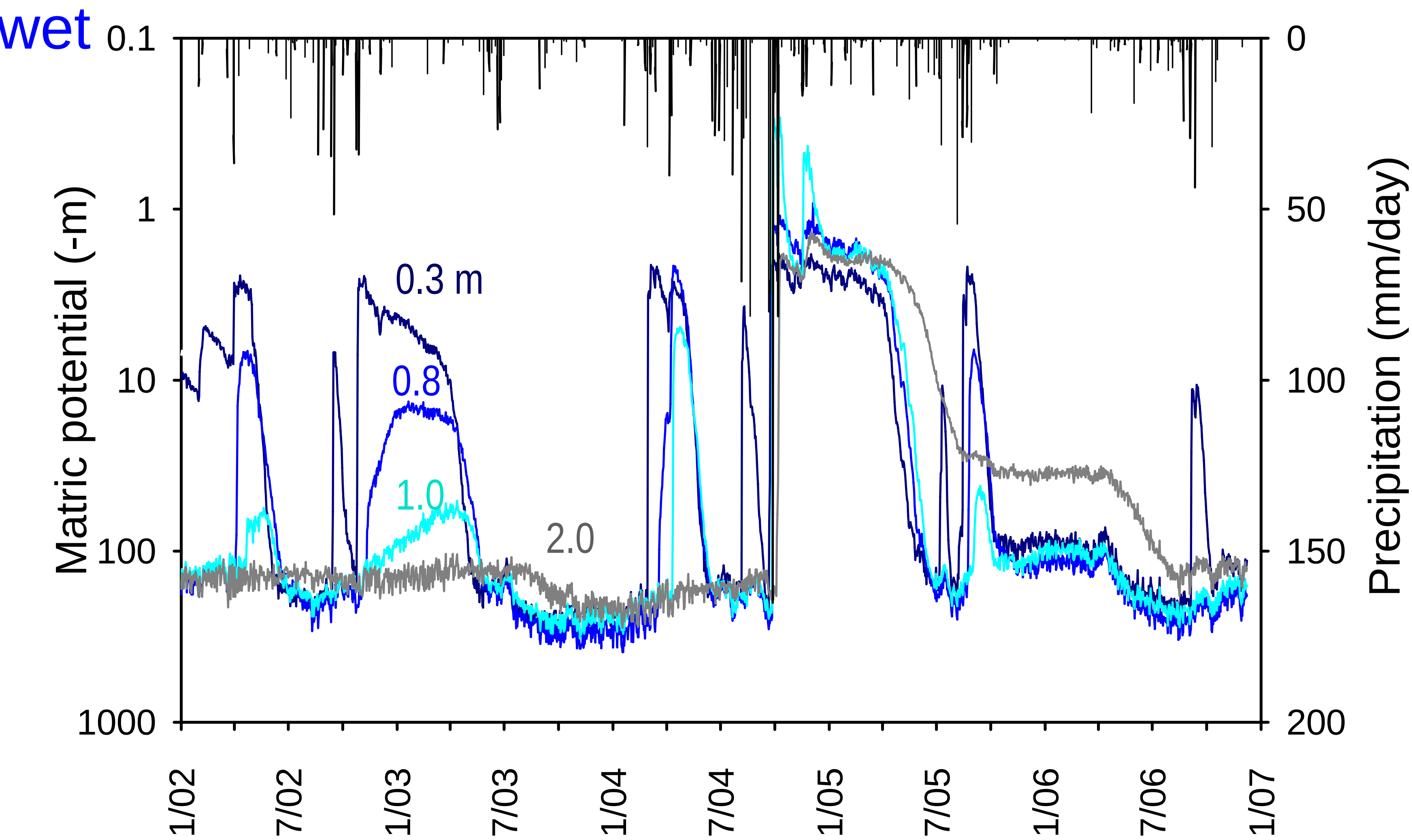
USGS, NAWQA
BEG, UT

Matric Potential Monitoring, Natural Ecosystem (Muleshoe National Wildlife Refuge)



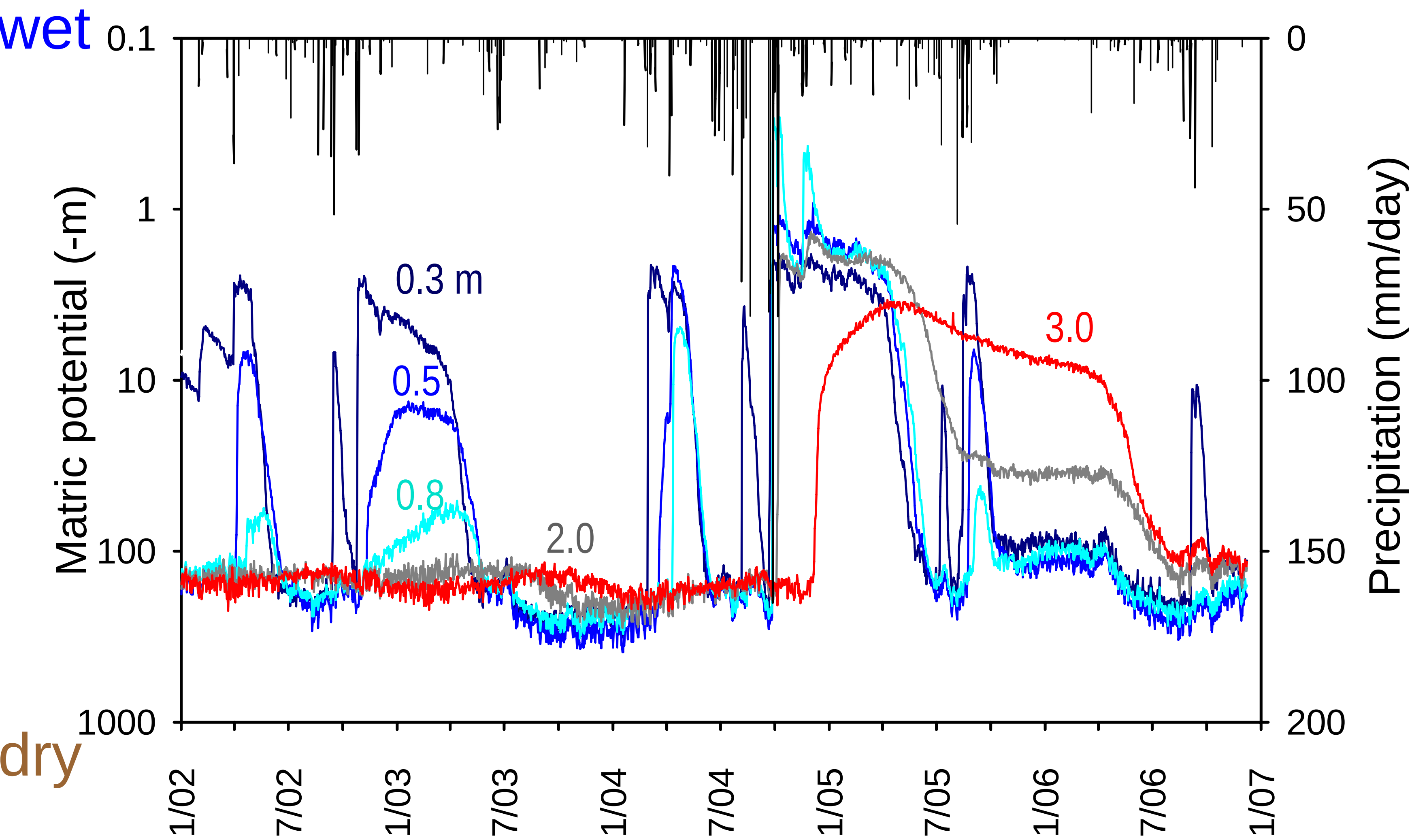
USGS, NAWQA
BEG, UT

Matric Potential Monitoring, Natural Ecosystem
(Muleshoe National Wildlife Refuge)



USGS, NAWQA
BEG, UT

Matric Potential Monitoring, Natural Ecosystem (Muleshoe National Wildlife Refuge)

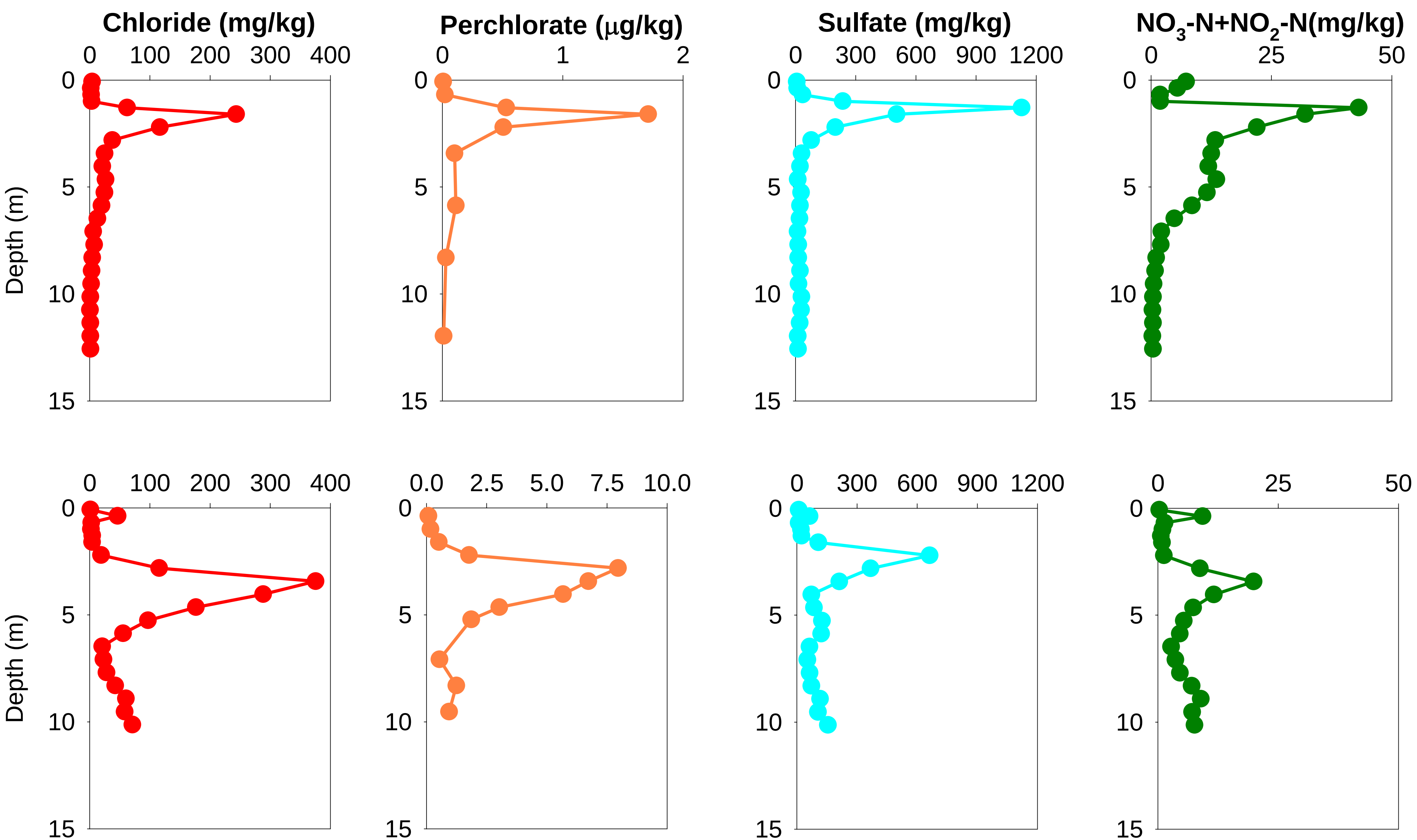


USGS, NAWQA
BEG, UT

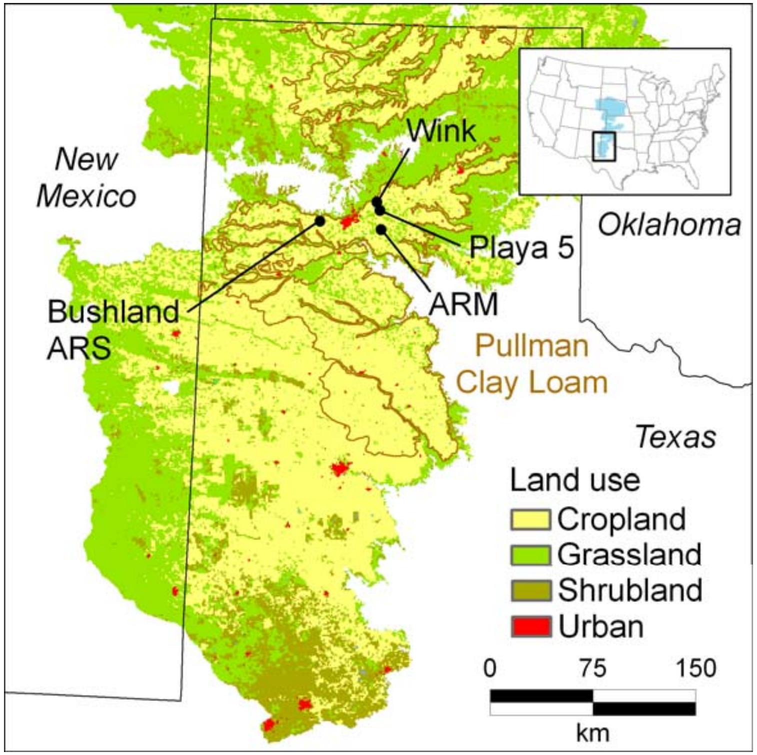
Rainfed Agriculture

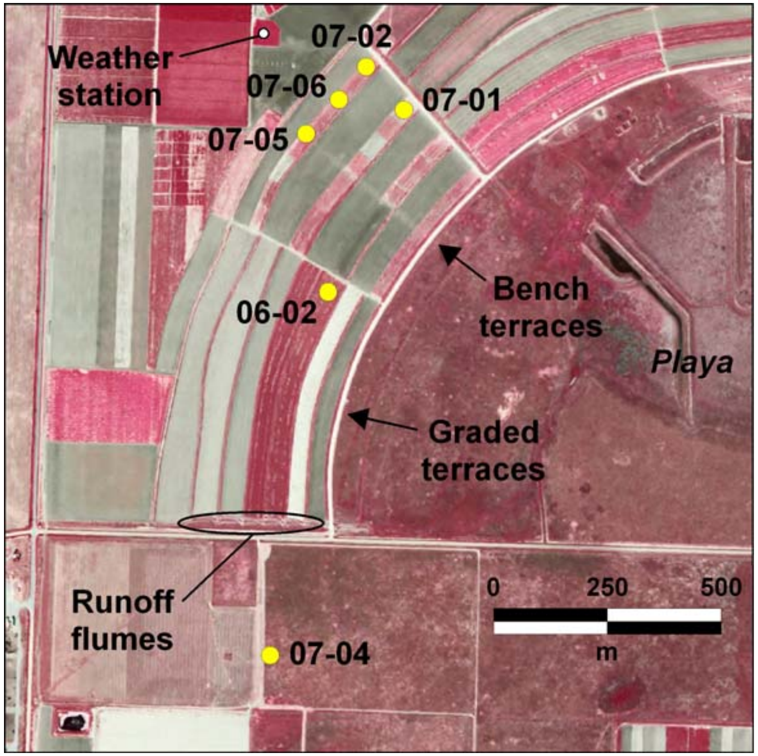
- Groundwater-level rises: mean recharge 24 mm/yr over 3,400 km^2 area = 5% of precipitation
- UZ profiles, varying levels of flushing, log normal distribution of recharge, mean 33 mm/yr
- Time lag between drainage and recharge ~ 60 yr
- Under new equilibrium conditions, volumetric recharge rate would be increased by up to a factor of 8 relative to pre-agricultural recharge rates.
- Mobilization of salts…chloride and sulfate
- Salt mobilization would increase groundwater TDS by up to 1.7 to 2.5 times depending on saturated thickness.

Irrigated Agriculture (Salt Accumulation)

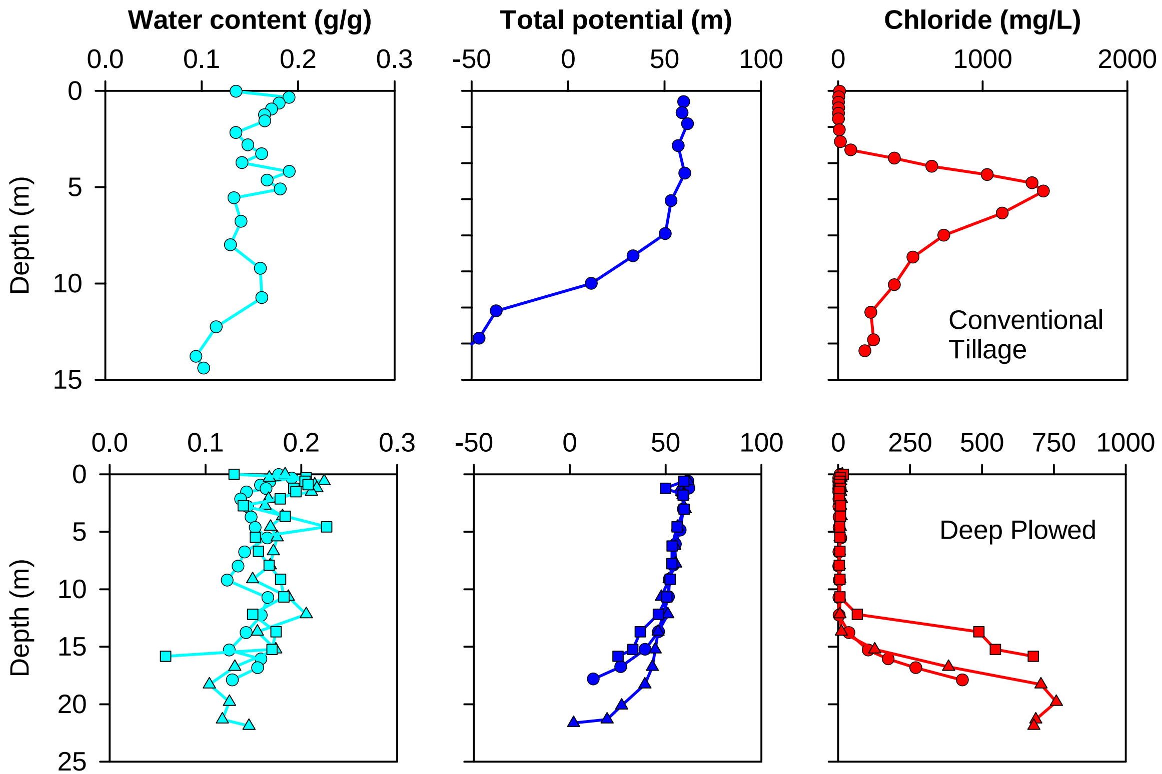


What is the Impact of Deep Plowing in Areas of Low Permeability Soils?





Deep Plowed Cropland



Recharge

9 mm/yr

60 – 90 mm/yr

45 – 80 yr to reach WT (75 m deep)

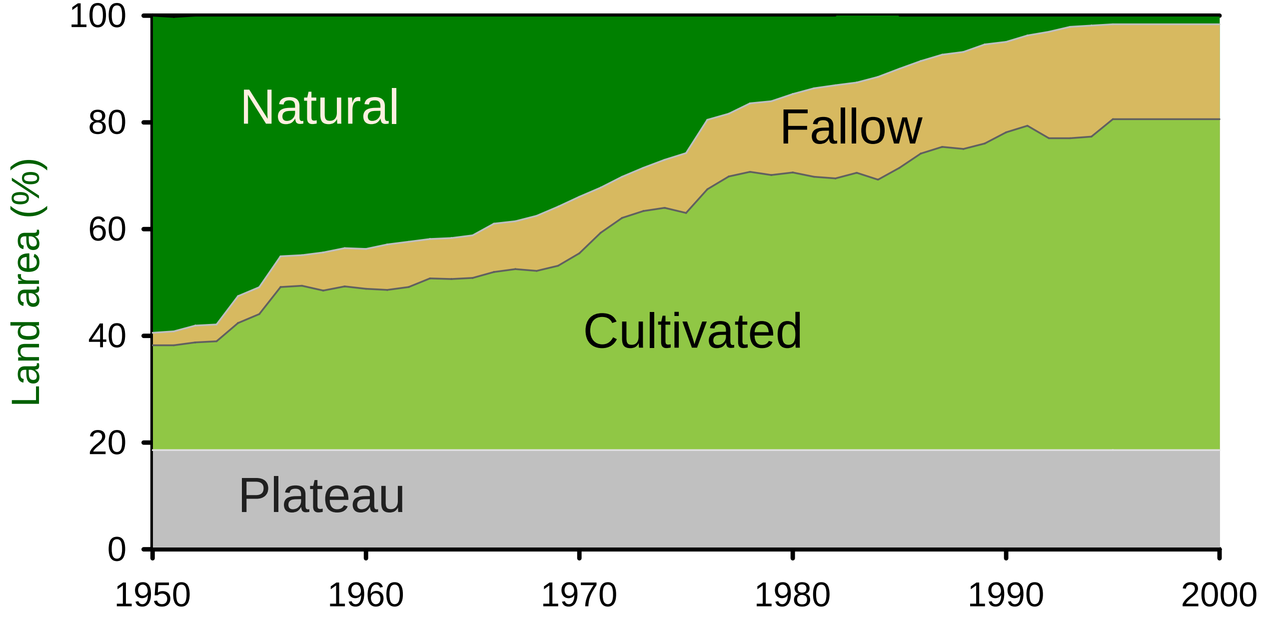
Basic Questions
Impacts of Changing Land Use on Water Resources

- Why is it important?
- How can we quantify impacts?
- What impacts does changing land use have on water resources?
- Where are similar impacts documented globally?
- How can we use understanding to develop sustainable water resources?

Impact of Land Use Change and Climate Variability in Water Resources in Niger

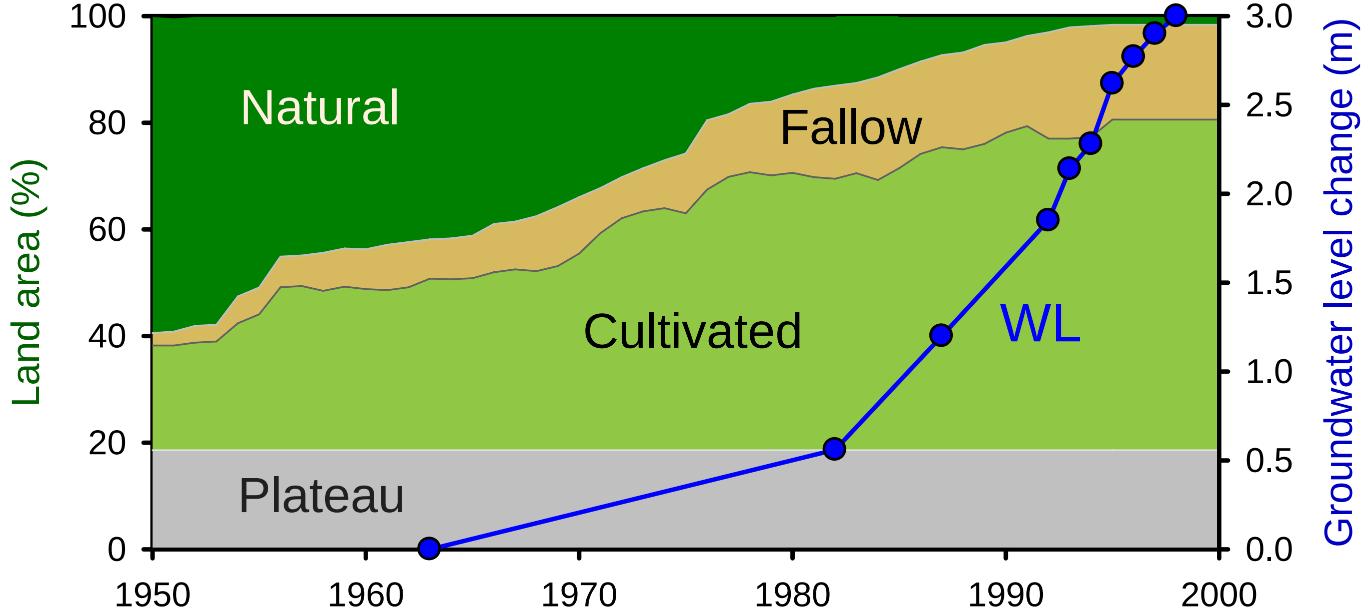
Studied since 1990s
Hapex-Sahel
Af. Monsoon Multidiscip. Analysis

Groundwater Level Rises Caused by Cultivation, Niger



Favreau et al., 2002, GW

Groundwater Level Rises Caused by Cultivation, Niger

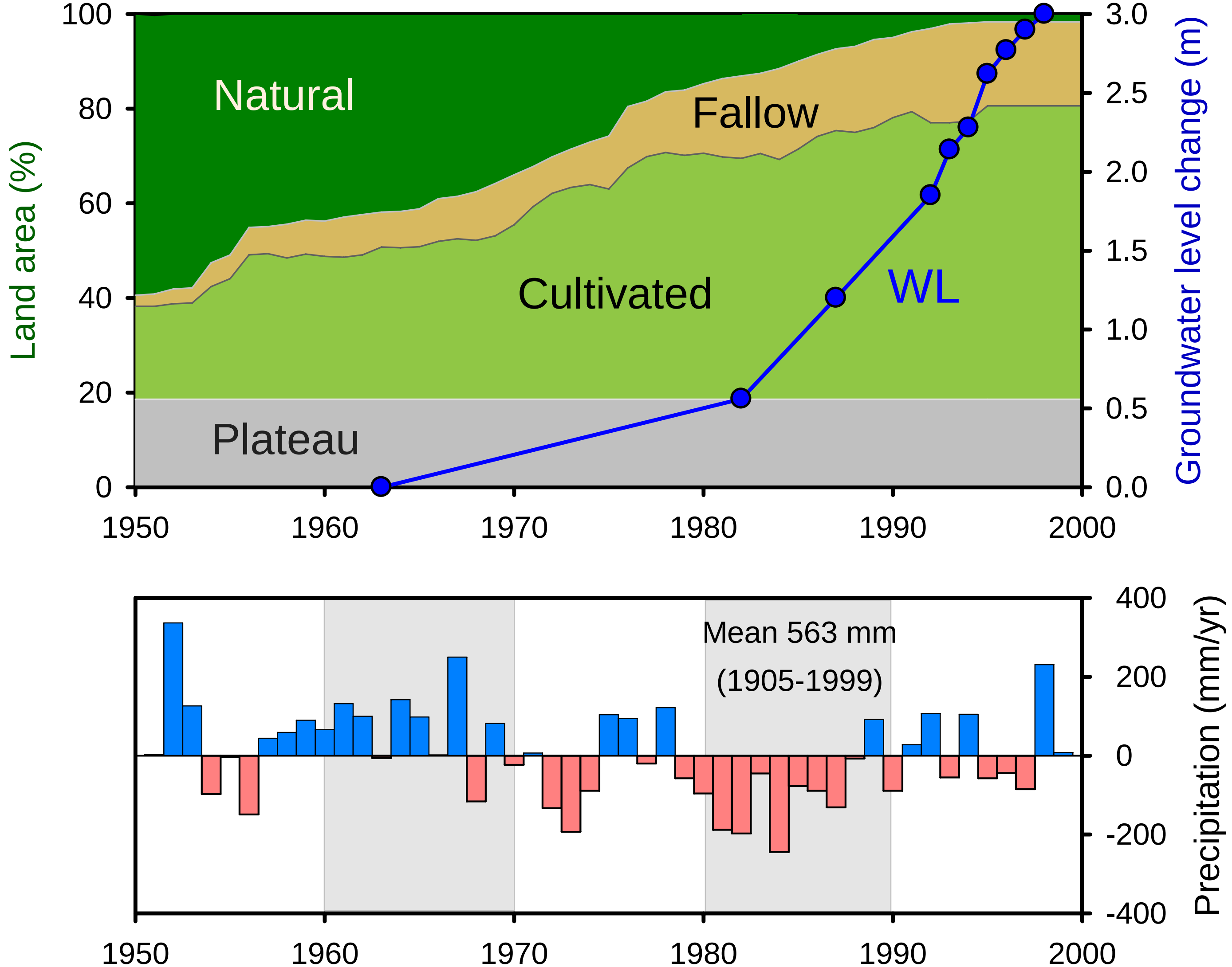


Recharge
1 - 5 mm/yr

Recharge
10 - 50 mm/yr

Favreau et al., 2002, GW

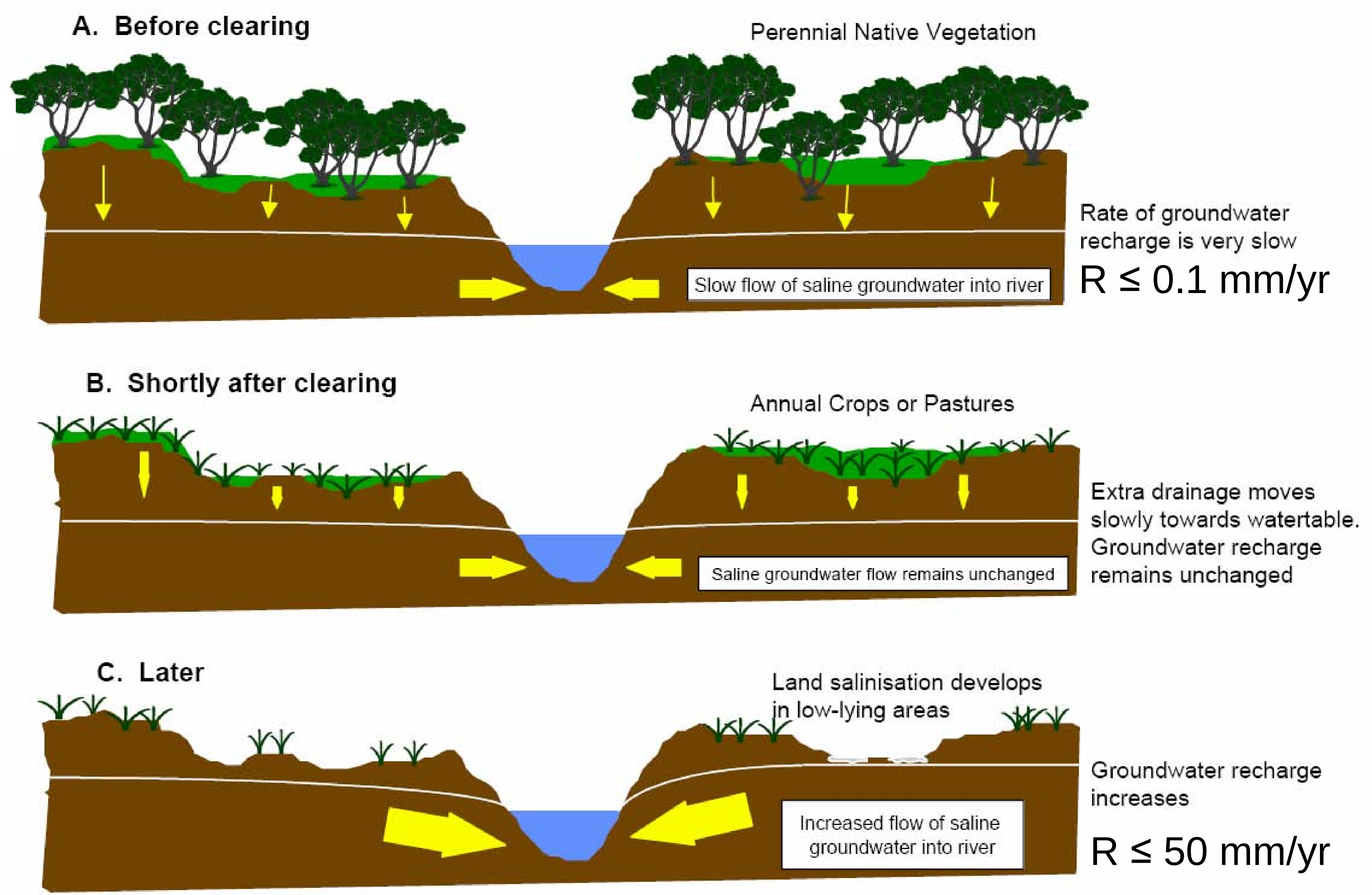
Groundwater Level Rises Caused by Cultivation, Niger



Favreau et al., 2002, GW

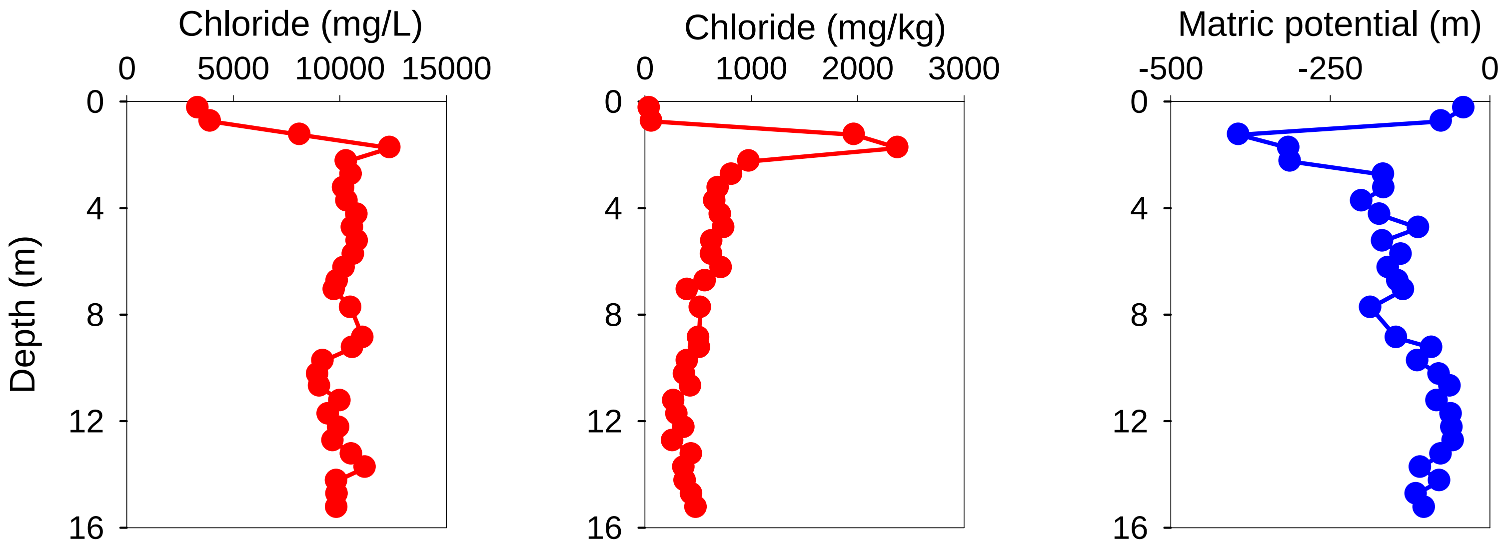
Land Clearance in Australia, Early 1900s

Impact of Rainfed Agriculture on Water Resources, Australia



Cook et al., 2001, CSIRO

Chloride Reservoirs in Mallee Vegetated Areas



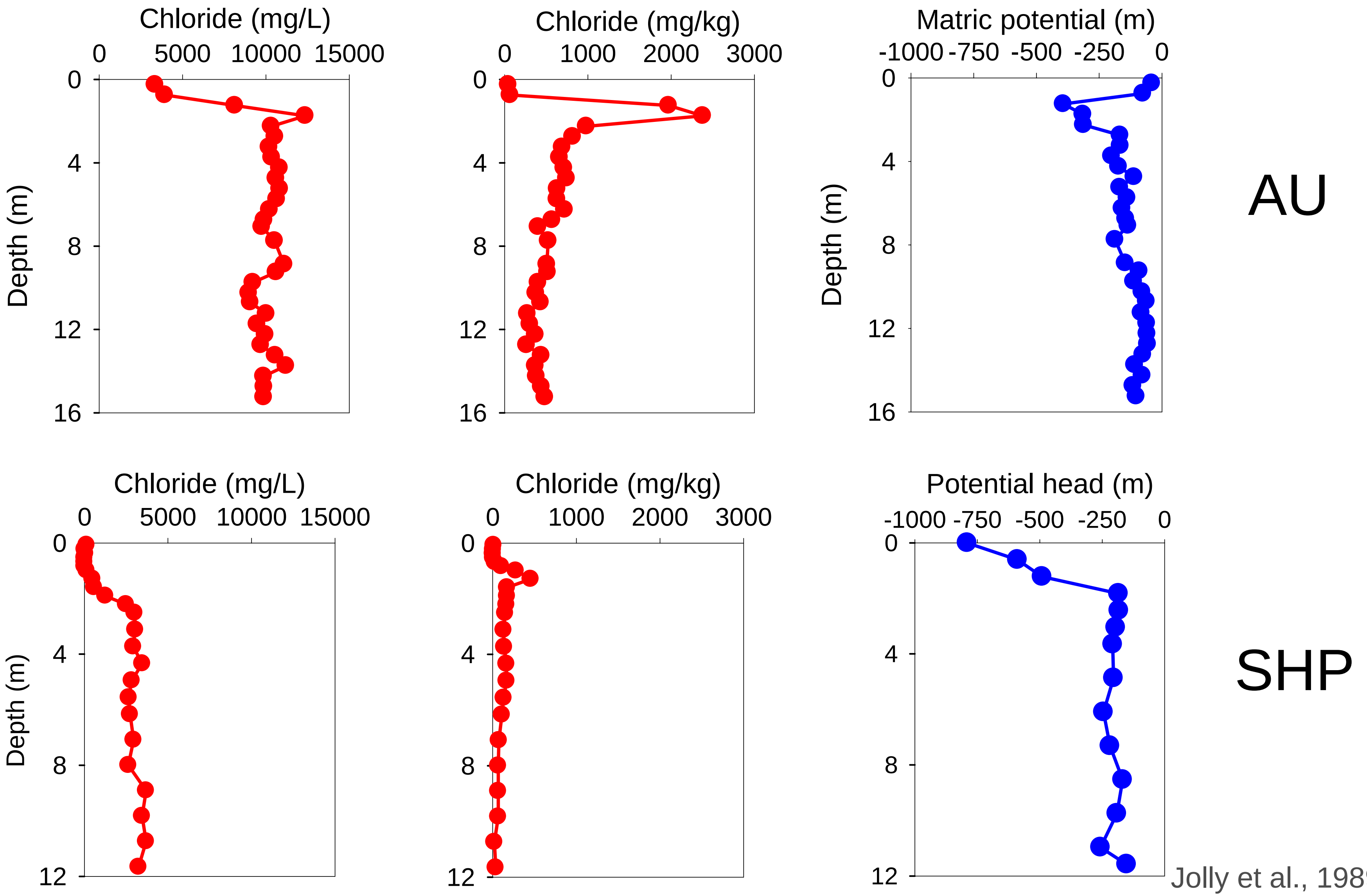
Cl_p = 4 mg/L

Profiles drying for up to 30,000 yr

Recharge ≤ 0.1 mm/yr

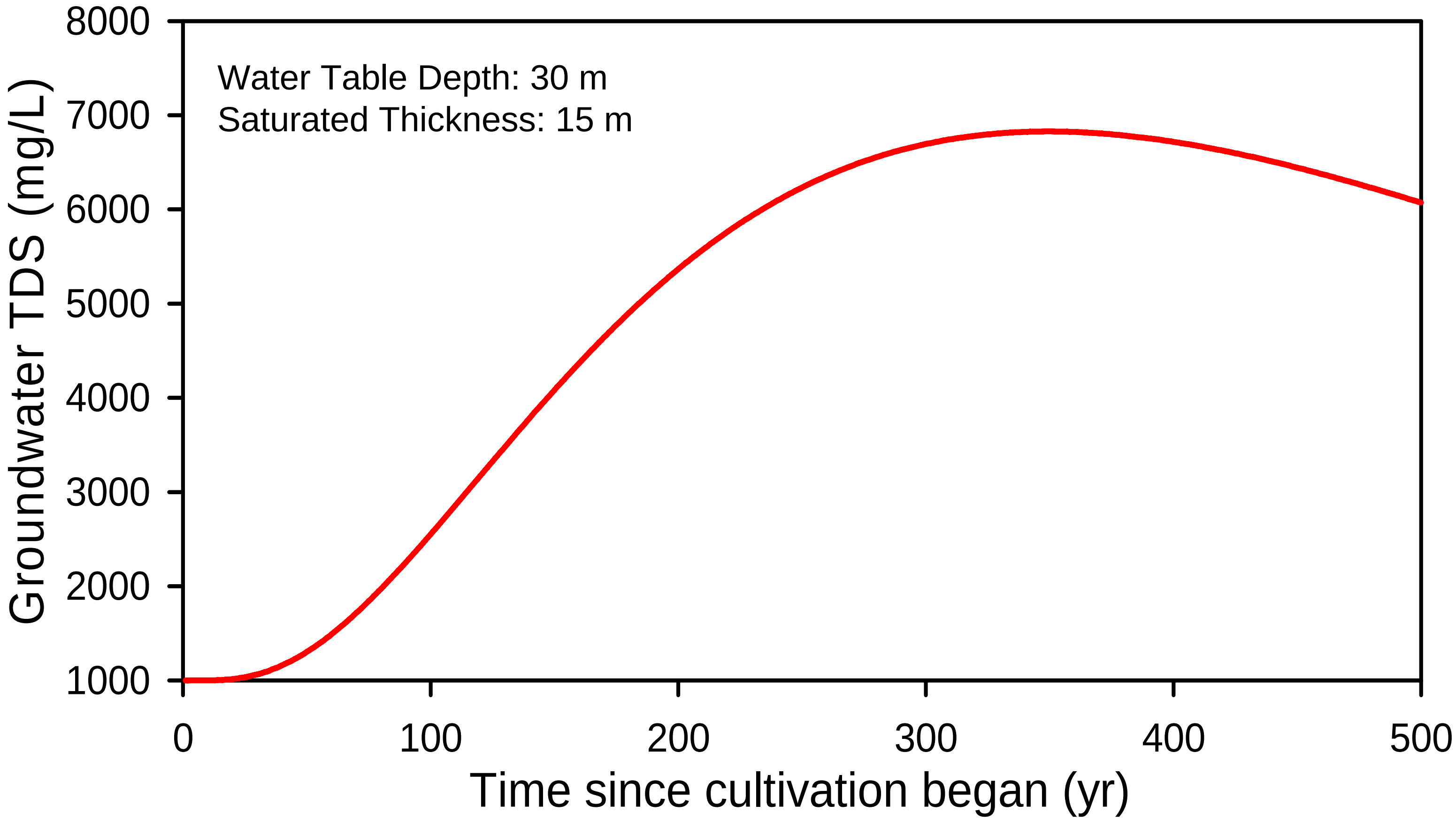
Jolly et al., 1989, J. Hydrol.

Comparison of Chloride Reservoirs in Australia and the Southern High Plains



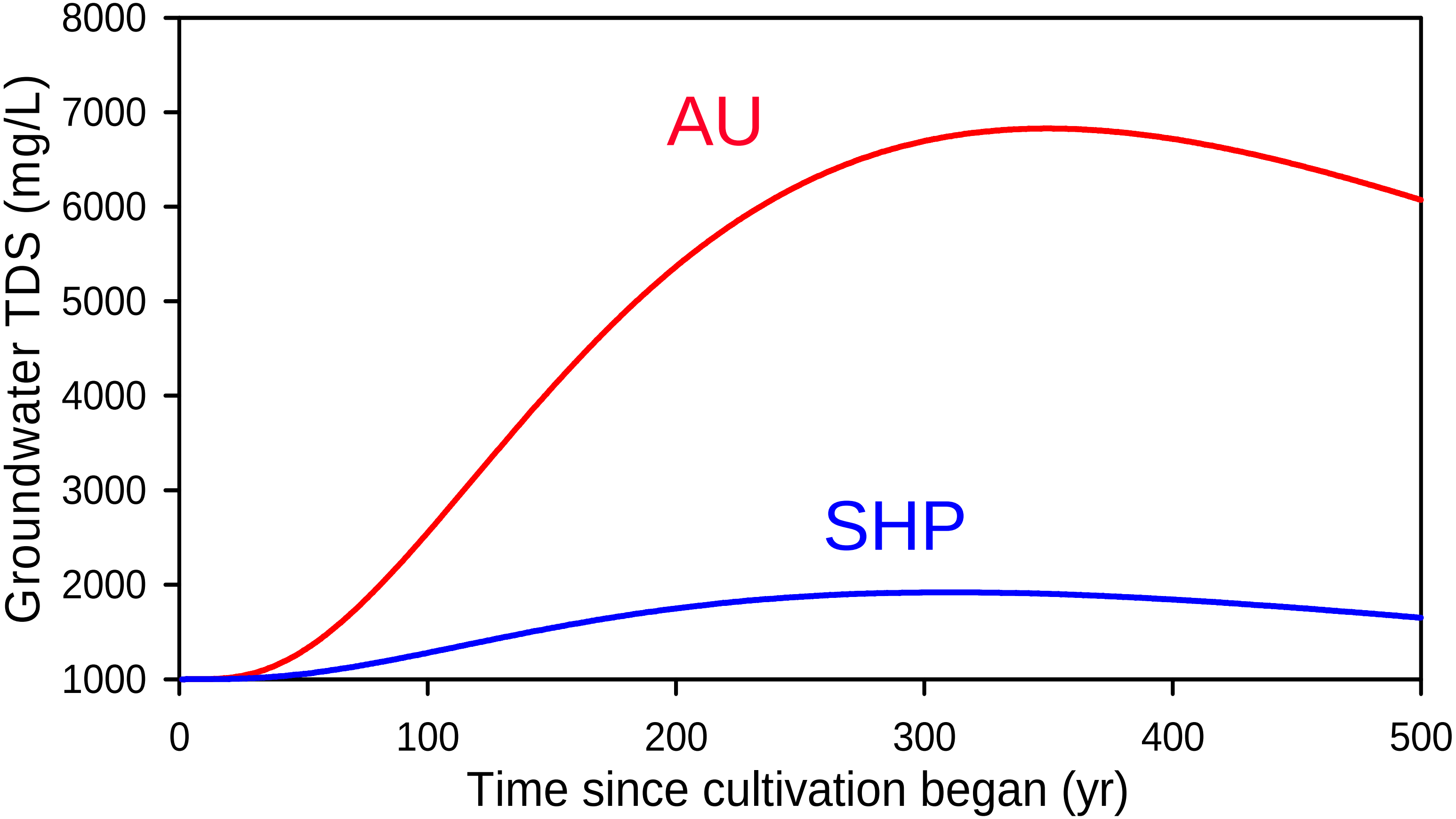
Jolly et al., 1989, J. Hydrol.

Impact on Groundwater Salinity



Cook et al., 1993, CSIRO

Comparison of Impacts on Groundwater Quality Australia and Southern High Plains



Cook et al., 1993, CSIRO

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Sustainable Water Resources Management

- Integrate land and water resources management (Blue Revolution, Ian Calder)
- Decrease dependence on irrigated agriculture
- Drop sectoral divisions between irrigated and rainfed agriculture (Comprehensive Assessment of Water Management in Agriculture)
  - Rainwater harvesting and supplemental irrigation in rainfed areas
  - Irrigation shift from semiarid to more humid settings
- Increase productivity of rainfed agriculture (more crop per drop, reduce evaporation, runoff, and drainage; decrease fallow periods)

Sustainable Water Resources Management
Southern High Plains

- Reduce irrigated agriculture
- Irrigated agriculture → rainfed agriculture
- Rotate rainfed agriculture with irrigated agriculture when groundwater levels rise near the land surface
- Convert natural ecosystems to rainfed agriculture
- Deep ploughing of rainfed systems to further increase recharge