Groundwater Management in Australia: a Research Perspective

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UNSW Australia

Never Stand Still | Global Water Institute

Federation of Thai Industries

Water Institute for Sustainability Forum

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WIS FORUM 2017

Overview

- UNSW
- UNSW Global Water Institute
- Water resources in Australia
- Managed aquifer recharge (MAR)
- Groundwater governance issues
- Groundwater organic contaminants
- Surface water – groundwater interactions
- Aquifers and unconventional gas production
- Groundwater confinement & aquifer compressibility
- Summary

UNSW

UNSW AUSTRALIA

UNSW

- Founded in 1949 and located in Sydney, Australia
- Has rapidly become one of Australia's leading research-intensive universities
- Ranked in the top 50 universities worldwide (QS)
- >20,000 postgraduate students
- Highly engineering and technology-focused with the largest and highest-rated engineering faculty in Australia
- 9 Schools (Departments) within the Faculty of Engineering
- School of Civil & Environmental Engineering ranked #16 in the world (QS)

UNSW: Industry and research-focused

10
ARC Centres of Excellence

5,758
Research Publications

2,115
Research Staff

$525m
Total Research Income

4,294
Higher Degree Research Candidates

11
Cooperative Research Centres

6
Affiliated Medical Research Institutes

7
National Health and Medical Research Council Centres of Excellence

12
National Research Centres

(2015 numbers)

UNSW: International outlook

- 14,000 international students out of a total of 53,000 students
- Multiple international research and education partnerships
- Member of Universitas 21 group of research-intensive universities
- An Australian leader in international research collaboration

UNSW Global Water Institute

UNSW AUSTRALIA

The UNSW Global Water Institute (UNSW-GWI)

Who are we?

We are **400** researchers, professional staff and PhD students hailing from 8 faculties and 14 specialist research centres across UNSW Australia.

Why do we exist?

1. To provide excellence in water education.
2. To connect water-related research expertise and facilities internally across the University.
3. To provide our external partners with direct access to our expertise and facilities.

Our expertise

Our expertise is grouped into seven broad categories and 38 key capabilities:

Water and wastewater management

- *Water and wastewater treatment*
- *Water recycling for potable and non-potable reuse*
- *Membranes*
- *Trace organics*
- *Physicochemical processes in natural and engineered systems*
- *Odorous and gaseous emissions*
- *Cyanobacteria and their toxins*
- *Risk assessment and management*
- *Ecotoxicology and whole effluent testing*
- *Urban stormwater and wet weather overflows*

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Our expertise *(continued)*

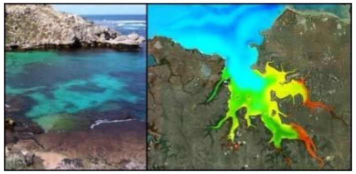
Water resource management and climate change

- *Groundwater resource and quality*
- *Climate change and climate variability impacts on water*
- *Hydroclimatology*
- *Hydrology and flood management*
- *Disaster risk management and resilience*
- *Remote sensing*
- *Oceanography*

Coastal and estuarine management

- *Coastal engineering and management*
- *Environmental and ecological engineering*
- *Civil engineering hydraulics*
- *Estuarine management*
- *Coastal hydrodynamics and sediment transport modeling*







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Our expertise *(continued)*

Aquatic ecosystems and biodiversity

- *River and wetland management*
- *Conservation practice*
- *Marine bio-innovation*
- *Biomonitoring of aquatic ecosystems*
- *Development of novel biomonitoring tools*
- *Pollution research*

Public health and social science

- *Public health and health services*
- *Environmental humanities*

Investigating water from public health and social science perspectives brings considerable relevance to the UNSW-GWI. Water cannot be properly understood or managed outside of such ‘human’ contexts.

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Our expertise *(continued)*

Policy, governance, institutions and sustainability

- *Water governance*
- *Sustainability assessment*
- *Adaptive management*

Industry specialisations

The water-related industries we have particular strengths in include:

- *Aquaculture and fisheries*
- *Water utilities*
- *Agriculture and horticulture*
- *Coal seam gas*
- *Mine water productivity and waste management*

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Collaboration – the key to success

UNSW-GWI is *actively seeking* long-lasting alliances with:

- National and international organisations
- Government agencies
- Other research providers
- Foreign universities
- Development banks
- NGOs
- Communities
- Partners in the corporate world

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Why connect with us

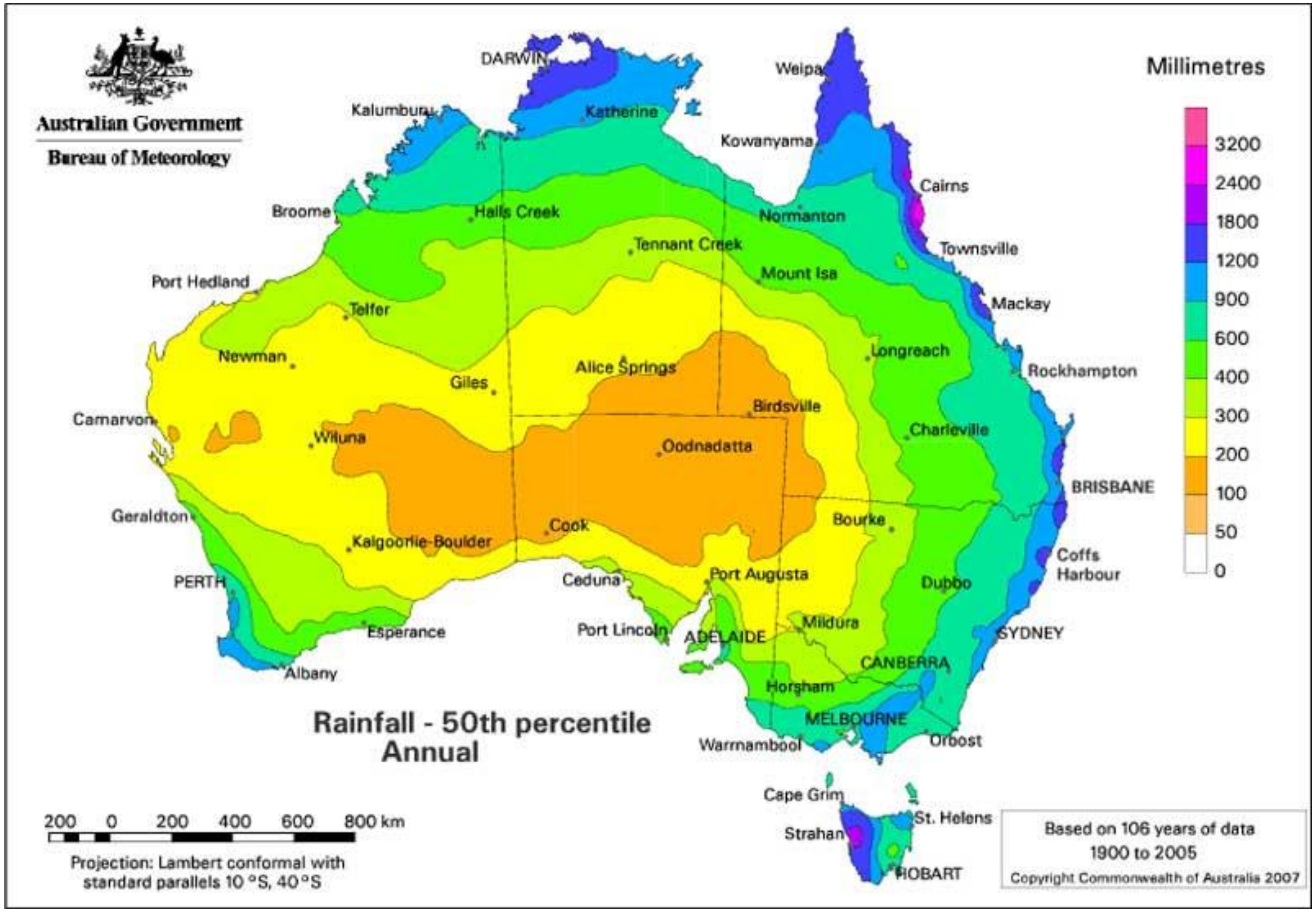
1. Global water issues are currently foremost on the minds of politicians, economists, industries, communities and within the science community.

2. We have an unparalleled ability to forge connections and facilitate mutually beneficial projects across the global water space.

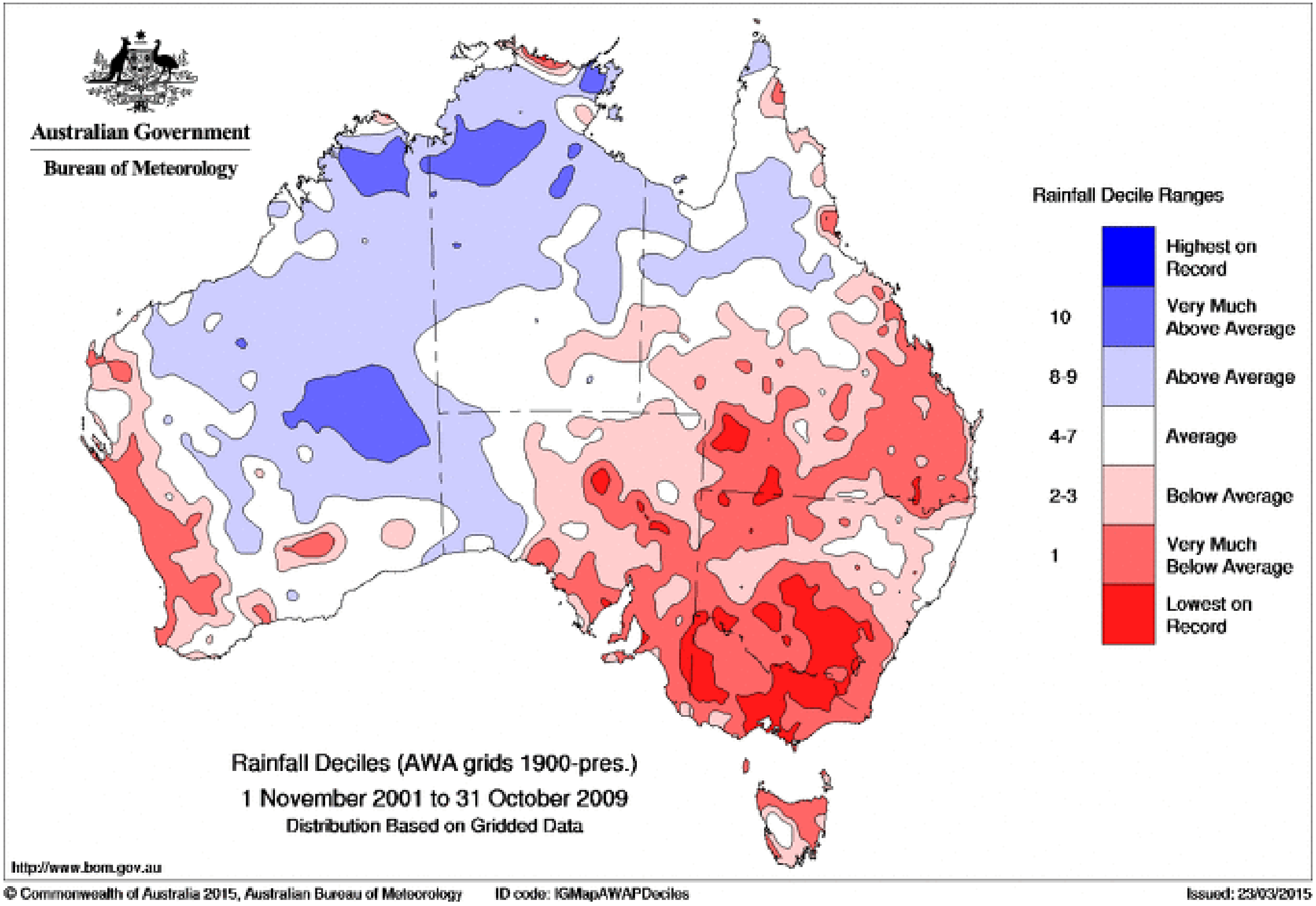
3. We offer a truly inter-disciplinary approach to the complex challenges facing water sectors worldwide and work with hundreds of industry partners, from small start-ups to the world's largest corporations.

Water Resources in Australia

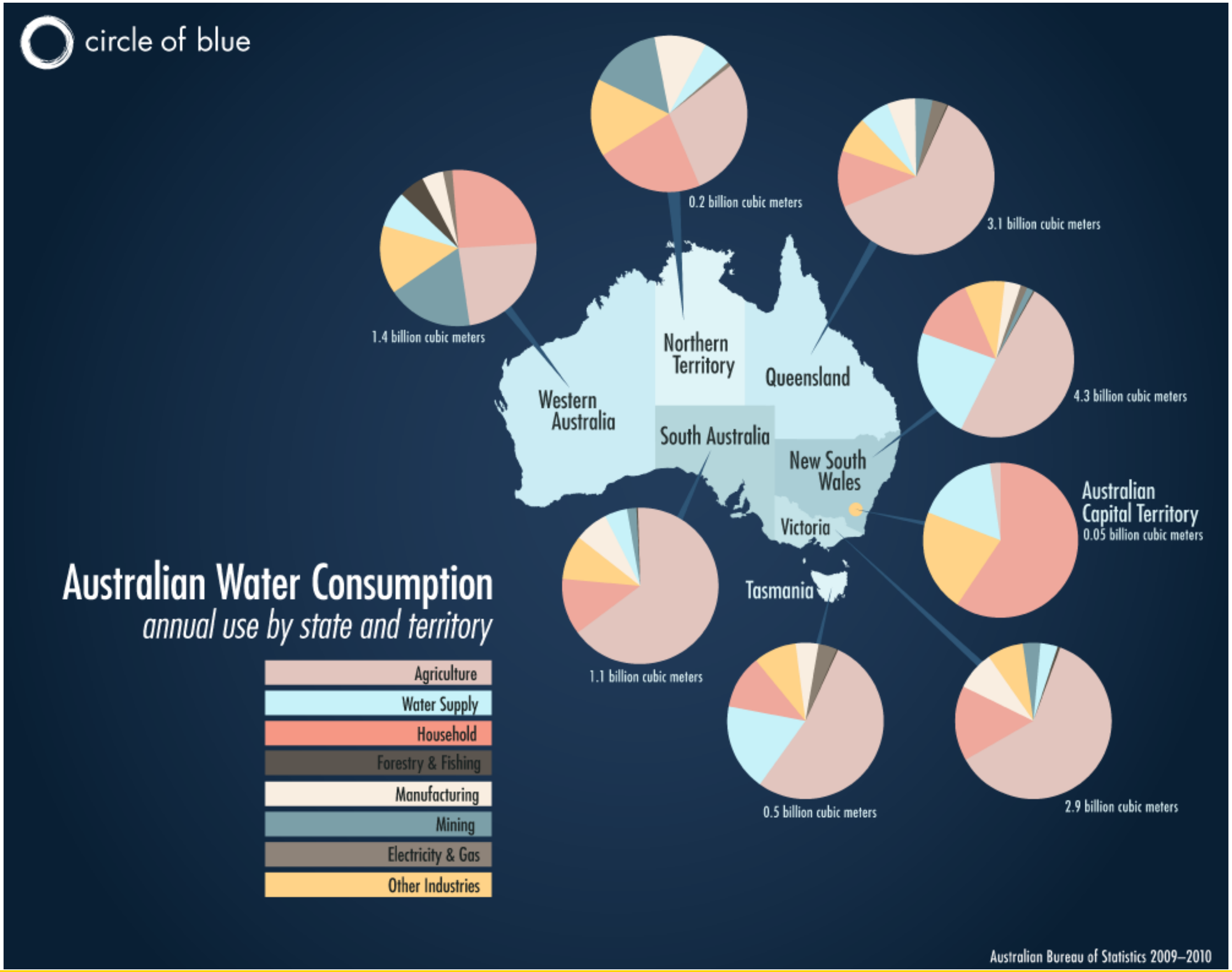
Precipitation in Australia



Millennium Drought



Water use in Australia

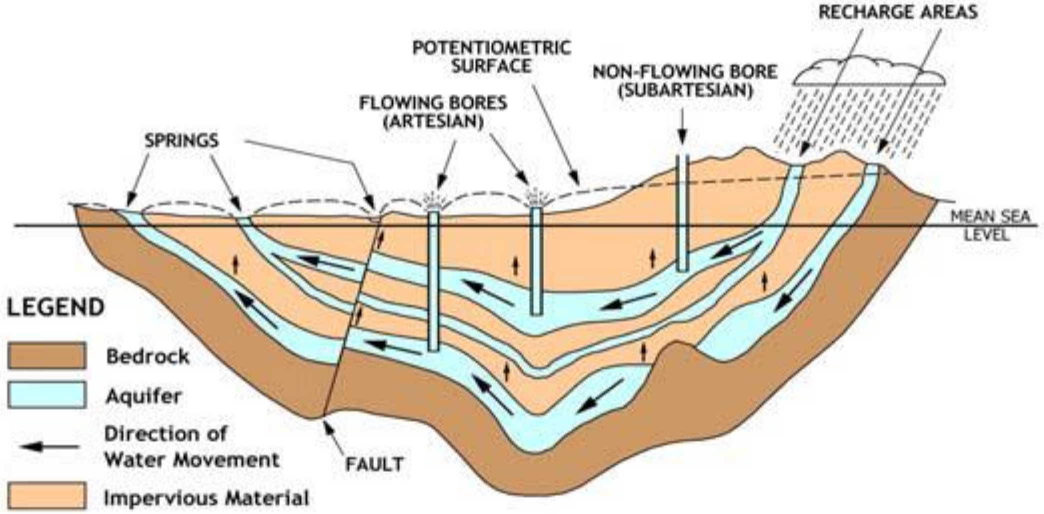


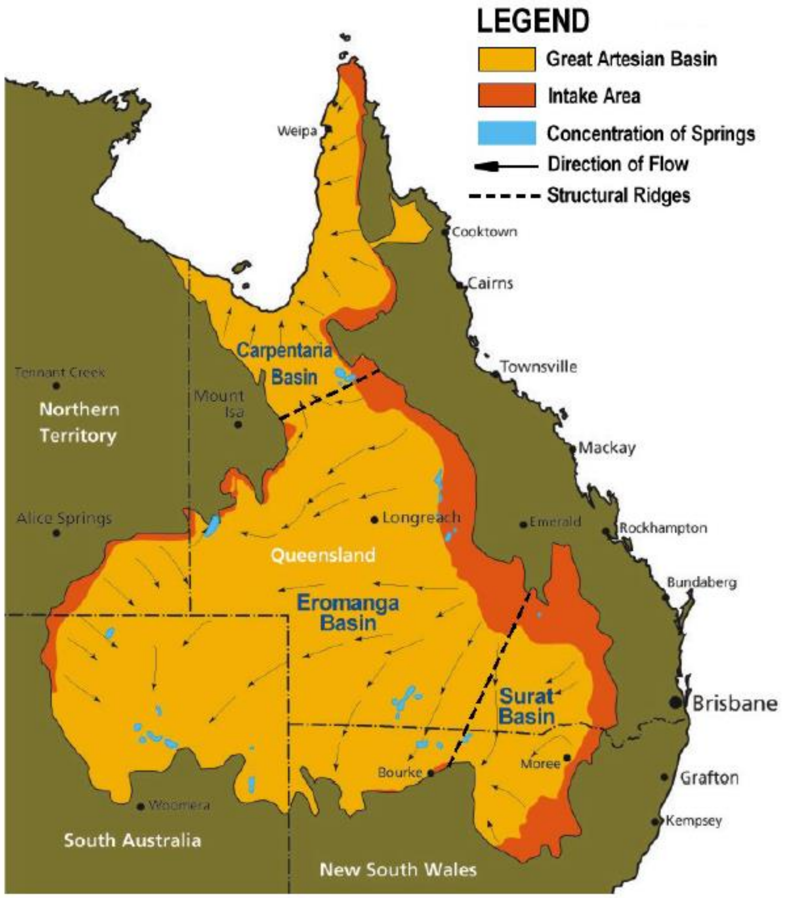
Water in Australia

- 30% of water used in Australia is groundwater
- Many parts of Australia would never have been settled if not for groundwater
- Some locations (e.g., Alice Springs) rely exclusively on groundwater for their water needs
- Even large cities are increasingly dependent on groundwater – for example, 46% of Perth's water supply is from groundwater
- Australia has several large (>1000km across) groundwater basins

Great Artesian Basin

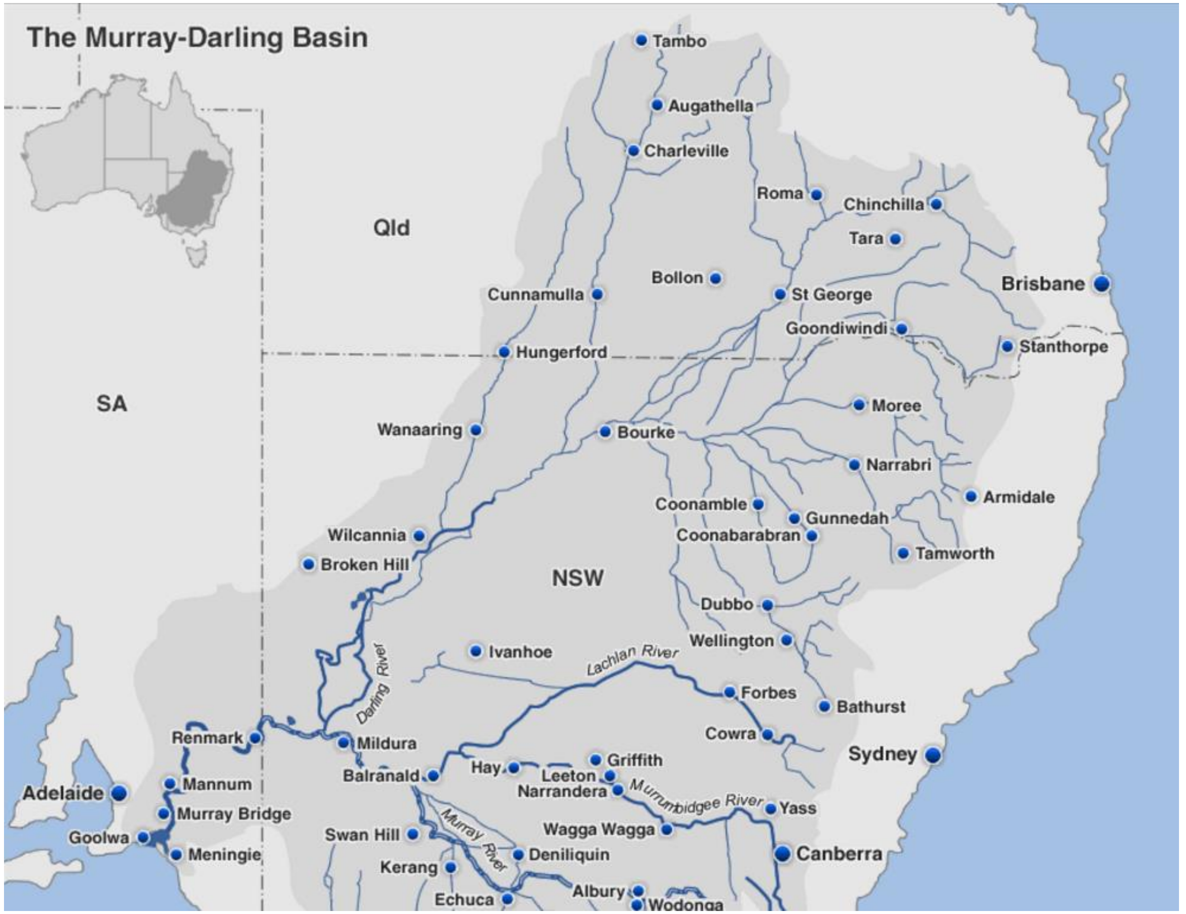
- Bores about 500 m deep on average
- Water ages up to 2 million years
- In many locations, bores may be free-flowing (artesian)
- Hydraulic heads up to **130 m** have been recorded at the land surface





Murray-Darling Basin

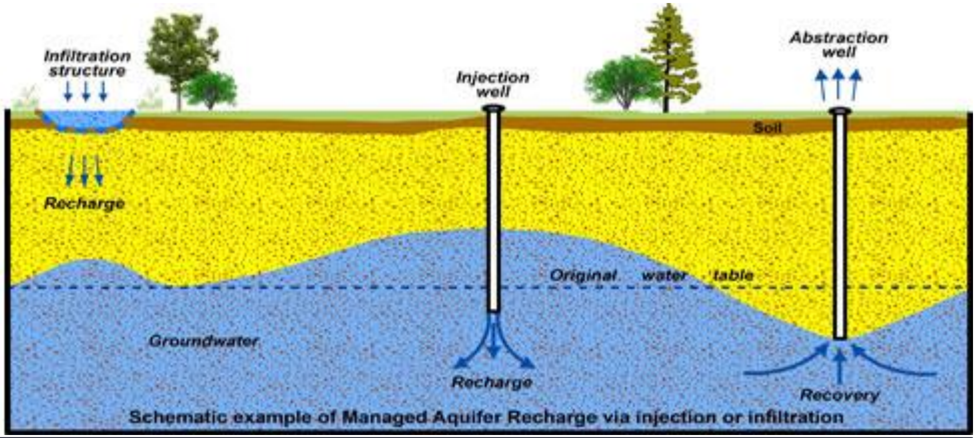
- A drainage basin
- A large amount of agricultural and industrial activity occurs in the basin area
- Surface water and groundwater now managed under a Commonwealth (federal) agency “Murray-Darling Basin Authority” (MDBA)
- MDBA is responsible, in part, for ensuring environmental flows in the rivers

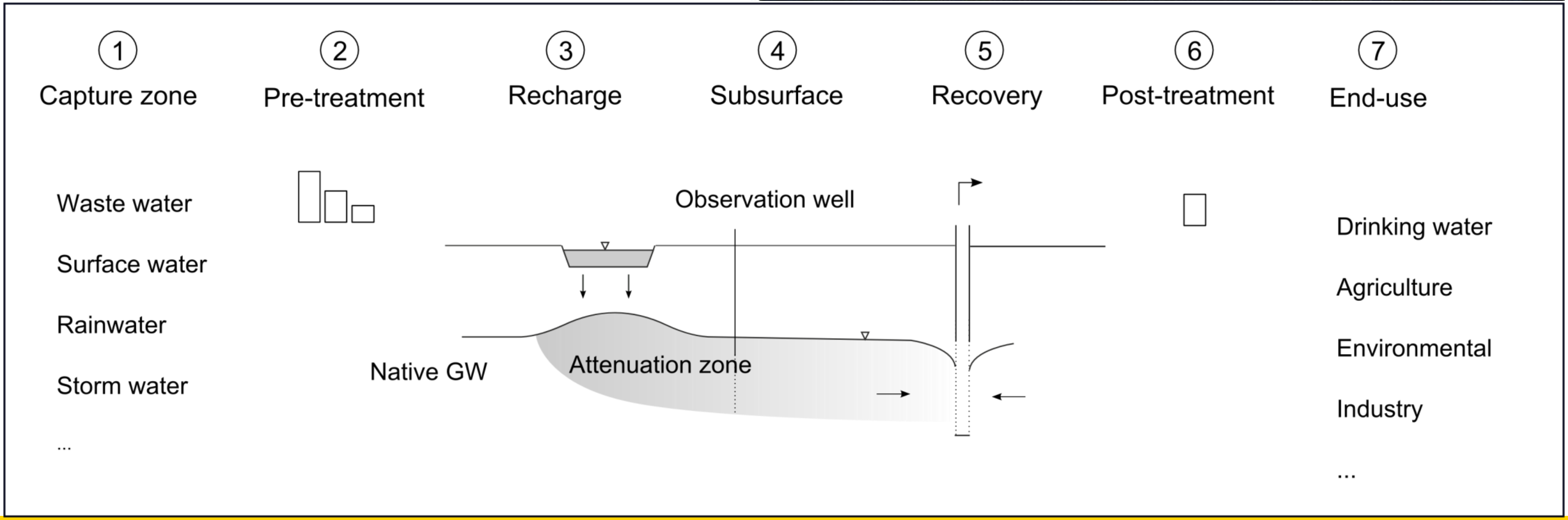


Managed Aquifer Recharge

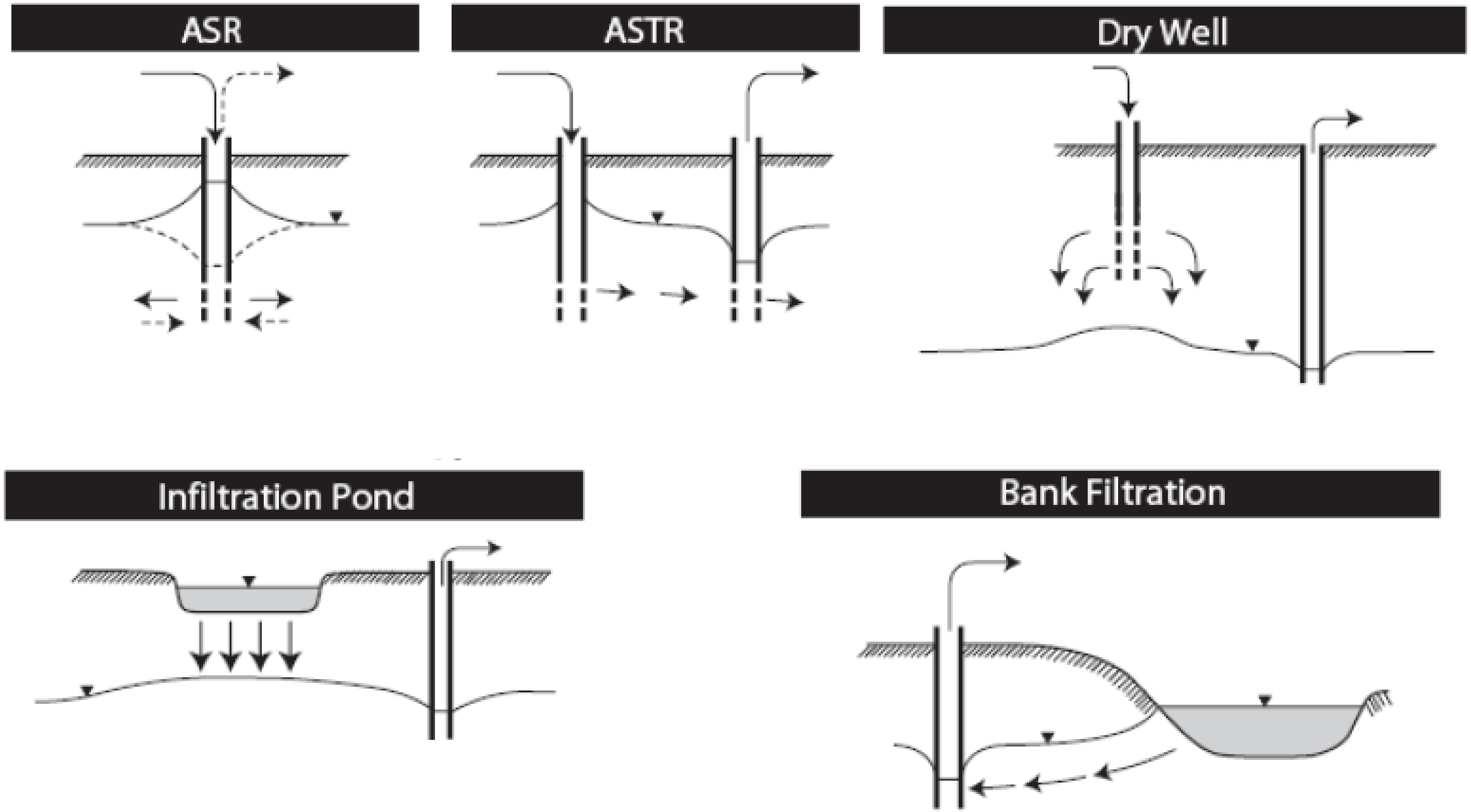
What is managed aquifer recharge (MAR)?

- MAR is the intentional replenishing of groundwater for future use using engineered structures and systems





Some types of MAR schemes



ASR = Aquifer Storage and Recovery. ASTR = Aquifer Storage, Transfer and Recovery

MAR advantages & disadvantages

+

- Improved security of water supply
- Potentially small surface footprint
- Natural water treatment
- Low-cost, low-energy
- Minimal evaporation loss, algae and mosquitoes
- Restoration of groundwater levels in aquifers
- Potential for mitigation of saltwater intrusion

−

- Local hydrogeological conditions need to be well understood
- Some water is “lost” to the aquifer
- Chemistry of input and output water must be monitored

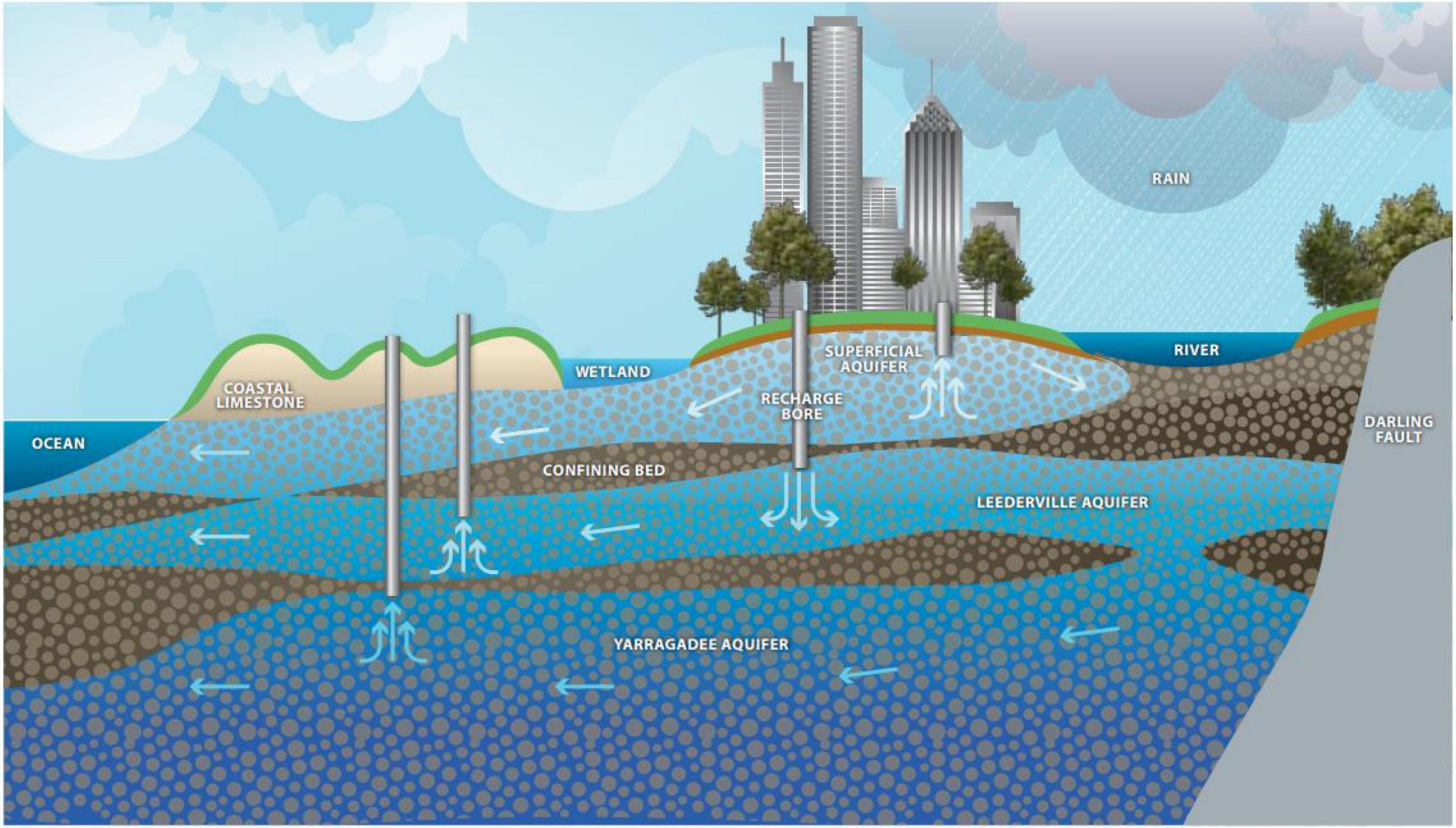
MAR schemes in Australia

Cost comparison

Storage type	Typical volumes (ML)	Approx. Cost per volume (THB/ML)	Land surface area required (m^2/ML)
Polyethylene rainwater tank	0.002 - 0.01	5,000,000	500
Concrete panel tank	4 – 8	6,600,000	250
Large concrete dam	350 - 200,000	100,000 – 250,000	100 – 200
Pond infiltration	200 - 600	25,000 – 50,000	20 – 60
Aquifer storage and recovery (ASR)	75 – 2000	100,000 – 250,000	1

Source: Dillon et al (2010)

MAR Example



RAIN
WETLAND
SUPERFICIAL AQUIFER
RIVER
COASTAL LIMESTONE
RECHARGE BORE
OCEAN
DARLING FAULT
CONFINING BED
LEEDERVILLE AQUIFER
YARRAGADEE AQUIFER

MAR steps to success: pre-commissioning

1. Identify stakeholders and enter into contact with relevant parties. This can include local and national government bodies, water associations, universities, industrial and residential users, and environmental authorities.
2. Assemble all existing data (hydrostratigraphy, aquifer hydraulic and mineral properties, borehole infrastructure, source water hydrochemistry, etc.).
3. Make initial assessment of data and identify any critical data gaps that need to be addressed in order to understand risks and to make a well-informed choice about the optimal location.

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MAR steps to success: pre-commissioning

4. Obtain the outstanding data needed to verify the feasibility of the pilot MAR scheme in a desktop study.
5. Identify and, where possible, quantify risks to MAR scheme viability, groundwater quality, aquifer integrity, surface water interactions, and other regional users of water resources. In particular, focus on hydrochemistry and aquifer properties. Assess potential source water quantity and quality and its variability over time.
6. Decide on location for the pilot MAR scheme and write risk mitigation and management plan including monitoring programme.

MAR steps to success: pre-commissioning

7. Estimate the potential maximum injection rate for the selected borehole(s) and determine ideal locations for monitoring piezometers.
8. Assess economic aspects including one-time costs (infrastructure, data collection, etc.) and running costs (pumps, maintenance, etc.)
9. Assemble a plan for the construction and installation of infrastructure (pipes, pumps, boreholes, pressure transducers, monitoring piezometers, monitoring infrastructure, etc.).
10. Acquire, or verify the possibility of acquiring, all necessary permits for construction and operation of the pilot MAR scheme.

MAR steps to success: post-commissioning

11. Enter into trial operation phase, initially at low rates of inflow. Ensure that all aspects of system are functioning correctly, including the monitoring infrastructure.

12. Analyse the operational and monitoring data from the initial trial period. Use this data to re-evaluate feasibility, risks and operation parameters.

13. Make recommendations for a further modifications and expansion of MAR scheme based on data obtained during the pilot study.

Groundwater Governance Issues

Courtesy of Dr. Cameron Holley (c.holley@unsw.edu.au)

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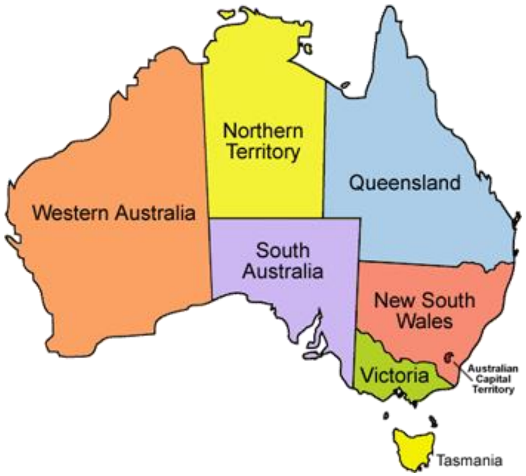
Water regulation history in Australia



- Common Law (laissez faire)

  pre 1880

- State Regulation (e.g. construction)

  most of 1900s

- National Framework (water rights/markets)

  1994 onwards

National water policy

- ***National Framework for Improved Groundwater Management 1996***
  - development of a nationally consistent definition of Environmentally Sustainable Development and approach to drilling, through the adoption of the National Drillers Licensing system
  - development of comprehensive plans for groundwater
  - identify sustainable yield allocation and use of aquifers
  - manage groundwater by same principles as surface water and improve integration of surface and groundwater
  - eliminate conflict of interest situations in GW assessment & management
  - education: increasing public awareness of the value & vulnerability of GW
  - improve well design and construction
  - market agenda: establish systems to support transferability of allocations
  - identify the costs of GW management for State and Federal Governments

National water policy

- 2005 Australian water resources assessment
  - GW use as a proportion of total national water use >30% in 2004-05
- National Groundwater Action Plan 2007
  - the National Groundwater Assessment Initiative
  - National Centre for Groundwater Research and Training
  - knowledge and capacity building
- 2007 Biennial Assessment of Progress against the NWI
  - considerable concern about the management of groundwater, including need to address over-allocation, failure to manage groundwater and surface water as a connected resource, lack of established measurement standards, and inadequate metering and monitoring
- NWC Statement on Groundwater 2008
  - More monitoring and licensing needed
- NWC disbanded (2015)

National plans for water security

- Efficient water use and improved environmental outcomes across the Murray Darling Basin
- Modernisation of Australia's irrigation infrastructure
- Nationwide programme to improve on-farm irrigation technology and metering
- Expanding the role of the Bureau of Meteorology to provide water data for better decision-making
- Completing the restoration of the Great Artesian Basin (bore capping and piping).

Groundwater and mining

- Growing concern over impacts of coal and other unconventional sources of extraction, especially Coal Seam Gas mining, on groundwater
- National reforms, including the NWI, had not evolved to integrate mining and uses such as unconventional gas within a single management framework (NWC 2014)
- 2013 'Water Trigger' amendment
  - CSG and large coal mining developments now require federal assessment and approval if they are likely to have a significant impact on water resources
  - Independent Expert Scientific Committee on CSG and Large Coal Mining Development provides scientific advice to decision makers (NWC 2014)

National Water Commission 2014, *Water for Mining and Unconventional Gas under the National Water Initiative*, NWC, Canberra

Groundwater and mining

- Despite the 'water trigger', improved regulation & better communication, numerous challenges remain:
  - developing a coordinated jurisdictional approach to improve understanding of potential water impacts
  - linking water planning more effectively with project approval processes
  - enabling accurate accounting of water takes and rules
  - implementing adaptive management measures that are conditioned on operational approvals
  - managing the cumulative environmental effects of mining operations

(EDO NSW, 2012; Baker and McKenzie, 2014)

Groundwater trading

- Around 49% by number and 21% by volume of entitlements on issue in Australia are groundwater entitlements (NSW, Qld, WA highest in volume)
- Groundwater trading has evolved significantly
- About 4% of the total entitlements on issue in 2012–13 were traded (NWC 2014)
- Trading of groundwater entitlements is relatively limited in most jurisdictions, accounting for around 12% of total entitlement trading.
- Groundwater allocation trading (NSW and Vic) makes up around 1% of total allocation trading (NWC 2014).
- Trading is restricted to within individual aquifers due to the lack of hydrological connectivity between systems and lack of physical infrastructure to link groundwater areas

Table 2.10: Groundwater allocation trading, Australia, 2012–13

Jurisdiction	Qld	NSW	Vic.	SA	WAa	NT	Tas.	ACT	AUST.
Number	0	233	213	104	55	0	0	0	605
Volume (ML)	0	62 243	18 488	7 764	10 620	0	0	0	99 115

a Western Australian allocation trades are leases.

http://www.nwc.gov.au/publications/topic/water-industry/trends-and-drivers-2012-13/section-2

http://www.globalwaterintel.com/archive/12/12/general/aussie-water-rights-trading-down-50.html

Organic Contaminants in Groundwater

Courtesy of Dr. Will Glamore (w.glamore@wrl.unsw.edu.au)

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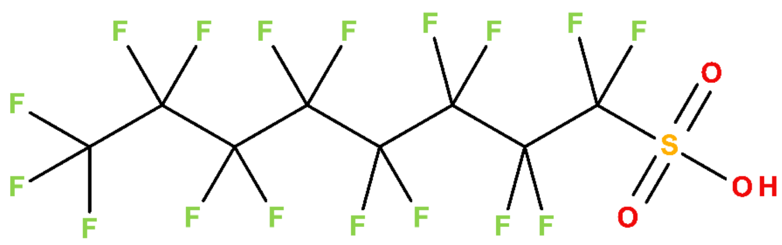
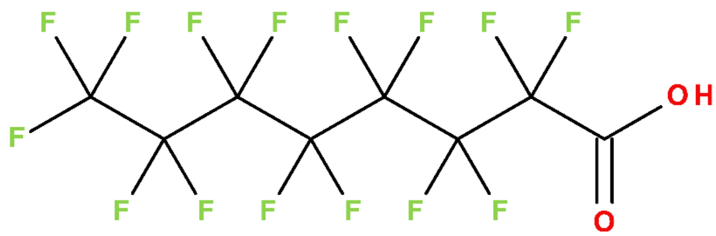
PFAS Compounds

- Per- and Poly-Fluorinated Alkyl Substances (aka PFAS: perfluorinated compounds)



Perfluorooctane sulfonic acid (PFOS)



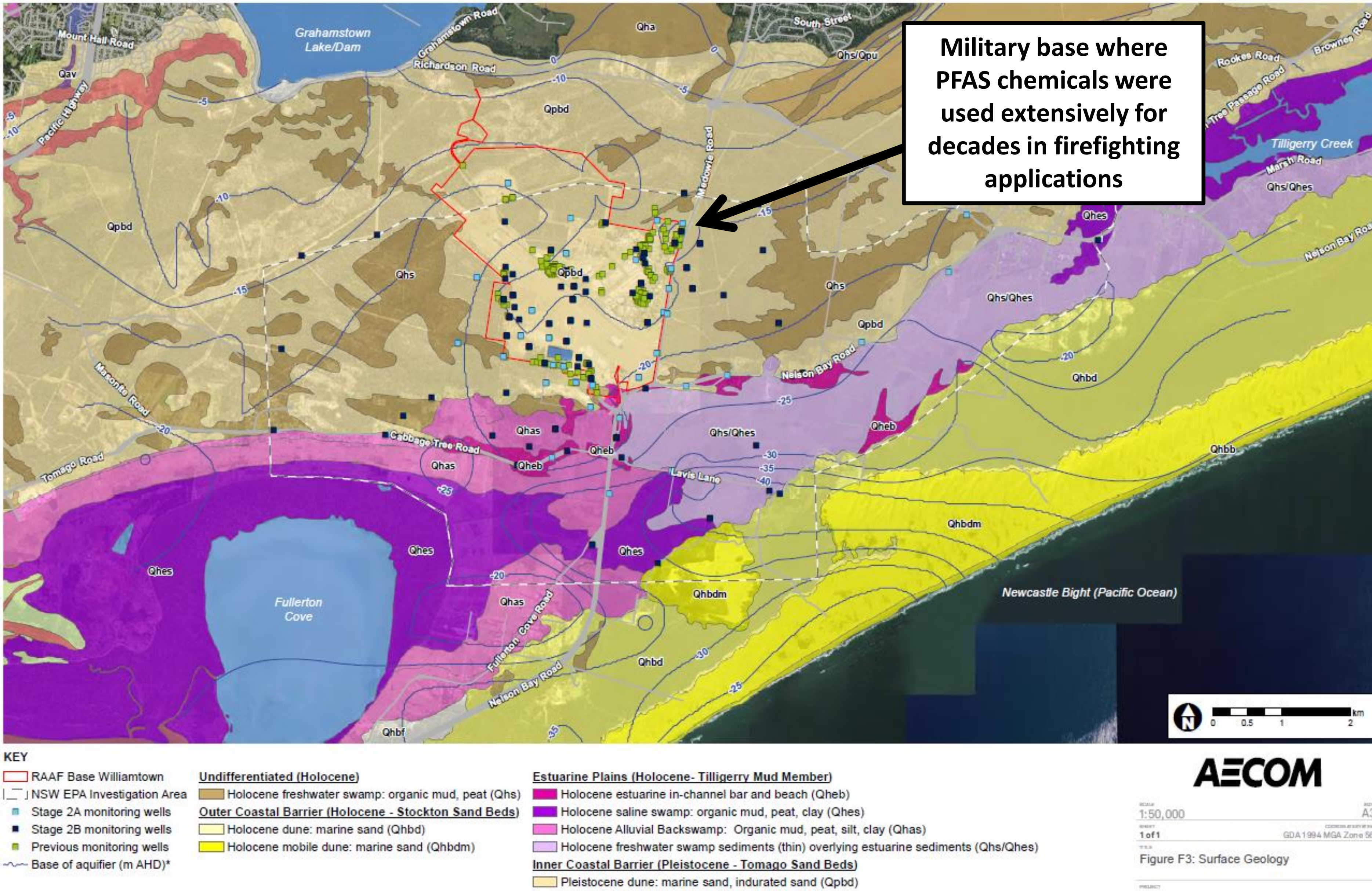
Perfluorooctanoic acid (PFOA)

- Highly soluble, “extremely” persistent
- **Risk:** Ingestion & inhalation >> contact
- C8 PFAS/PFCs banned or phased out

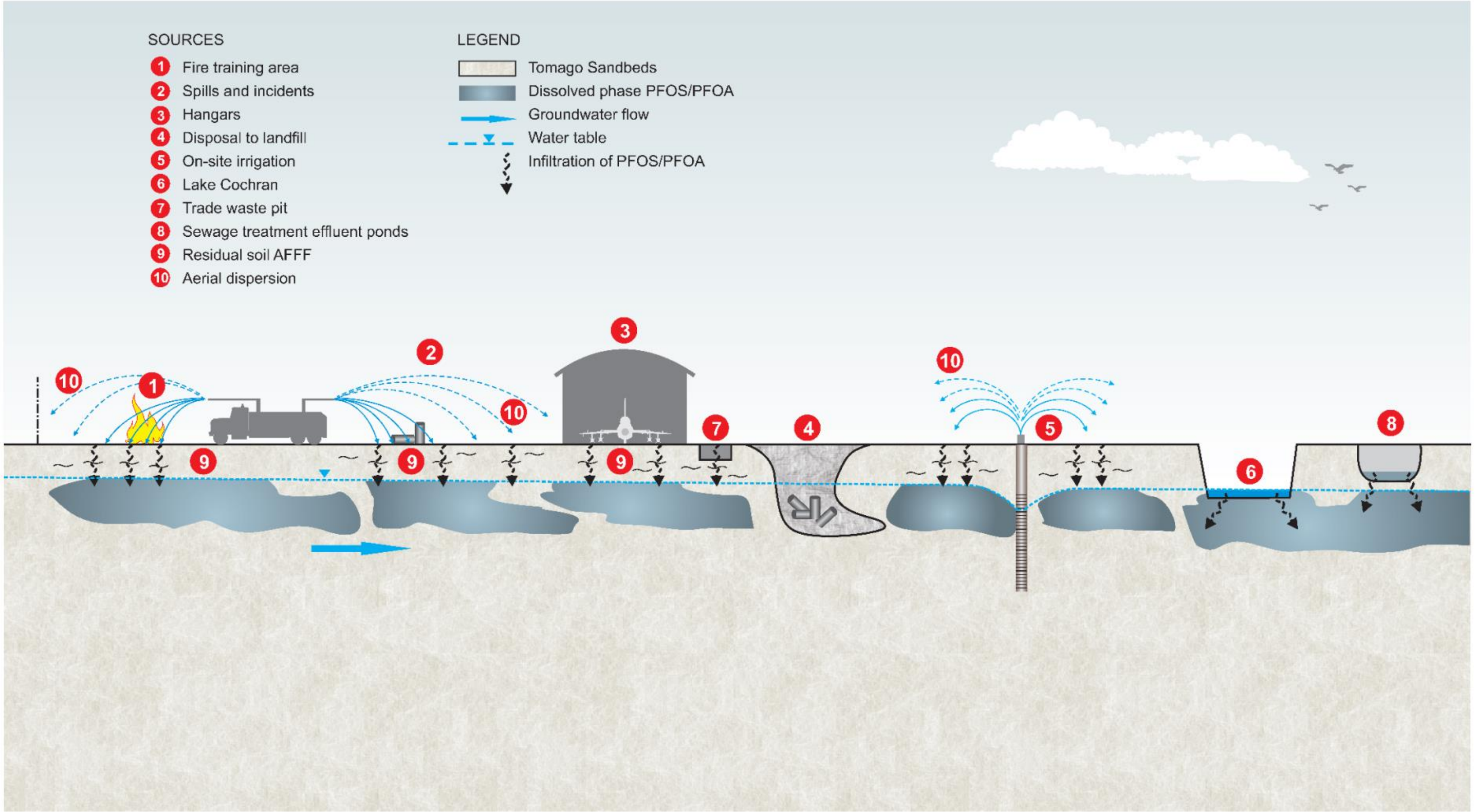
PFAS History

- 1949: 3M began producing PFOS-based compounds by electrochemical fluorination resulting in the synthetic precursor perfluorooctane sulfonyl fluoride.
- 1968: organofluorine content was detected in the blood serum of consumers
- 1976: it was suggested to be PFOA or a related compound such as PFOS
- 1997: 3M detected PFOS in blood from global blood banks
- 1999: the U.S. Environmental Protection Agency began investigating perfluorinated compounds after receiving data on the global distribution and toxicity of PFOS, the key ingredient in Scotchgard.
- 2000: the phase out of the production of PFOS, PFOA, and PFOS-related products. PFOS and PFOS-related chemicals are still currently produced in China.

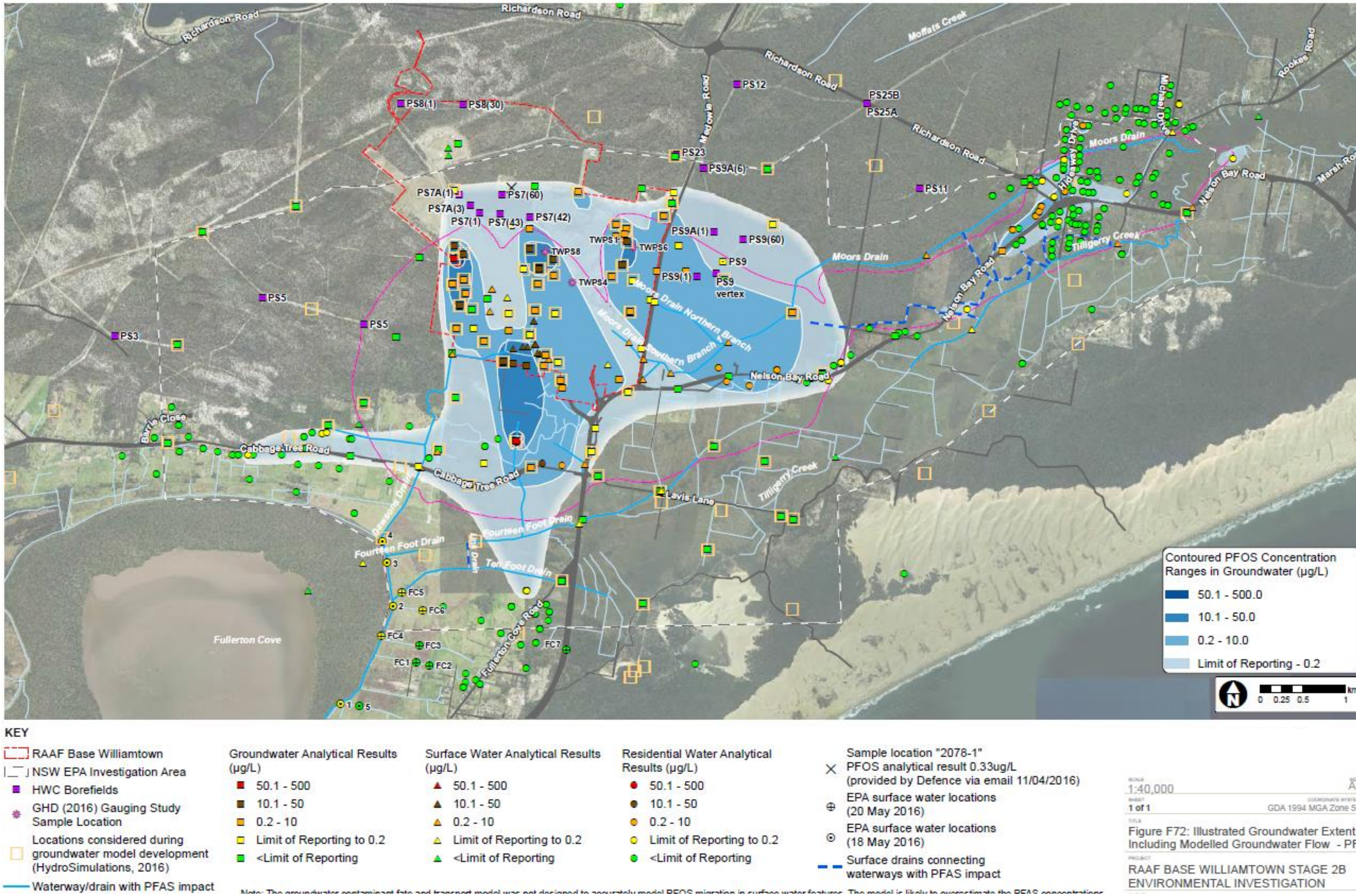
Williamtown

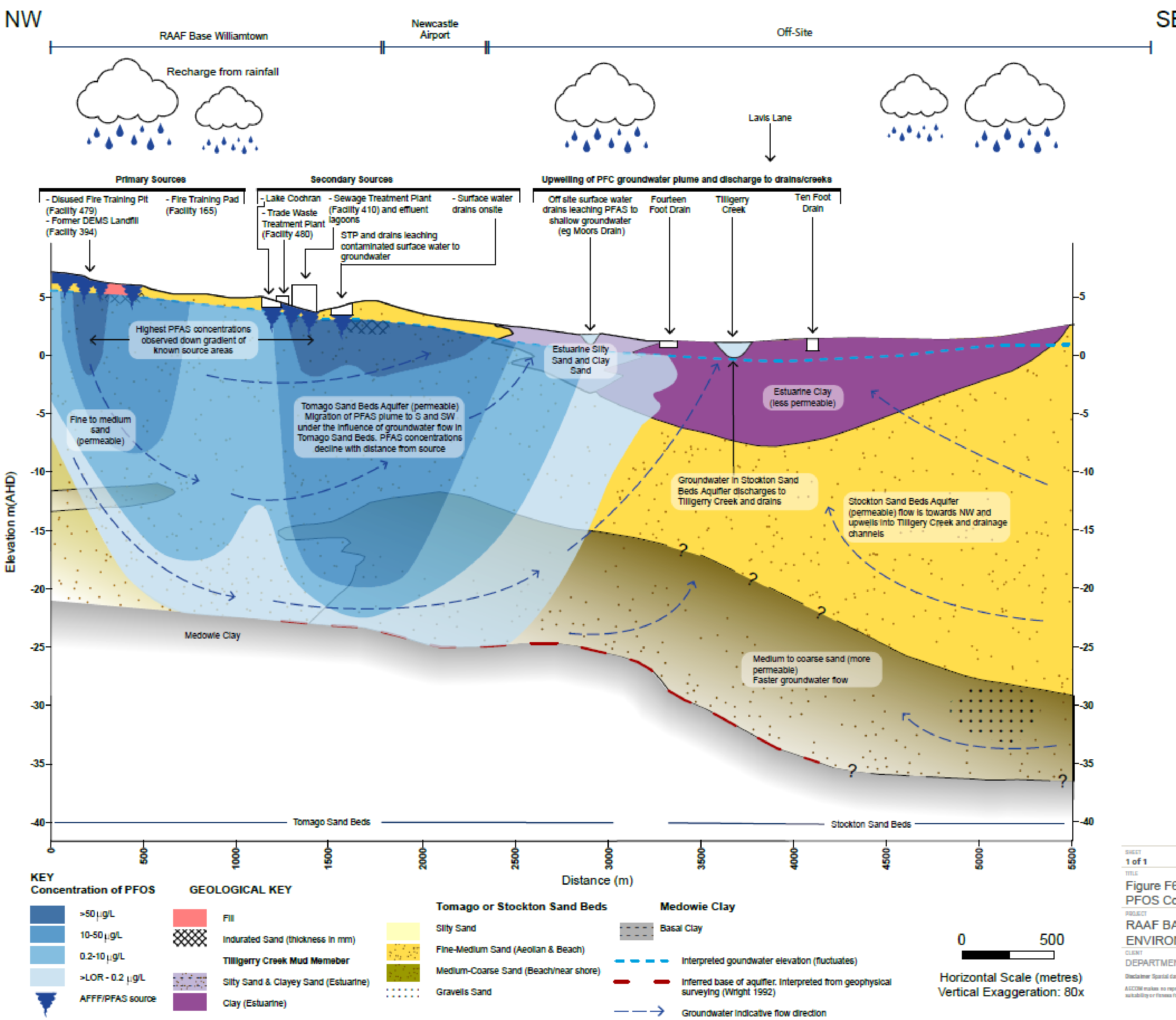


Potential contaminant transport pathways



Contaminant plume measurements and mapping





SHEET
1 of 1

TITLE
Figure F65: Conceptual Site Model: PFOS Concentration and Groundwater Flo

PROJECT
RAAF BASE WILLIAMTOWN STAGE 2B ENVIRONMENTAL INVESTIGATION

CLIENT
DEPARTMENT OF DEFENCE

Recommendations and ongoing steps

- Human Health Risk Assessment
- Ecological Risk Assessment
- Remediation Planning
    - Containment vs. Remediation
    - Acquisition vs. Compensation
    - Impacts on Wetland, Fisheries, etc.
- State-wide approach

Example of wetland remediation: Big Swamp, Manning River

Surface Water – Groundwater Interactions

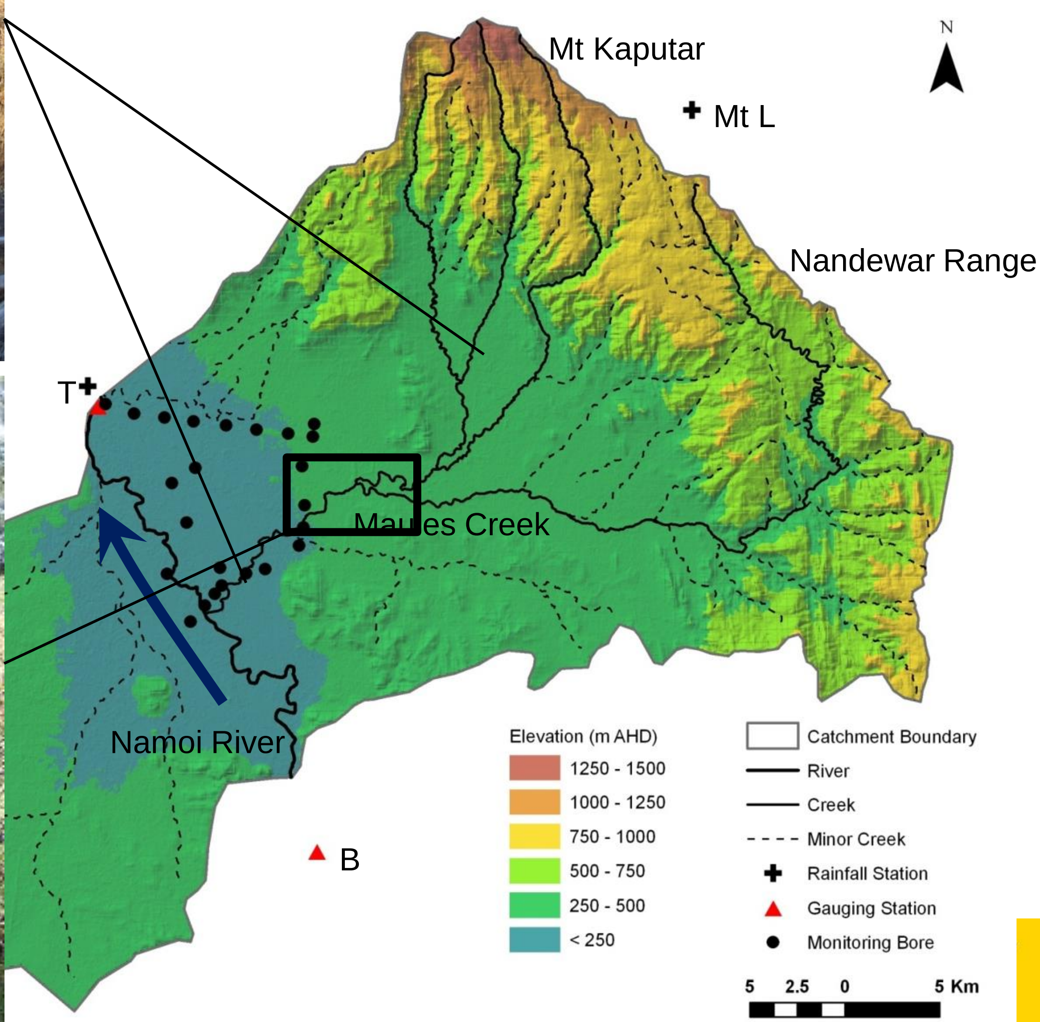
Some slides courtesy of Dr. Martin Andersen (m.andersen@unsw.edu.au)

Surface water – groundwater interactions

- Effective groundwater management means understanding and measuring the effects that water use has on the interaction between surface water (rivers, lakes, etc.) and groundwater
- The nature of surface water – groundwater (SW-GW) interactions plays a vital role in water quality and availability, as well as ecological health
- Some previously gaining sections of rivers are becoming losing due to factors including climate change, industrial (mining) water use, and agricultural water use
- Many geophysical, geochemical, and ecological tools are at now our disposal for understanding the effects of changes to SW-GW flow behaviour

Elfin Crossing Experimental Site

An excellent SW-GW laboratory

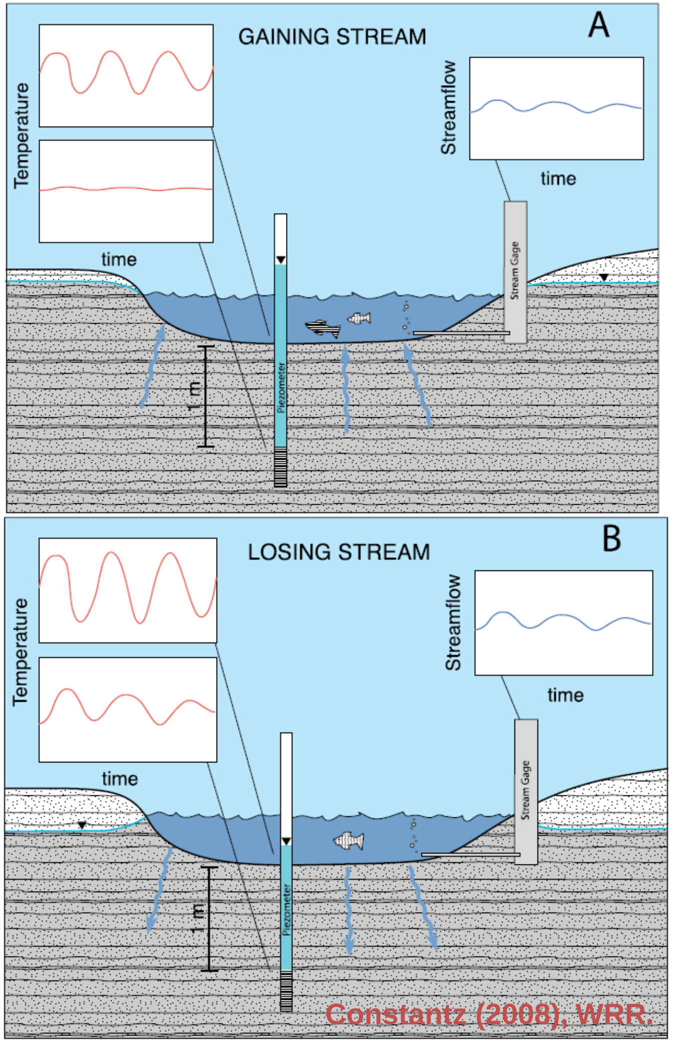


A geophysical tool: Fibre-optic distributed temperature sensing (DTS)

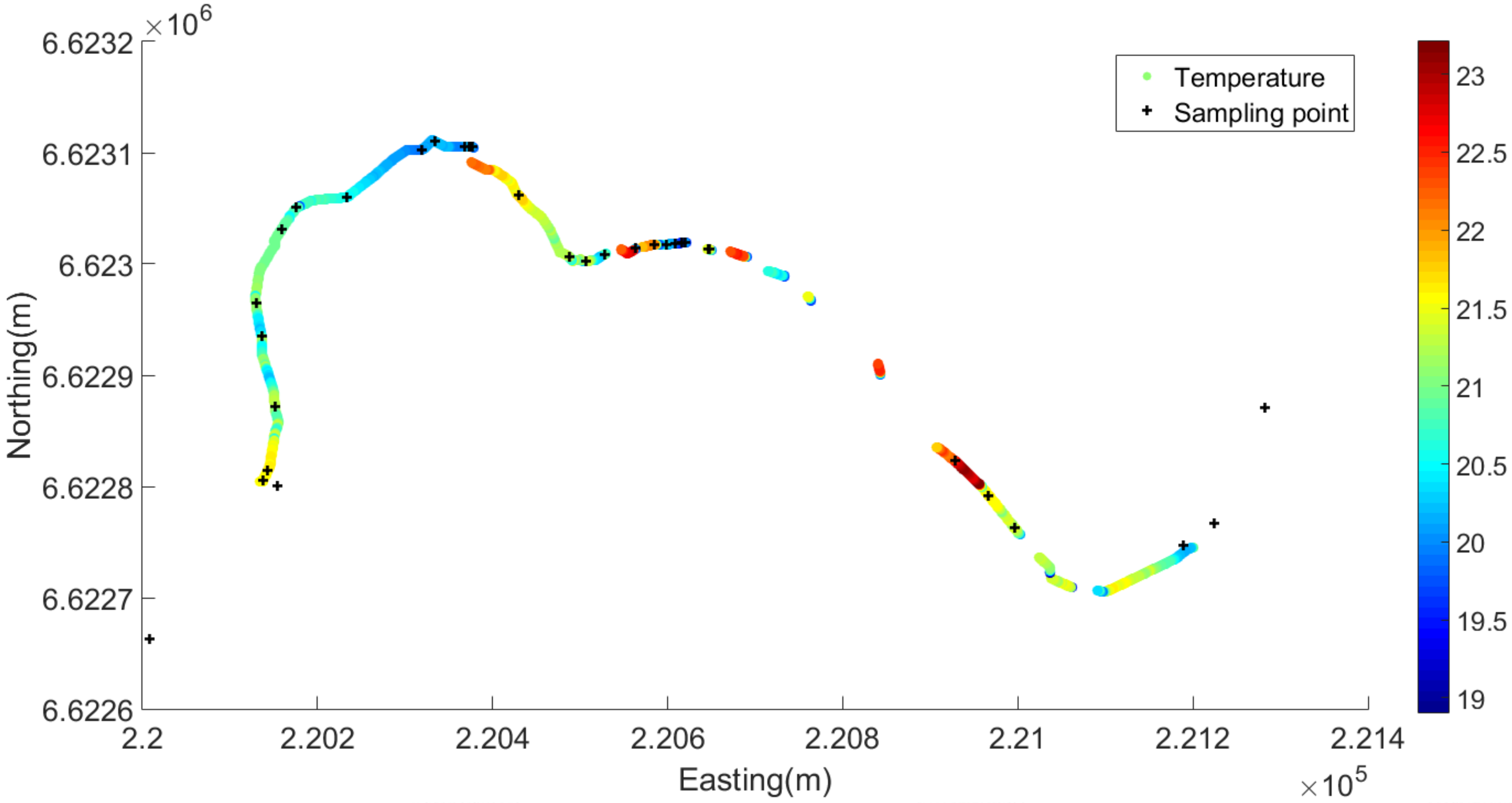
- DTS makes use of the fact that the energy levels of photons travelling in a fibre is affected by temperature
- Lengths of fibre up to several kilometres long can be used to measure temperature at intervals of ~1 m or ~1 cm in a coiled configuration

SW-GW exchange affects temperature

- The diurnal and yearly heating cycles provide drivers for temporal changes in subsurface temperature
- Penetration depths of temperature signals depend on many factors including instrumentation and hydrological conditions: ~2 meters (diurnal) & ~15 meters (annual)
- Gaining conditions (net GW → SW flow) increase signal dampening
- Losing conditions (net SW → GW flow) decrease signal dampening



Temperature as a qualitative tool



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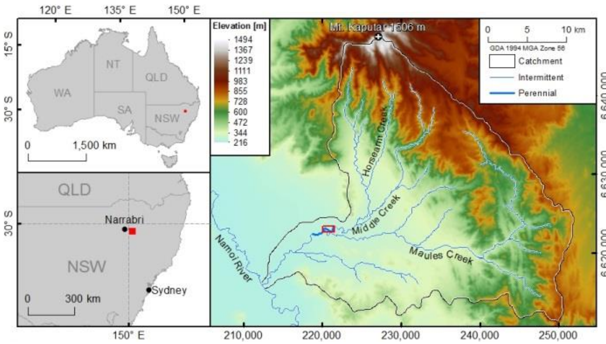
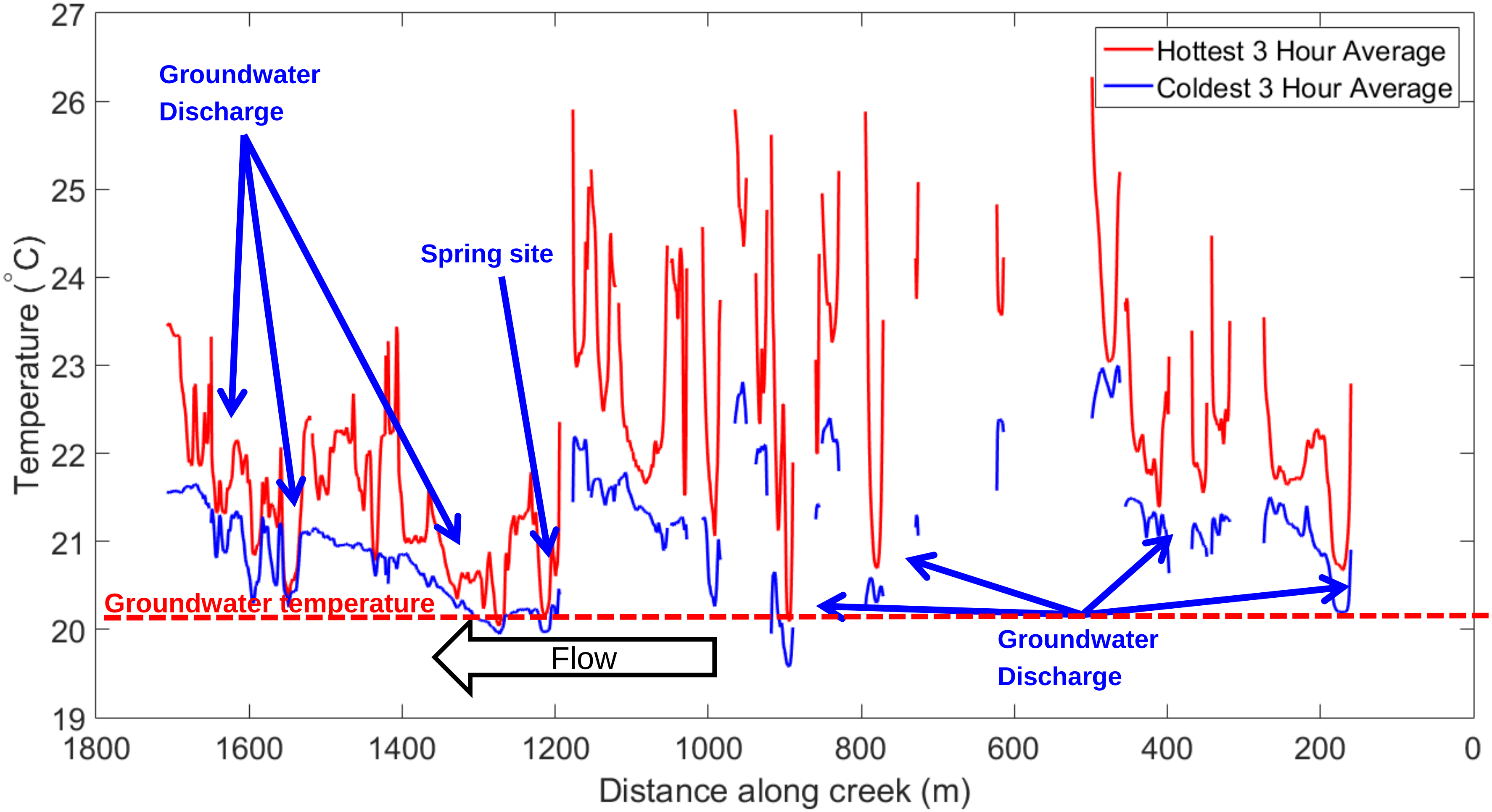
Temperature as a qualitative tool





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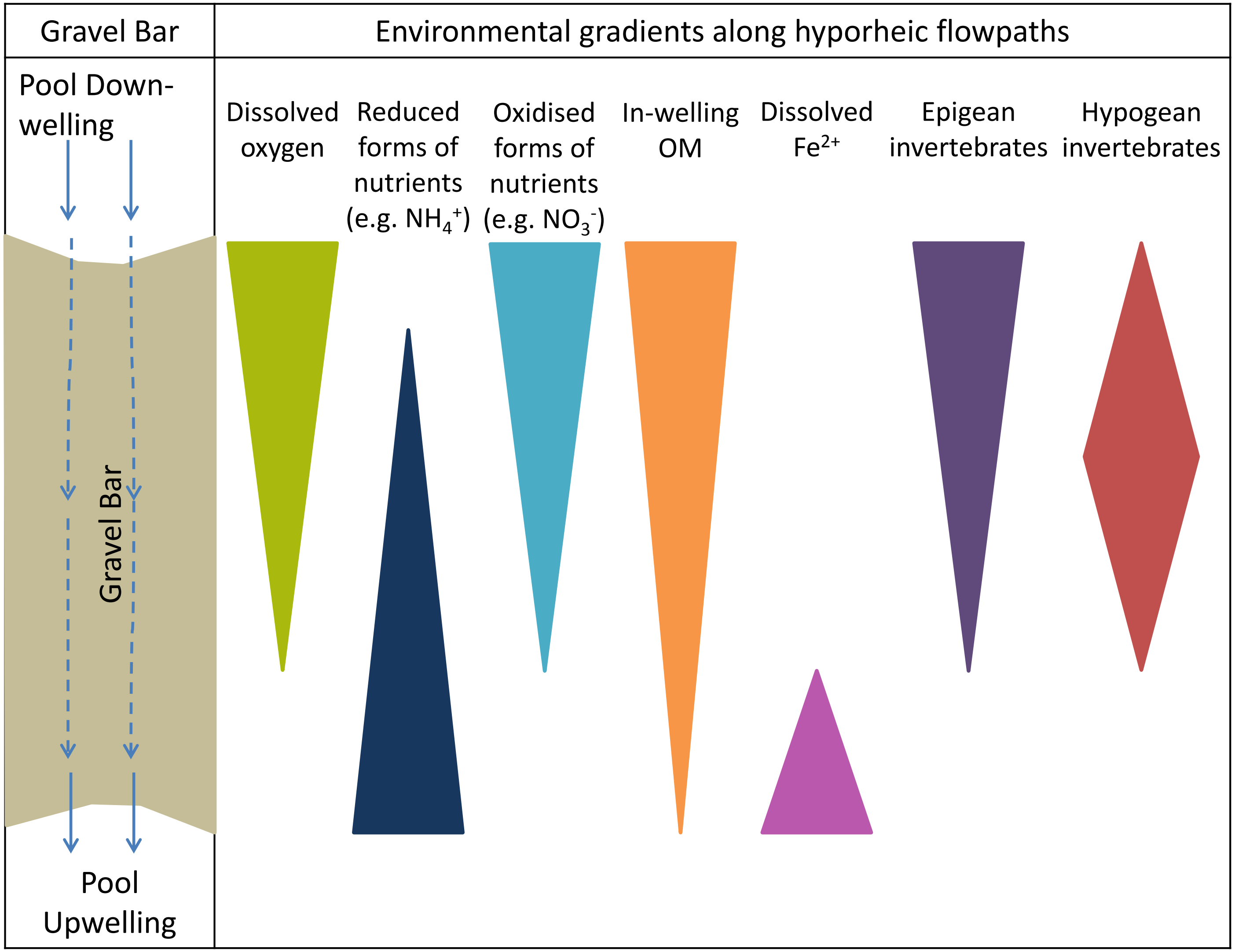
Chemical and Ecological Gradients



Streambed Ecology

- Stygofauna abundance and community structure linked to redox-conditions
- Water quality linked to flow direction (recharge or discharge)
- Stygofauna abundance and community linked to changed flow paths

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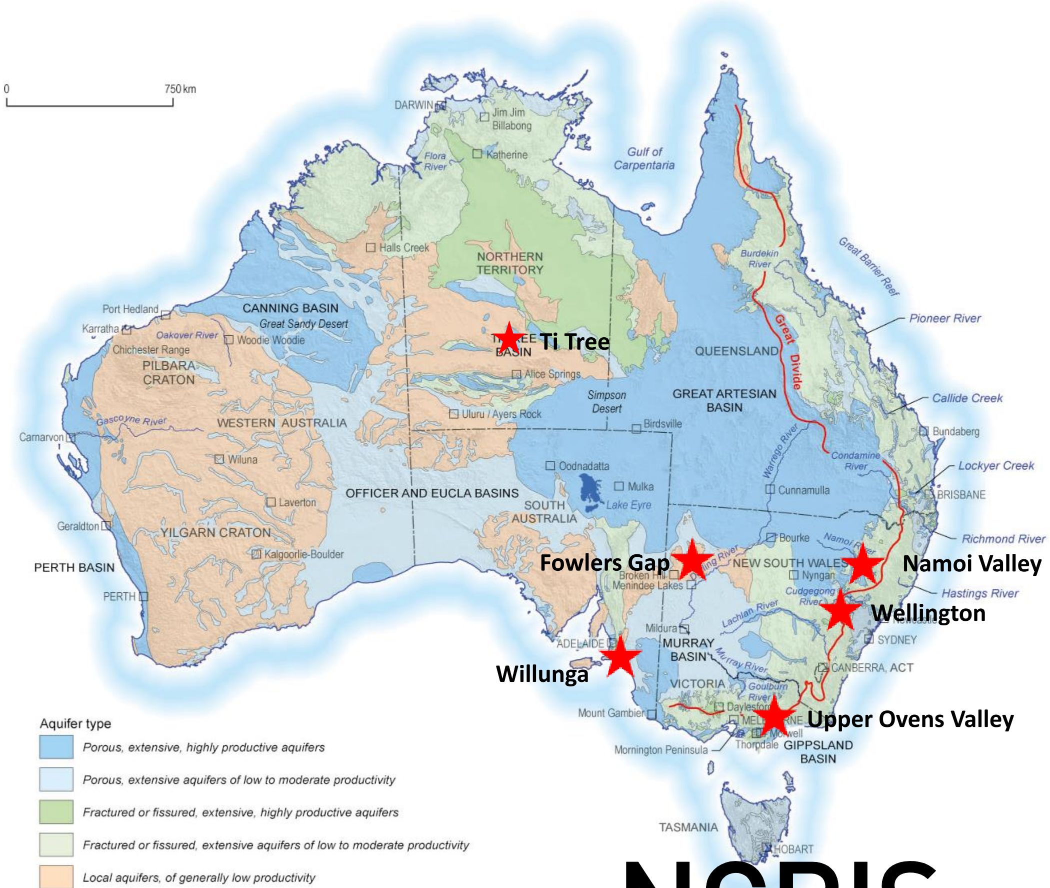
NCRIS Groundwater Infrastructure

- Effective water management relies on an understanding of the interactions between surface water and groundwater
- As drilling is expensive, a better understanding of the nature of impacts of increased demands on water resources can be gained by using physical, chemical, and ecological tracers



NCRIS
National Research Infrastructure for Australia
An Australian Government Initiative

- http://www.connectedwaters.unsw.edu.au/ncris
- http://groundwater.anu.edu.au/

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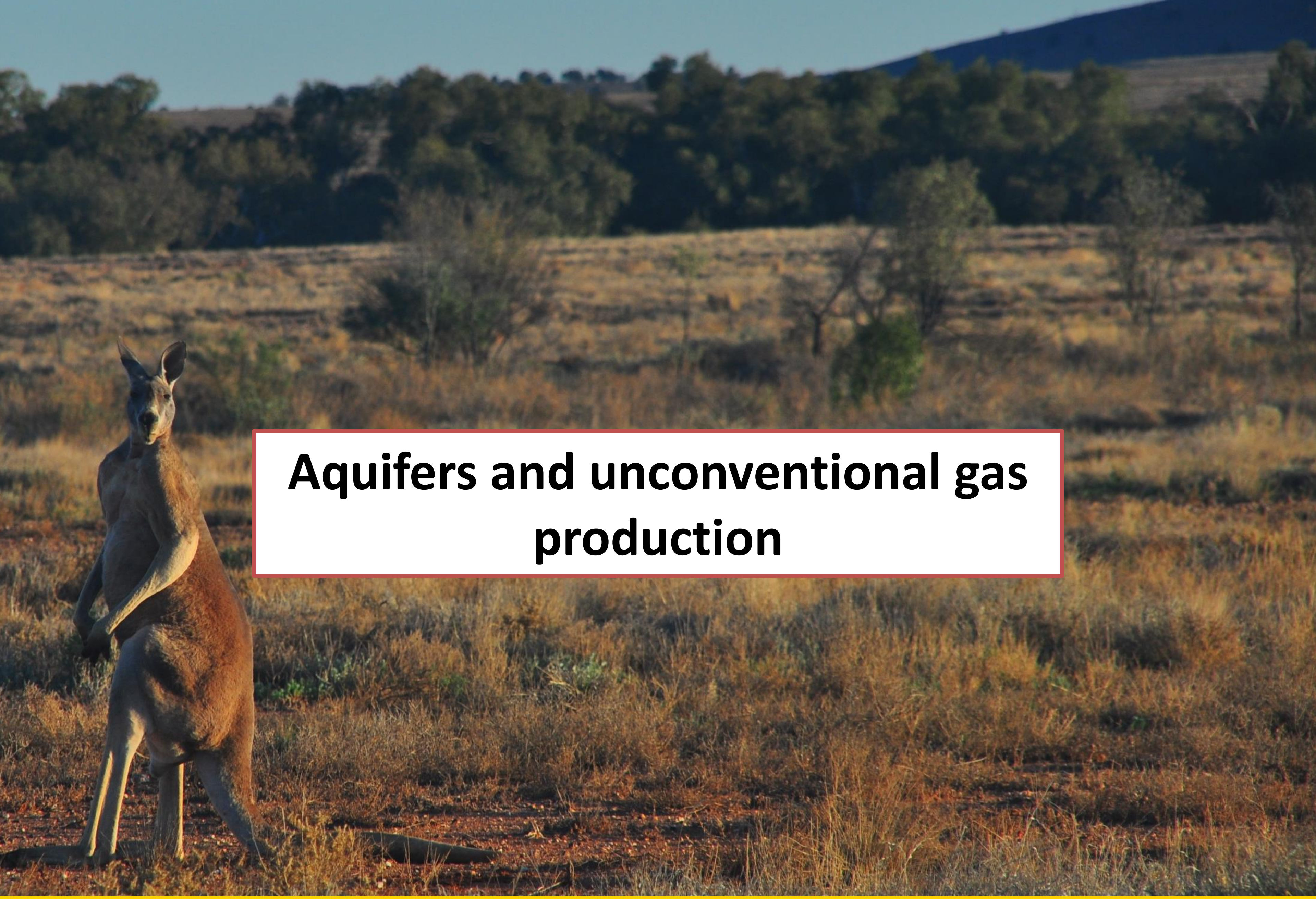

Aquifers and unconventional gas production

Some slides courtesy of Dr. Bryce Kelly (bryce.kelly@unsw.edu.au)

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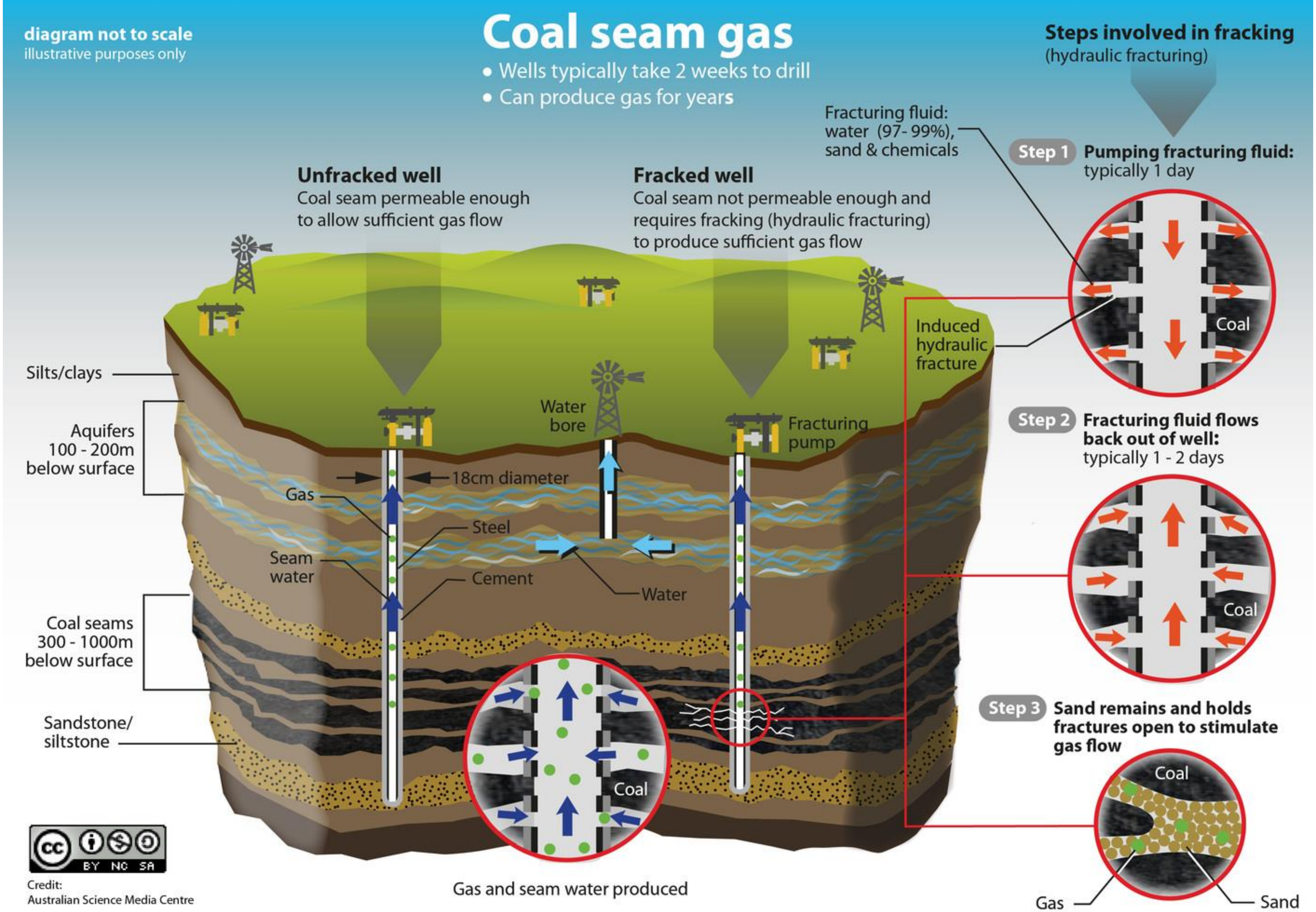

diagram not to scale
illustrative purposes only
Coal seam gas
• Wells typically take 2 weeks to drill
• Can produce gas for years
Steps involved in fracking (hydraulic fracturing)
Fracturing fluid: water (97- 99%), sand & chemicals
Step 1 Pumping fracturing fluid: typically 1 day
Unfracked well
Coal seam permeable enough to allow sufficient gas flow
Fracked well
Coal seam not permeable enough and requires fracking (hydraulic fracturing) to produce sufficient gas flow
Induced hydraulic fracture
Coal
Silts/clays
Aquifers 100 - 200m below surface
Water bore
Fracturing pump
Step 2 Fracturing fluid flows back out of well: typically 1 - 2 days
18cm diameter
Gas
Steel
Seam water
Cement
Water
Coal seams 300 - 1000m below surface
Step 3 Sand remains and holds fractures open to stimulate gas flow
Sandstone/ siltstone
Coal
Gas
Sand
Gas and seam water produced
Credit:
Australian Science Media Centre
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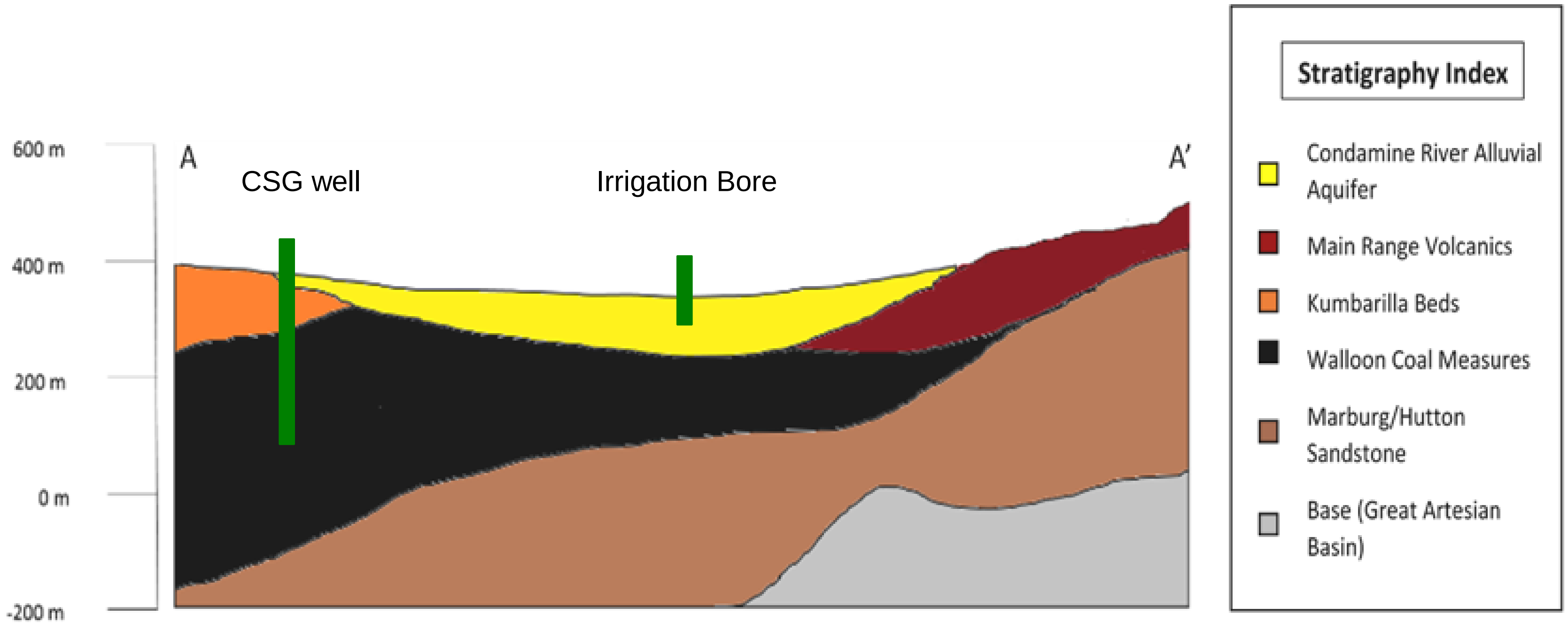
Groundwater management concerns

Geological Context:
Surat Basin / Condamine Catchment



Isotopes of Methane

- Methane is a compound consisting of one carbon atom bonded with four hydrogen atoms (CH_4).

- Carbon within CH_4 exists as one of two stable isotopes – ^{12}C or ^{13}C.

Mass Number
Atomic Number C

6 protons and 6 neutrons $^{12}_{6}C$

6 protons and 7 neutrons $^{13}_{6}C$

- ^{12}C stable (98.89 %)
- ^{13}C stable (1.11%)
- ^{14}C decays radioactively (10^{-10} %)

Different Sources and Sinks:
Different $\delta^{13}C$ Values

- Some of the major sources of methane are wetlands, bacteria in saturated soils (methanogens), ruminants, coal, landfill, and urban gas leaks.

- Southern Ocean air $\delta^{13}C = -47$ ‰

- Bacteria in the saturated zone produce methane. Common wetland readings for $\delta^{13}C$ are in the range -60 to -80 ‰.

- Gas from Walloon Coal Measures -45 to -58 ‰

Isotopic signatures

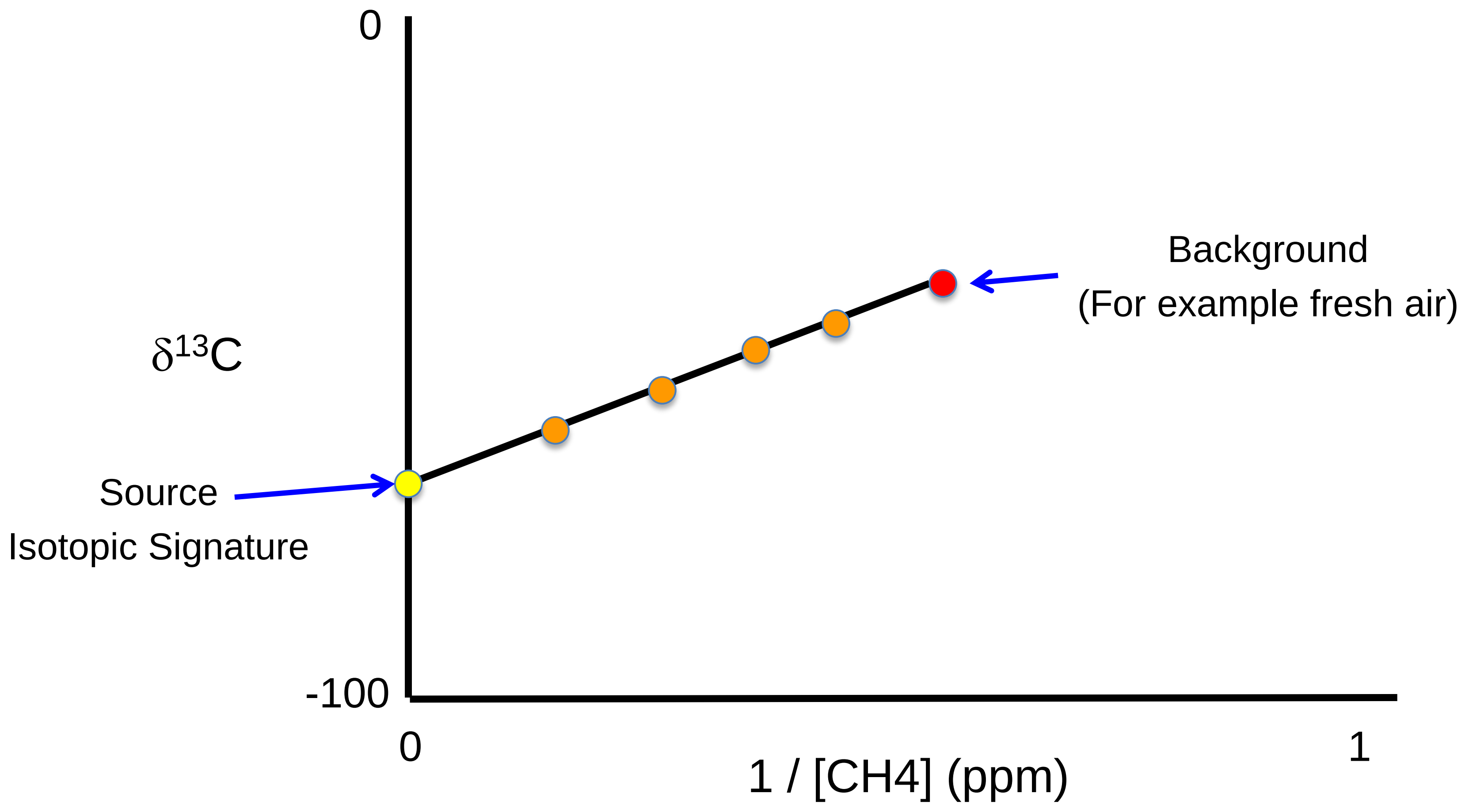
The ratio of ^{13}C to ^{12}C in methane ($\delta^{13}C\text{-}CH_4$) has the potential to act as a source signature.

Air sample   Background air   Point source

$$\delta^{13}C\text{-}CH_{4\,(a)} = [CH_{4\,(b)}]\,(\delta^{13}C\text{-}CH_{4\,(b)} - \delta^{13}C\text{-}CH_{4\,(s)})\,(1/[CH_{4\,(a)}]) + \delta^{13}C\text{-}CH_{4\,(s)}$$

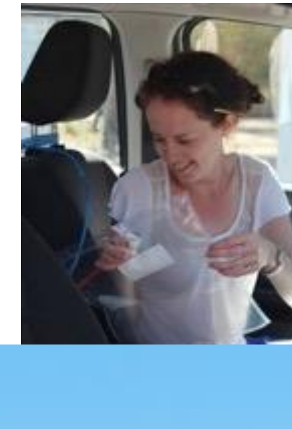
$\delta^{13}C\text{-}CH_4$ is reported versus the Vienna Pee Dee Belemnite scale for carbon.

Isotope Mixing Plots

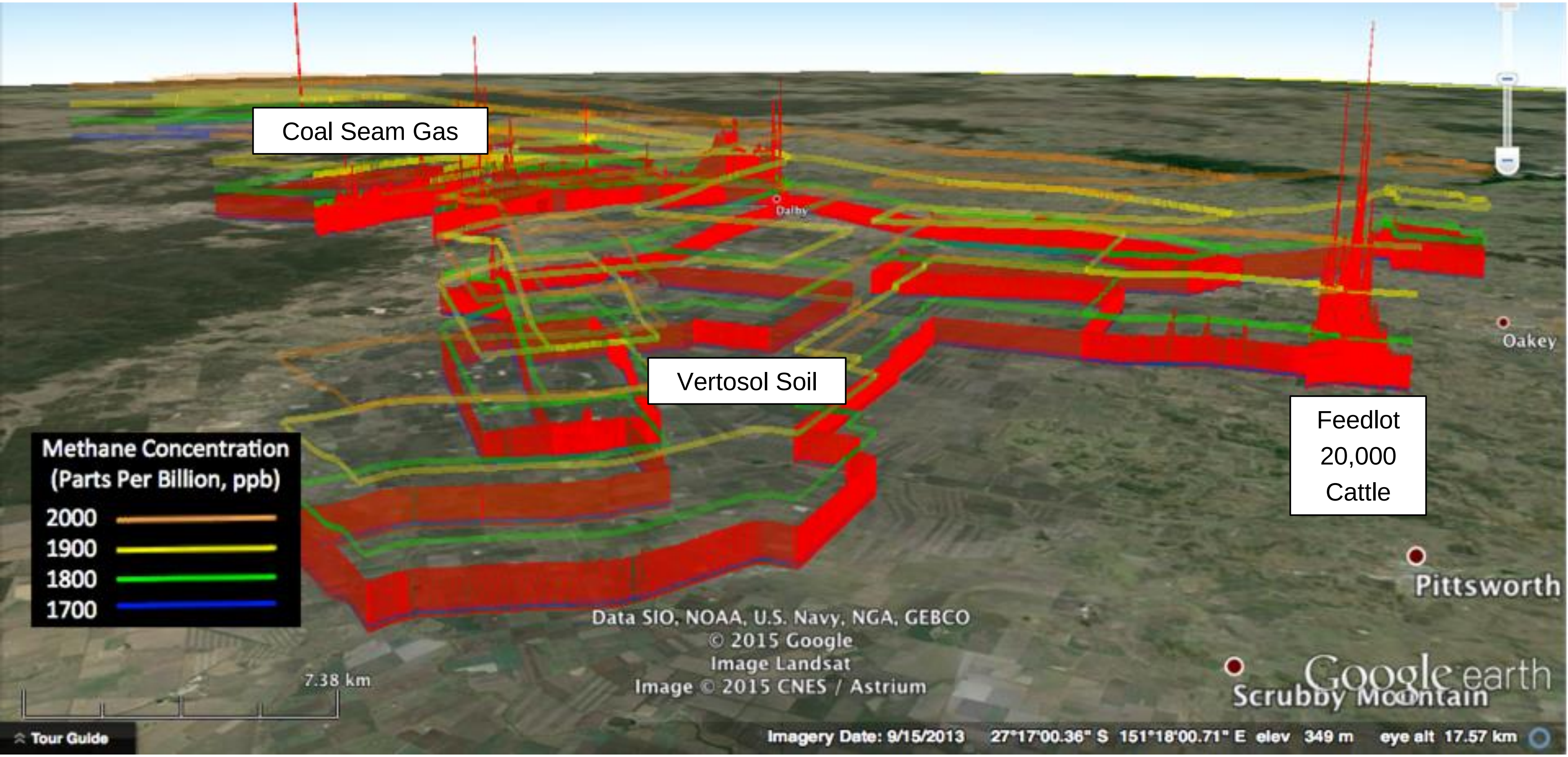


Mobile Methane Surveying

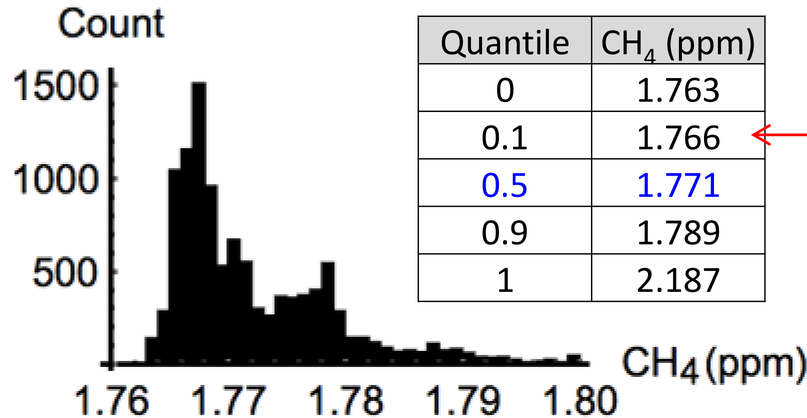
- A simple, rapid method to detect effects on groundwater from unconventional gas
- Methane measurement equipment deployed in a utility vehicle with an air inlet above the roof.
- Measurements were made every 5 seconds to a precision of <0.5 ppb for CH_4.



Surat Basin and Adjacent Condamine Catchment

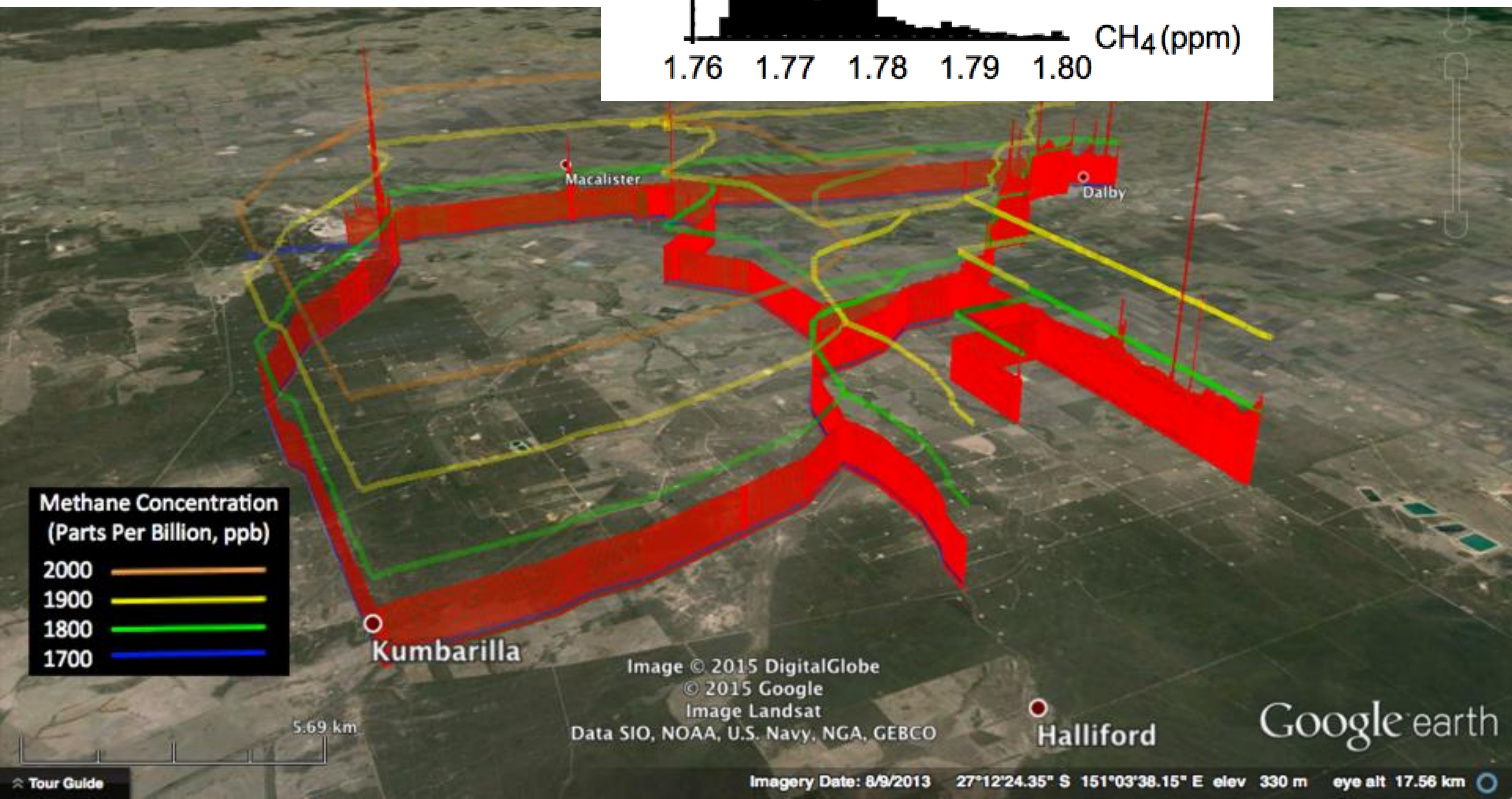


Coal Seam Gas Production: Surat Basin, Qld

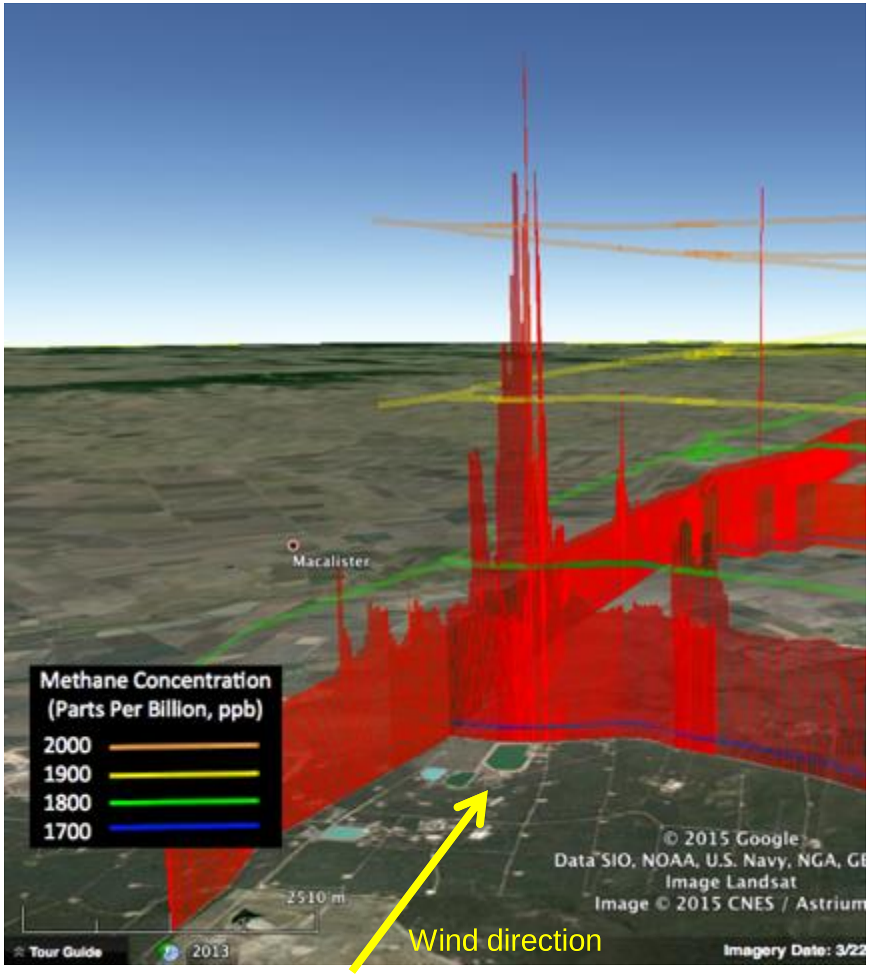


Quantile	CH_4 (ppm)
0	1.763
0.1	1.766
0.5	1.771
0.9	1.789
1	2.187

Dryland Median



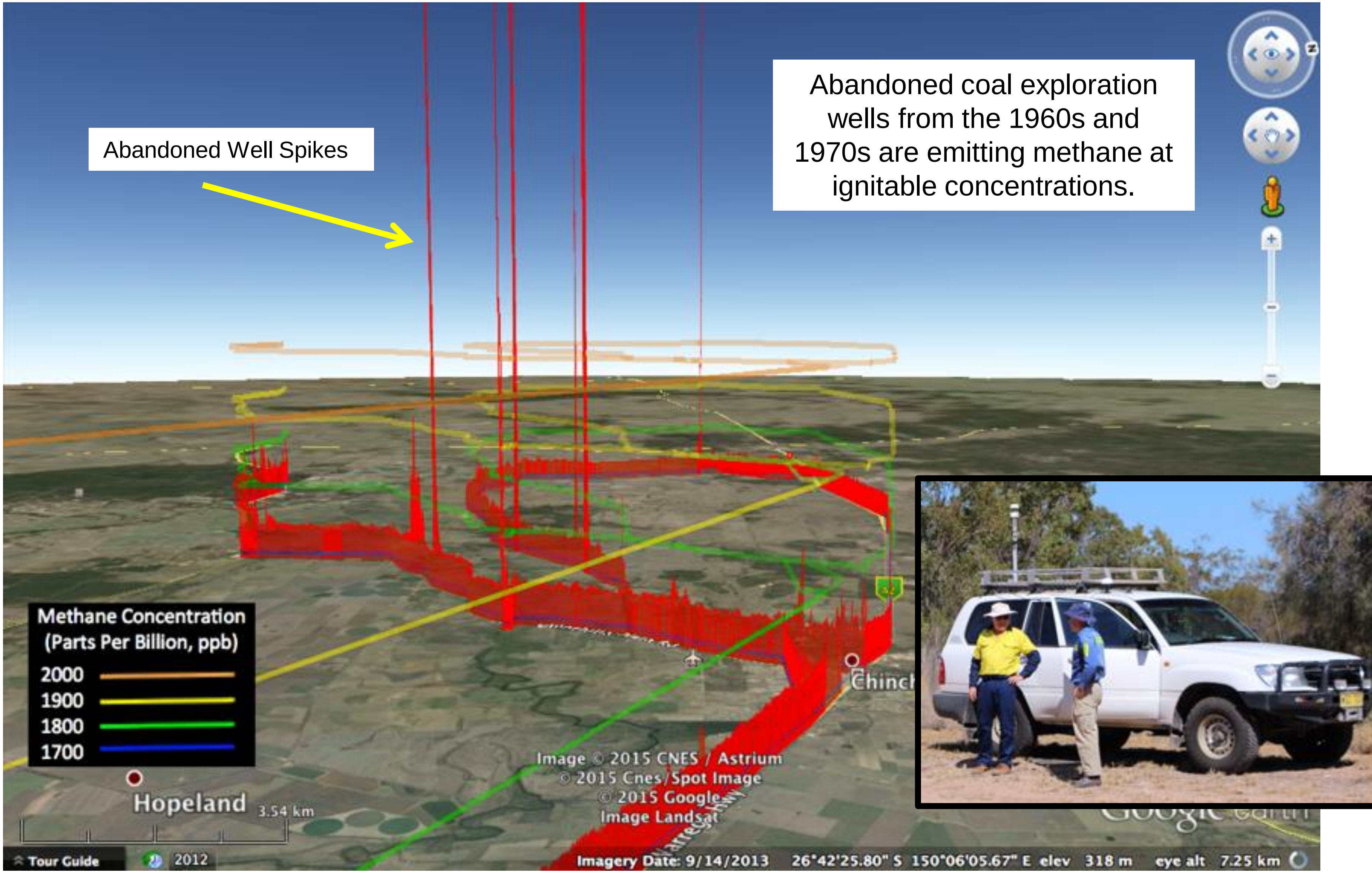
Emissions from Co-Produced Water-Holding Ponds



The isotopic signature of the gas coming off the water storage pond is:

$\delta^{13}C$ is -50.8 (-55.8 to -45.8) ‰

Leaking Abandoned Wells



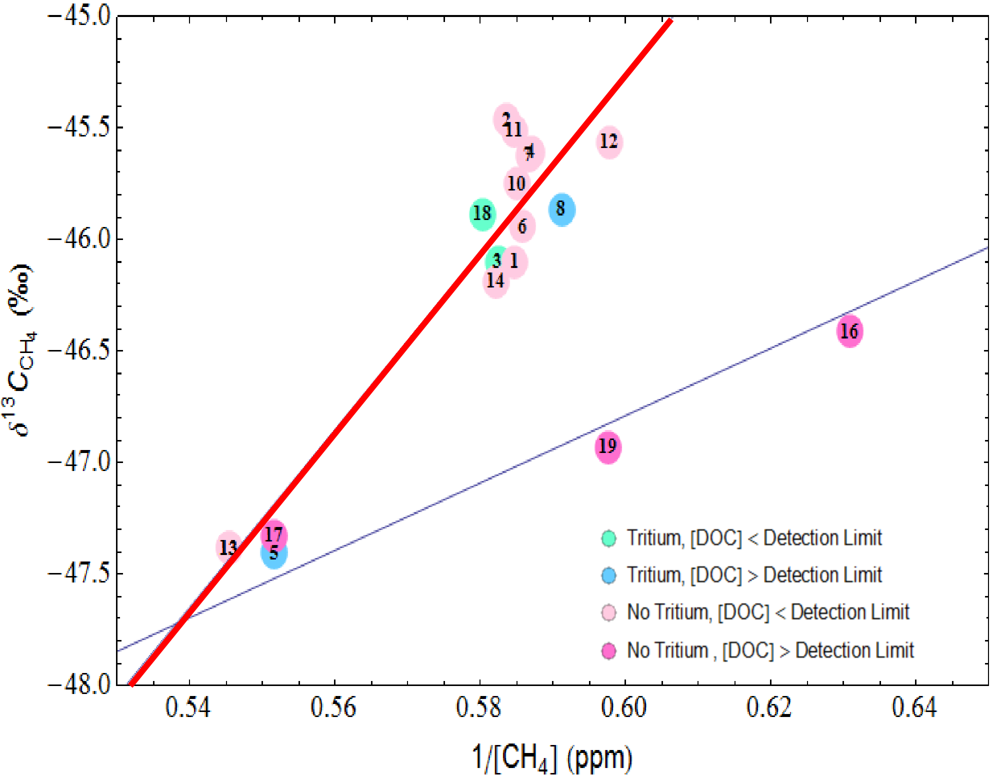
Leaking From Abandoned Wells

Ignitable concentration of methane leaking from this abandoned well.

Field methods: Groundwater samples

- Gas samples were taken from bores that were identified using the new mobile methane measurement technique
- The levels of carbon isotopes of methane were then measured
- These measurements allow us to determine if the methane is due to CSG leakage

Gas samples from irrigation boreholes



- At certain locations, microbiological activity is the main contributor to methane in groundwater
- CSG leakage is not yet a concern in these locations

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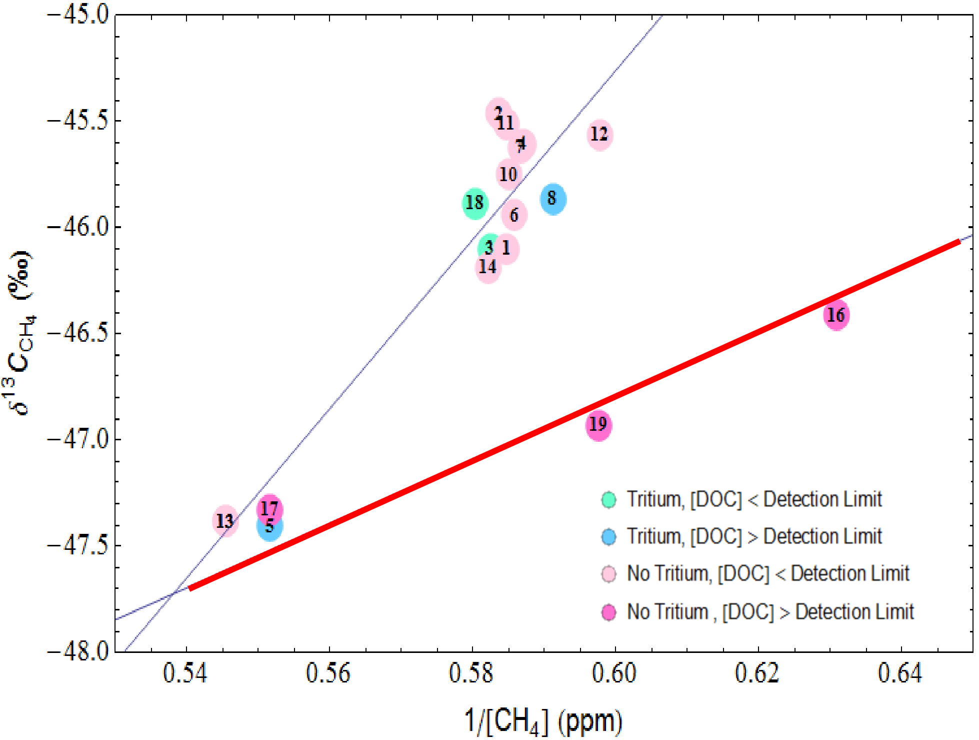
Gas samples from irrigation boreholes



- Results suggest that in certain locations there is connectivity between coal seam gas producing layers and the overlying aquifer
- Lack of tritium confirms that this methane is not the result of surface contamination

Summary

- New methane isotope method can determine where there are high concentrations of methane in groundwater
- The method can help determine the source of methane: microbiological or CSG-induced
- In the study area, hydraulic connections between the CSG production strata and shallow aquifers do exist
- Abandoned exploration wells are an unquantified concern that should be addressed

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Groundwater Confinement & Aquifer Compressibility

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Earth tides and atmospheric tides

- Earth tides are small (<10^{-5} % of g) variations in gravitational forces experienced at the Earth's surface and subsurface
- Atmospheric tides are akin to ocean tides, although the behaviour is different due to thermal expansion of air, different viscosities/densities, and other factors
- Like ocean tides, Earth tides and atmospheric tides have several periodic components and are dominated/driven by the relative positions of the Sun, Earth and Moon

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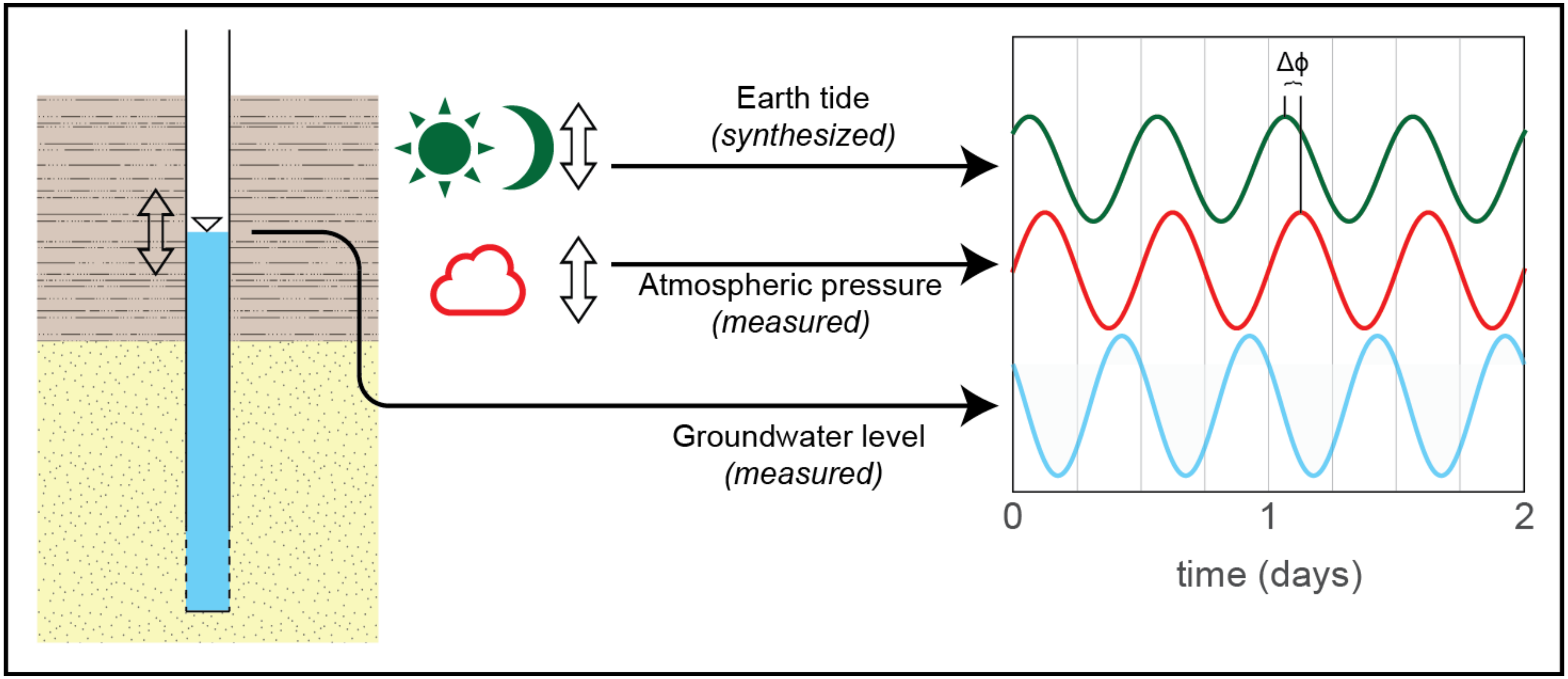
Effects of *tides* on groundwater levels



Calculation of aquifer properties using *tides*

$$BE = \frac{S_2^{GW} + S_2^{ET}\cos(\Delta\phi)\frac{M_2^{GW}}{M_2^{ET}}}{S_2^{AT}}$$

Magnitudes of S2 & M2 components and S2 phase shift

Barometric efficiency

$$BE = 1 - \gamma$$

Loading efficiency

$$\gamma = \frac{\alpha}{\theta\beta + \alpha}$$

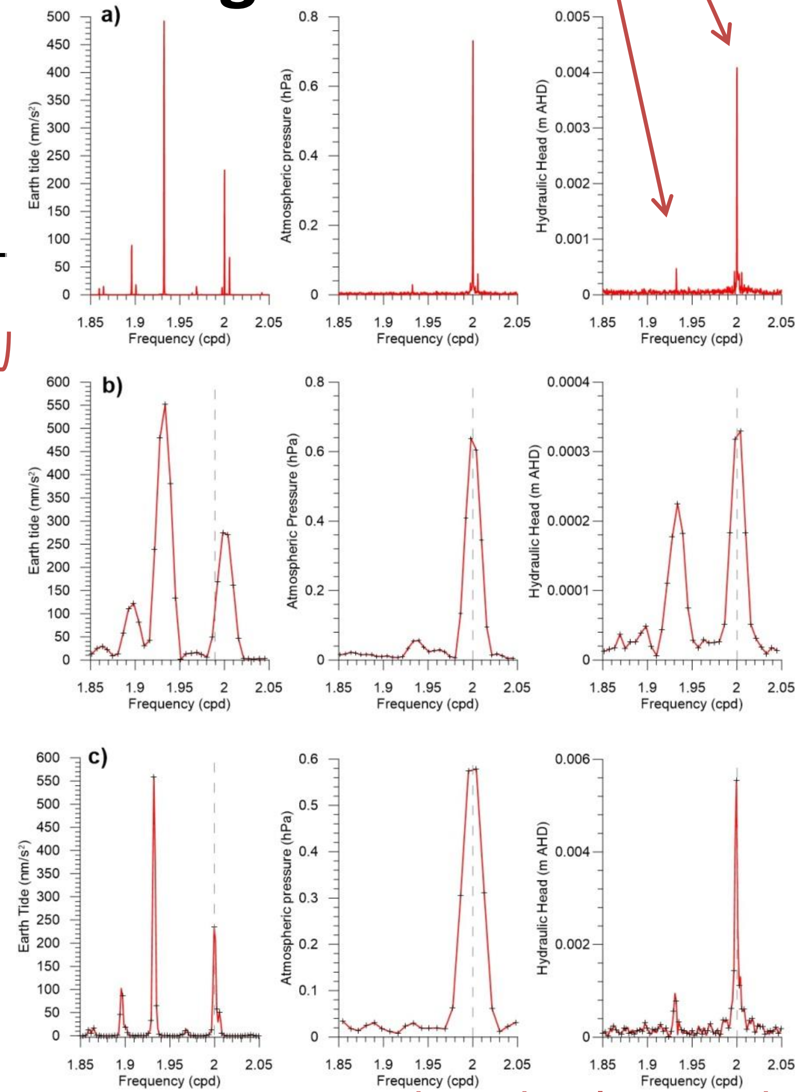
Matrix compressibility

Fluid compressibility

$$S_s = \rho g\,(\alpha + \theta\beta)$$

Specific storage

Porosity



(Acworth et al. 2016, GRL)

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Subsidence

- Knowing the matrix compressibility permits assessment of subsidence risk

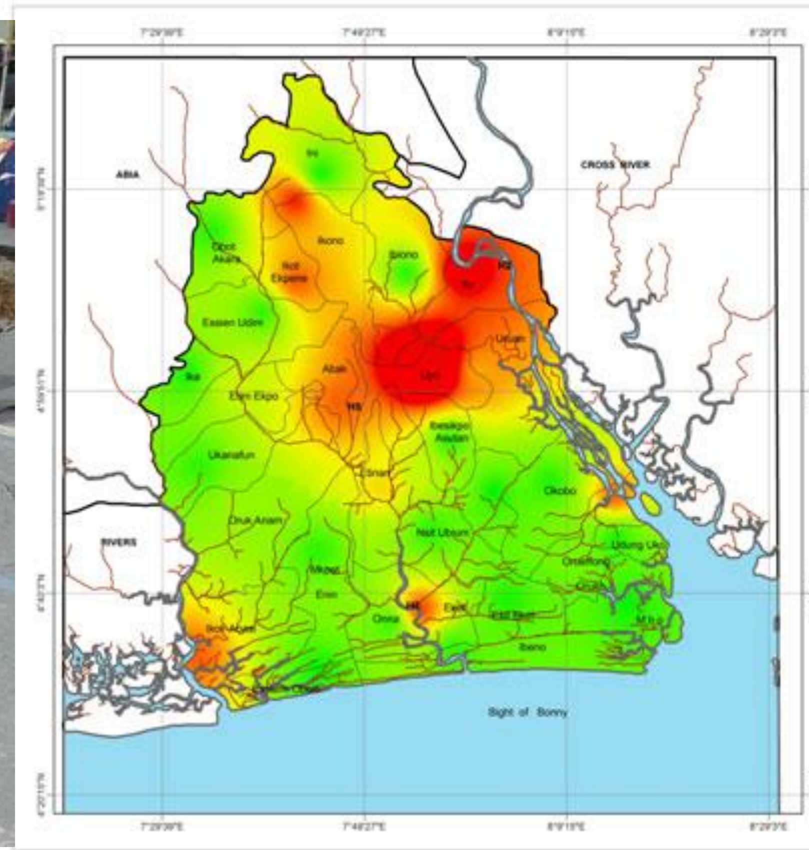
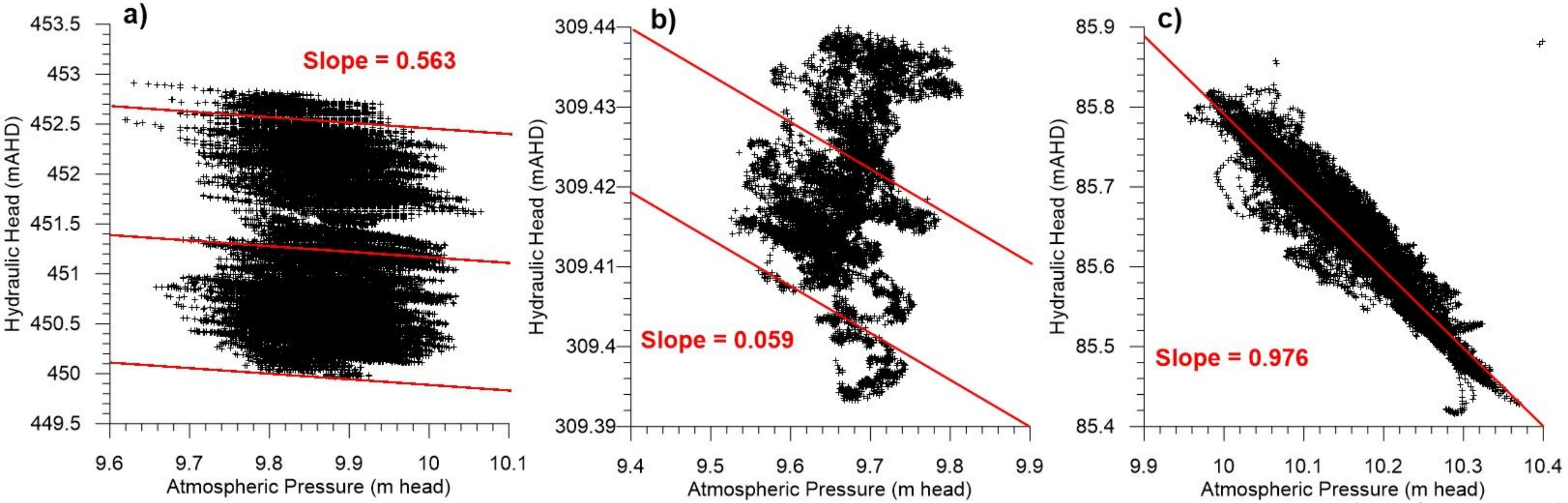


Fig. 1: Subsidence Index map of the study area

Calculation of aquifer properties using *tides*

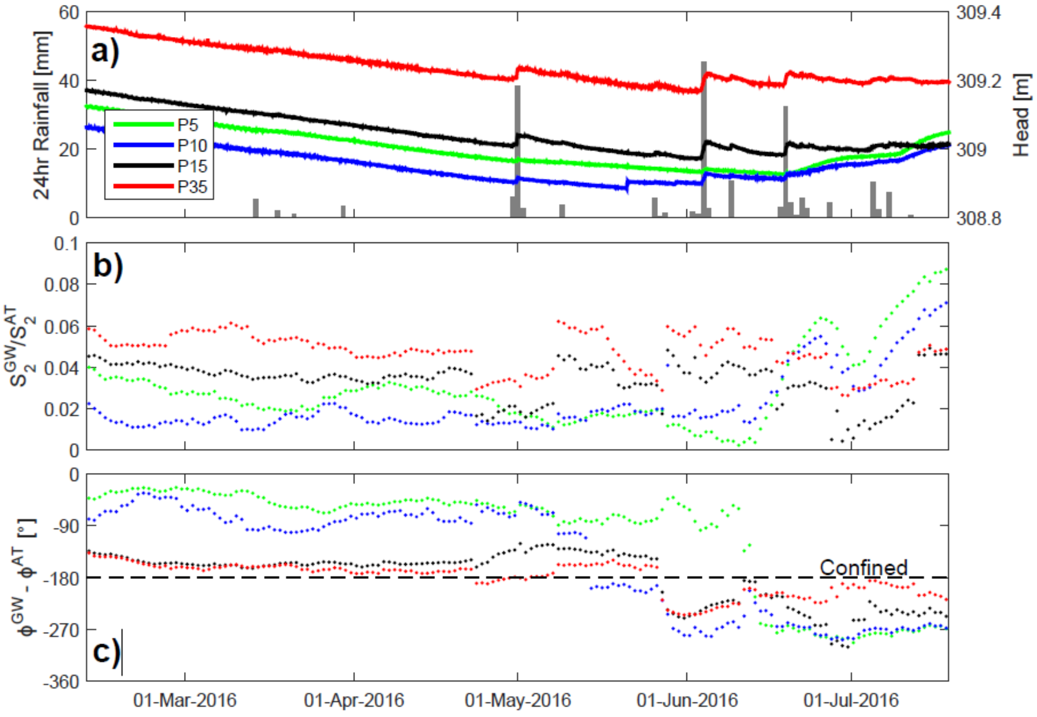
- This passive method can accurately determine the barometric efficiency of aquifers using only GW and barometric time-series
- With a reasonable estimate of porosity, the method allows for the calculation of matrix compressibility
- No GW abstraction is needed and archival data can be used

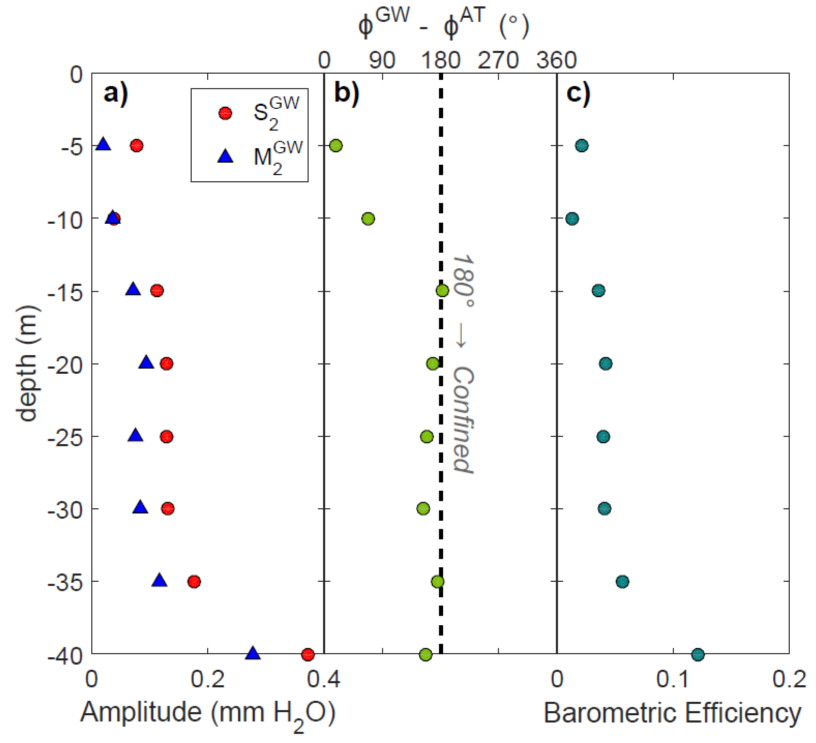


(Acworth et al. 2016, GRL)

Changes in confined state over depth and time

- Variations in the state of confinement have been observed by investigating atmospheric and Earth tides in a clay-rich subsurface
- This shows that clay-rich sediments may exhibit seasonal changes in subsidence risk and connection to the aquifer





Summary

Summary

- Groundwater is a vital contributor to the Australian economy
- Climate variability and varied usage demands result in a complex set of challenges for Australian groundwater
- MAR requires a systematic approach in order to maximise success and learning
- An understanding of the connectivity of surface water and groundwater is required to properly address water resource questions
- A unique combination of skills in hydrogeology, geophysics, geochemistry, environmental engineering, ecology, and law allows UNSW researchers to lead a large and diverse set of groundwater research projects

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