What can we learn about groundwater systems from advanced pore pressure analysis and tracers?

IAH Victoria, 6 Aug 2019

Prof W Timms

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46TH IAH CONGRESS MALAGA 2019

GROUNDWATER MANAGEMENT AND GOVERNANCE

COPING WITH WATER SCARCITY

22ND - 27TH SEPTEMBER 2019

MALAGA, SPAIN

Tidal Subsurface Analysis (TSA) adding value to water level monitoring pressure data

McMillan et al. 2019 to be presented at IAH Malaga

AUSTRALASIAN GROUNDWATER CONFERENCE

24 - 27 November 2019

Brisbane Convention & Exhibition Centre Queensland

How realistic are groundwater drawdown predictions? A quantitative evaluation of reported specific storage values

Timms et al 2019 to be presented at AGC Brisbane

What can we learn about groundwater systems from pore pressure analysis and tracers?

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Lots!

With thanks to teams, collaborators & students

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What surprises have sprung up on us in water?

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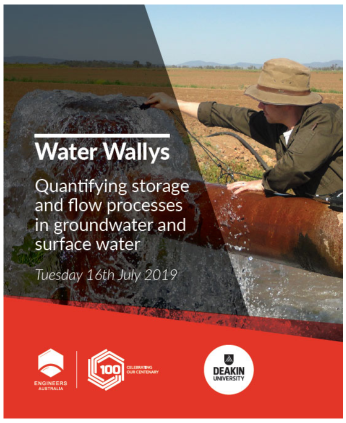
- Surprise - unexpected or unpredicted
- What can we learn from water surprises?



Examples ?

- Lakes that have disappeared
- Lack of 'return' flows from irrigation to rivers
- Slope failures near water sources
- Drying of landscapes beyond 'normal'
- Flash flooding 'firsts'
- Wetlands drying or releasing acidic water
- Increased groundwater extractions and drawdown
- Saline scalds and shallow watertable
- Trace metals mobilised in coal seam gas waters & fly ash
- Electricity generation effects on fresh waters
- 'Silly' groundwater storage values
- Mining effects beyond predictions
- Leaking basements or tunnels

Risk of water 'surprises'

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Don't forget that **Risk = likelihood x consequences**

Likelihood of occurring in short term or long term may be low.

Yet consider the consequences for people, equipment, production, and the environment.

Level	For people	For equipment	For production	For environment
5	Fatality/permanent disability	>$500k damage	>$500k loss	Licence revoked
4	Major injury	$100-500K damage	$100-500K loss	Prosecution
3	Av. Lost time injury	$50-100K damage	$50-100K loss	Infringement notice
2	Minor injury	$5-50k damage	$5-50k loss	Reportable non-compliance
1	Medical treatment or less	<$5k damage	<$5k loss	Incident – no regulation

Australian Geo-mechanics Society, 2007 and Galvin, 2016

Knowing we don't know

THE LIMITS OF MODELLING: KNOWING WE DON'T KNOW

Modelling the impact of mine developments on groundwater is critical for protecting ecosystems and agriculture, but it can go astray if we don't recognise that all models lack certainty

Link

By Emma White, University of Melbourne

"All models are wrong, some models are useful…

Limited empirical data indicate that surprises occur in 20–30% of model analyses."

Bredehoeft 2005, *Hydrogeol J.*

2019 NCGRT Groundwater modelling uncertainty workshop. Report download.

2019 Darcy lecture

IESC – new explanatory notes released and more coming. Links here.

2018 CSIRO workshop, Conceptualisation and modelling: *New insights from teaming-up environmental tracers and geophysics*

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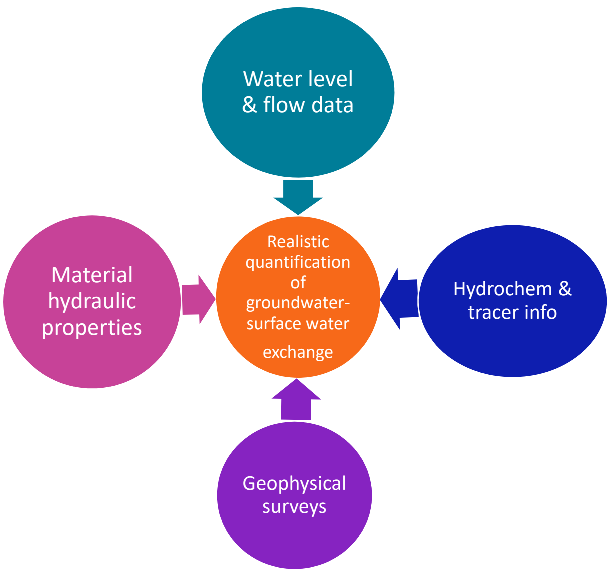
Multiple lines of evidence

Are there multiple lines of evidence ?

Is there sufficient data for the level of confidence needed relative to the risk?

Eg.
Surface water flow gains from groundwater discharge



Are our hydraulic parameters realistic & unique?

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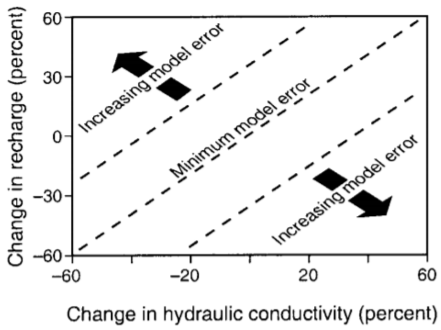
The estimated recharge is often non unique

Scanlon et al 2002



It is well known that calibration of numerical groundwater models to hydraulic head observations along provides an estimate of:

- Ratio of hydraulic conductivity to recharge (for steady state conditions)
- Ratio of hydraulic conductivity to storativity (for transient conditions)

Haitjema, 2006

Is groundwater recharge realistic?

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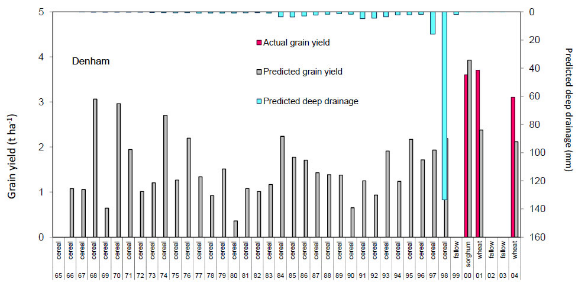


Timms et al. 2012 *HESS journal*

At a site in the Murray-Darling:

Elevation survey of river compared with shallow and deep aquifers levels.

Monitoring of groundwater levels, rainfall, soil moisture, water tracers.

Testing of infiltration rates and aquifer permeability.

Comparison with historic data on hydrology and crop yields.

Modelling of soil water balance including crop yields, deep drainage and groundwater recharge.

Finding: only one recharge event in ~25 years. Need to adapt management to these recharge conditions

Are specific storage values realistic?

Specific storage Ss values for confined aquifers, are much smaller than specific yields Sy for unconfined aquifers.

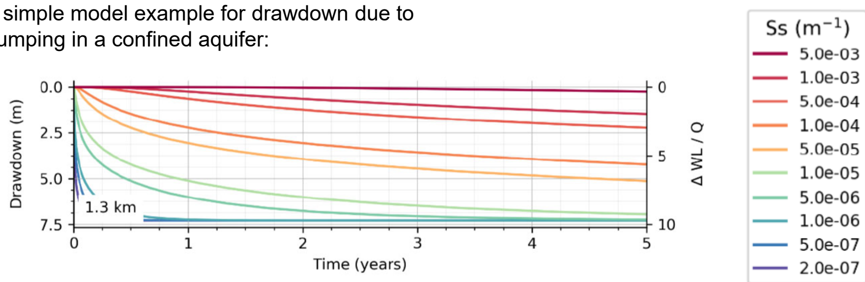
Water volume released per metre of drawdown for specific storage S_s values:

1×10^{-3} m^{-1}	1 L
1×10^{-6} m^{-1}	0.001 L

Drawdown in time & space is sensitive to Ss

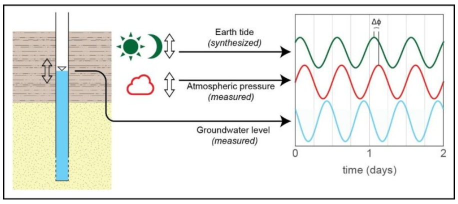
Up to 99.9% of the water balance is unaccounted for if using Ss ***too high by x1000***

A simple model example for drawdown due to pumping in a confined aquifer:



Anderson et al 2018 UNSW WRL Report

New techniques for in situ values of hydraulic and poro-elastic parameters



https://theconversation.com/squeezed-by-gravity-how-tides-affect-the-groundwater-under-our-feet-74928

Reviews of Geophysics

REGULAR ARTICLE
10.1029/2018RG000630

Key Points:
- Earth and atmospheric tides occur globally, are predictable or observable, and induce groundwater oscillations under semiconfined conditions
- Tides, in combination with poroelastic theory, enable groundwater system characterization and hydrogeomechanical property quantification
- Analyzing groundwater responses to Earth and atmospheric tides is an underutilized passive technique to quantify subsurface properties

Utilizing the Impact of Earth and Atmospheric Tides on Groundwater Systems: A Review Reveals the Future Potential

Timothy C. McMillan[1,2], Gabriel C. Rau[1,3], Wendy A. Timms[4], and Martin S. Andersen[1,5]

[1]Connected Waters Initiative Research Centre (CWI), School of Civil and Environmental Engineering, UNSW, Sydney, New South Wales, Australia, [2]School of Minerals and Energy Resource Engineering, UNSW, Sydney, New South Wales, Australia, [3]Institute of Applied Geosciences, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, [4]School of Engineering, Deakin University, Waurn Ponds, Victoria, Australia, [5]Water Research Laboratory (WRL), School of Civil and Environmental Engineering, UNSW, Sydney, New South Wales, Australia

Abstract Groundwater extraction is increasing rapidly in many areas of the world, causing serious

Evolution of new know-how in this area over many years:

Timms and Acworth (2005) *Hydrogeology J.; Acworth et al. (2015) Hydrogeology J; Acworth et al. (2016) Water Resources Research, Cook et al (2017) Hydrogeology J.; David et al (2017) Journal of Hydrology, Acworth Rau Timms et al.(2017) Water Resources Research, Acworth et al (2018) Geophysical Research Letters, Rau et al (2018) Journal of Geophysical Research: Earth Surface: McMillan et al. (2019) Reviews of Geophysics*

A new tool: TSA analysis of high frequency pore pressure data

Groundwater response to earth & atmospheric tides is passive.

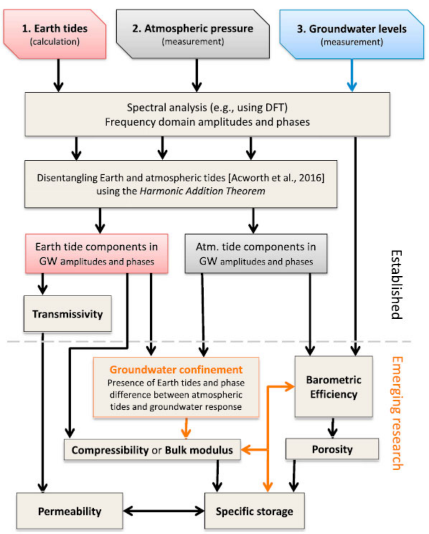
Can use water level time series at any borehole.

- Data at least every 6 hours for 4-6 months with appropriate resolution is needed.

Passive, relatively inexpensive techniques that compliment and extend aquifer pump testing that is subject to logistical constraints.

Value add to BIG datasets to derive in situ hydraulic parameters, quantify groundwater confinement.

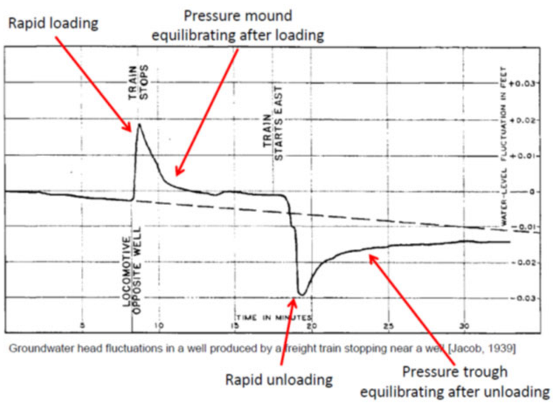
Depending on site data, can derive Ss, K, matrix compressibility and porosity and quantify degree of aquifer confinement.



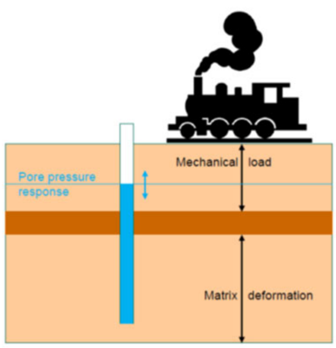
McMillan et al. (2019) *Reviews of Geophysics*

Subsurface poroelasticity

A famous example:



Groundwater head fluctuations in a well produced by a freight train stopping near a well [Jacob, 1939]



Jacob (1939)

Groundwater: tidal subsurface analysis (TSA), both barometric and earth tides

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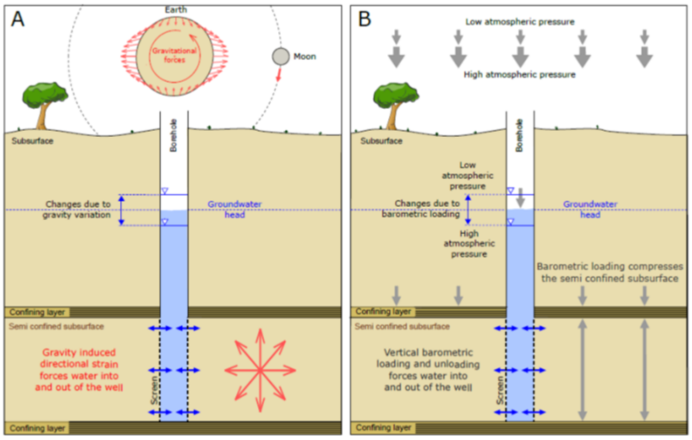

Figure 1: Representation of groundwater head measured in a well penetrating a semiconfined aquifer with a relatively rigid matrix subjected to A) strains caused by Earth tides (using the moon as an example celestial body) and B) barometric loading caused by atmospheric tides.

McMillan, Rau, Timms, Andersen (2019)

A new tool: TSA analysis of high frequency pore pressure data

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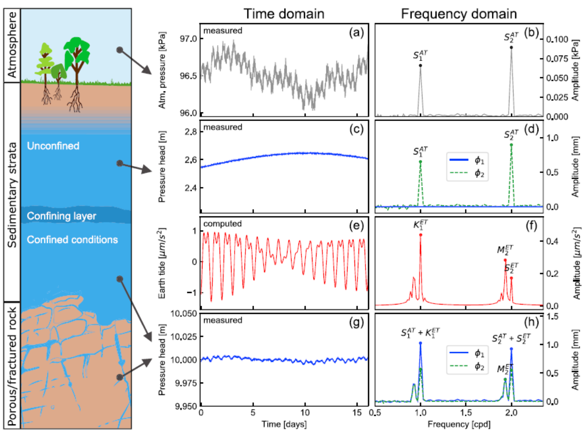
Influences of earth and atmospheric tides can be disentangled using the harmonic addition theorem.

The results can be used to characterise groundwater systems and quantify subsurface properties.



Acworth et al (2016); Rau et al (2018)
McMillan et al. (2019) *Reviews of Geophysics*

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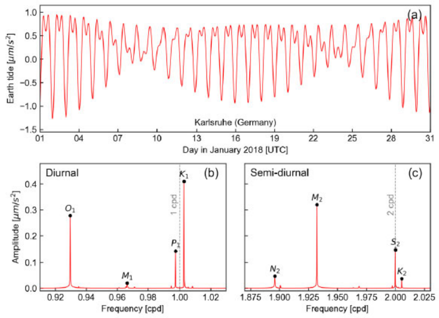
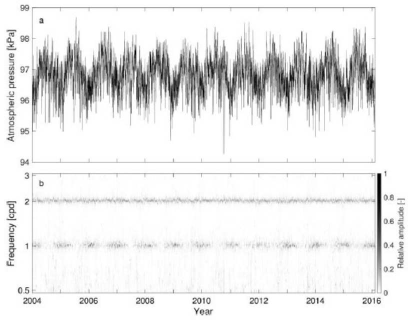


Earth tides: Changes in gravity caused by the movement of celestial bodies calculated using *PyGTide* [Rau, 2018]



Atmospheric tides: Gravitational and thermally induced atmospheric pressure changes [Acworth et al., 2016]

Groundwater: tidal subsurface analysis (TSA), both barometric and earth tides

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Darwin name	Frequency [cpd]	Tidal Potential $[m^2/s^2]$	Tidal Gravity Variation $[m/s^2]$	Tidal Dilation [-]	Description	Attribution
			Diurnal			
O_1	0.929536	5.363385	8.26E-06	3.347E-08	Principle Lunar diurnal	Earth
M_1	0.966446	10.286769	1.58E-05	6.419E-08	Lunar Diurnal	Earth
P_1	0.997262	7.407625	1.14E-05	4.622E-08	Diurnal Lunar perigee	Earth
S_1	1.000000				Principle Solar Atmospheric Pressure (thermal)	Atmosphere
K_1	1.002738	22.924982	3.53E-05	1.431E-07	Lunar Solar Diurnal	Earth
			Semidiurnal			
N_2	1.895982	12.963403	1.996E-05	8.089E-08	Lunar elliptic Semidiurnal (variation in moon distance)	Earth
M_2	1.932274	42.060943	6.477E-05	2.625E-07	Principle Lunar Semidiurnal	Earth
S_2	2.000000	19.309855	2.973E-05	1.205E-07	Principle Solar Semidiurnal	Atmosphere/Earth
K_2	2.005476	11.791770	1.816E-05	7.358E-08	Lunar Solar Semidiurnal	Earth

Table 1: Table of major tidal components ordered according to frequency in cycles per day [cpd]. Tidal gravity variations $[m/s^2]$ and tidal dilation are calculated from the tidal potential $[m^2/s^2]$ as $g * V/R$ and $= V/g * (\frac{L}{S}h - 3\frac{L}{S}l)/R$ respectively, where V is the tidal potential, g is gravity, R is the radius of the earth and $\frac{L}{S}h$ and $\frac{L}{S}l$ are assumed love numbers of 0.6 and 0.07 respectively . Note that S_1 has been included due to its large superposition effect on the other tidal components although it is not of gravitational origin. Table adapted from *Darwin* [1899] *Munk and MacDonald* [1960] and *Agnew* [2010].

Water level and pore pressures are different

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What is the difference between the train and earth tide and atmospheric (EAT) induced stresses?

- EAT are small stresses = small (linear strain responses)
- EAT are fast stresses = undrained response
- Atmospheric tides are different act both on subsurface and water level → an inverse response

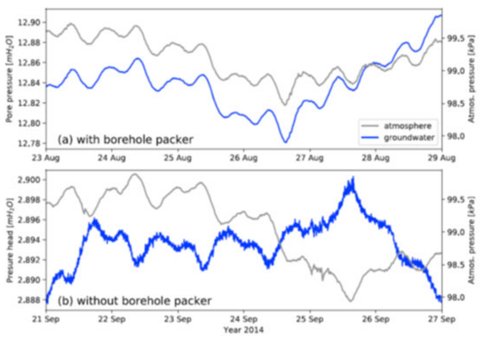

Figure 10. Example of the phase relationship between pore pressure, pressure head, and atmospheric pressure during two passive investigation phases in a borehole (NMRDC1, data from; Cook et al., 2017): (a) Pore pressure (hydraulic head) is in phase with the atmospheric pressure when the borehole is sealed from the atmosphere (here by temporary installation of a borehole packer). (b) Pressure head is inverse to (out of phase with) the atmosphere when the borehole is open to the atmosphere.

McMillan et al (2019) *Reviews of Geophysics*
After Cook et al (2017) *Hydrogeology J.*

Specific storage – physical limits

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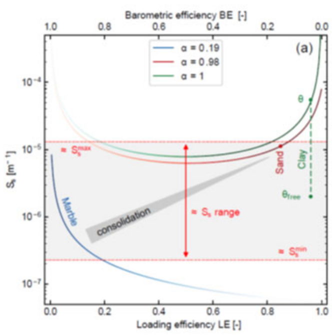
Theoretical specific storage, Ss for consolidated to unconsolidated systems, considering physical limits from poro-elastic theory. If Ss values are outside these physical limits, the water balance is missing flow components (eg. vertical leakage, lateral inflows). Ss values are currently a significant uncertainty for numerical models.



Minimum approx. value of S_s 2.3 x 10^{-7} m^{-1} (solid rock-marble)

Maximum approx. value of S_s 1.3 x 10^{-5} m^{-1} (*unconsolidated sediments)

* More work needed for clayey materials, particularly uncertain for smectites

Rau et al 2018 *JGR-ES*

How confined is my aquifer? Tidal analysis of water level data to characterise confinement

McMillan et al 2019 EGU Vienna

What is groundwater confinement?

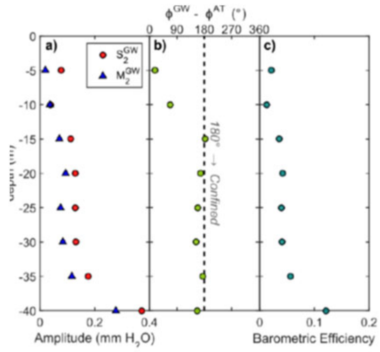
- Pressure head is higher than the lower boundary of a capping low permeability geological unit (Domenico and Schwartz, 1997)
- Pore space is not drained when water is extracted

Specific storage Ss or specific yield Sy

Unconfined vs. confined is a simplification of reality.

The amplitude and phase lag of selected earth tide signals can indicate degree of confinement.

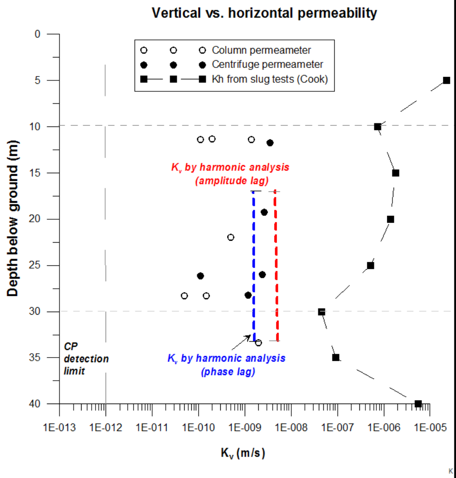
Example: CL aquitard site, Liverpool Plains
Shows increasing confinement from 10 to 40 mbg.



Acworth et al 2017

Example: vertical hydraulic conductivity from phase lags of pore pressure

- CL aquitard research site, Liverpool Plains NSW
- ***Vertical permeability of the aquitard sequence is ~10^{-9} m/s***, determined from
  - phase lag of moisture loading at site scale, and BE analysis
  - permeability testing with formation water at core scale (in situ stresses within a geotechnical centrifuge)
- This is 100 times leakier than glacial till and siltstone aquitards, but currently a negligible vertical hydraulic gradient with diffusive dominated solute transport



Crane et al. *HESS* 2015
Timms et al. *HESS* 2014, 2016
Acworth et al., AJES 2015
Timms and Acworth, 2005 *Hydrogeology Journal.*

Hydrogeology of constrained zone

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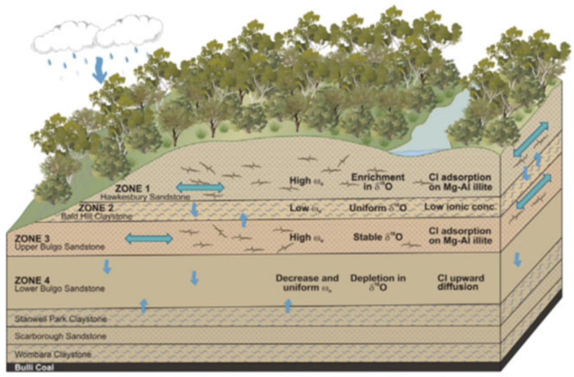
Multi-layered aquitards in the constrained zone are important under shallow waters. Aquitard (cemented sandstones, claystones) integrity varies pre/post mining.

Lines of evidence:
- Hydro-geomechanics
- Water chemistry & isotope tracers



• our article in *The Conversation*

David K, W. Timms, L. Barbour and R. Mitra (2016). *Journal of Hydrology*

David, K., Timms, W., Baker, A.(2015) *Science of the Total Environment.* 538, 1010 – 1023.

Industry in-kind data provided

Specific storage – two independent and in situ methods for each strata

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Unit	Depth (mBG)	Porosity	LE_{et}	S_s (m^{-1})	LE	S_s (m^{-1})
			earth tides		barometric pressure	
HBSS1	9.7	0.11	0.68	1.6E-06	0.67	2.12E-06
HBSS2	125	0.09	0.80	2.0E-06	0.64	1.57E-06
BGSS1	169	0.03	0.30	1.9E-07	0.40	2.81E-07
BGSS2	247	0.07	0.30	4.5E-07	0.35	5.90E-07
SBSS1	274	0.13	0.50	1.2E-06	0.32	1.03E-06

• In compressible formations the pore-water carries nearly the entire applied load (i.e. LE=1) while in stiff formations the load is shared by the water and soil skeleton (i.e. LE<1)

• Stiff formations with increasing depth

• Porosity from wireline density logs

David K, W. Timms, L. Barbour and R. Mitra (2016). *Journal of Hydrology*

School of Mining Engineering

UNSW AUSTRALIA

Specific storage – changes over time associated with underground mining

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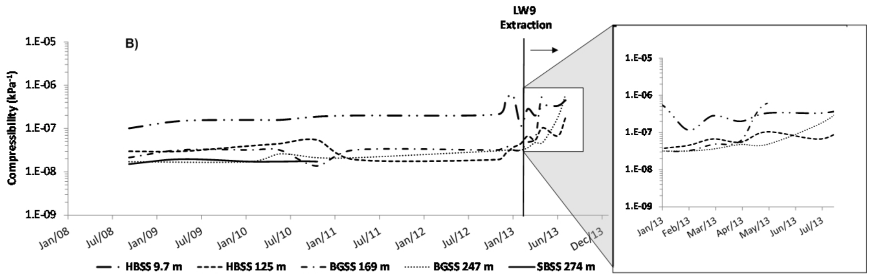
A systematic change in S_s due to disturbance during mining within hydrostratigraphic units were up to two orders of magnitude. Consequently, the drawdown and inflow estimation may not be realistic if constant S_s is assumed.



S_s changes at ~250 m depth indicated this confined aquifer may have became unconfined, while other zones remained confined.

David K , W. Timms, L. Barbour and R. Mitra (2016). *Journal of Hydrology*

School of Mining Engineering

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Specific storage and compressibility

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The specific storage of the strata (*Ss* with dimensions m^{-1}) depends on

density of water (ρ)
the porosity (ϕ)
compressibility of water (β)
compressibility of the formation (βp)

$$S_s = \rho g(\phi\beta + \beta_p)$$

Assumes incompressible particles (ie. not clay)

Jacob, C. E. (1940). On the flow of water in an elastic artesian aquifer. *Eos, Transactions American Geophysical Union*, *21*(2), 574–586.

Strata or formation compressibility β is also known as α.

Compressibility α is related to bulk modulus, Young's modulus and Poisson ratio depending on uniaxial/directional stress-strain relationships.

Workflow established for estimating ground surface settlement based on in situ monitoring of matrix compressibility….

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Another line of evidence….

What are environmental water tracers?

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Tracers can be:
- in aqueous phase, solid phase, or in pore water eg. VE isotopes
- environmental tracers, or applied tracers eg. dye tracer tests

Environmental water tracers:
- Conservative (non-reactive) eg. chloride
- Reactive indicators of surface sources eg. nitrate, atrazine, caffeine
- Stable isotopes eg. oxygen-18, novel trace element isotopes
- Radio isotopes eg. tritium, carbon-14
- Compound specific isotopes eg. oxygen-18 on SO_4
- Noble and dissolved gases eg. argon-39, CFC's
- Organic tracers eg. fluorescence
- Bio-markers eg. eDNA

Distinctive end-members essential to 'fingerprint' water sources and mixing

Trends towards smaller volumes, less expensive, greater range of tracers

Water tracers to optimise groundwater management

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Deakin Uni & ANSTO project: Prof Wendy Timms, with Dr Karina Meredith (ANSTO), Dr Ellen Moon, Dr Bill Howcroft, Devmi Kurukulasuriya

Aims: optimisation of water management for mine voids by using water tracers and isotopes.

Are there effective hydraulic barriers between surface waters and voids? How connected are wetlands and shallow aquifers? ***How long will it take for flows and storage to recover after changes?***

- Funded by ACARP Category 1 competitive grant, $296,000 over 2019-2020
- Demonstration sites at underground mines
- Review and develop decision support for selecting suitable suites of tracers

Tracers for residence time in groundwater

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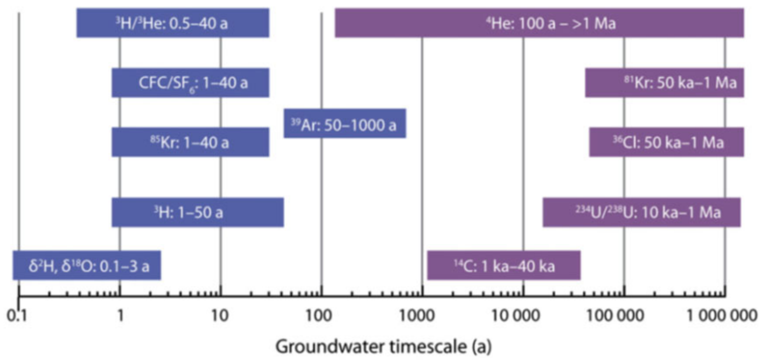

Lu et al, 2014 *Earth-Science Reviews*
After Aggarwal, 2013

How do local wetland systems work?

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Research program funded by NSW Government (OEH), UNSW ACSMP and UNSW CWI, co-lead by Prof Timms

Research in progress at Thirlmere Lake and other peat wetland sites in Sydney basin

How do the wetlands work? How much rainfall, groundwater? ***How to restore wetlands that have dried*** due to stresses from urban runoff, mining, wildfire etc?

How to improve predictions of any important changes in the water supply & World Heritage wild rivers?

Multi-method eg. hydrology, geology, geophysics, tracers

David et al 2018. Application of porewater stable isotope method to characterise a wetland system. *HESS journal*

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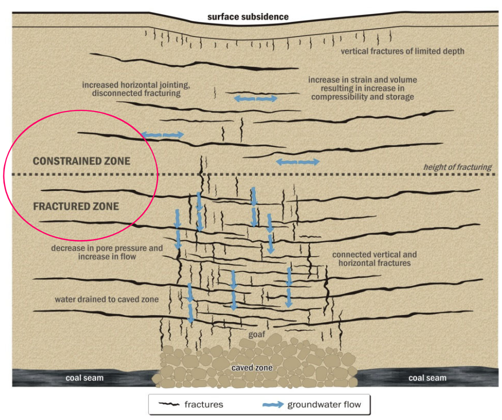

Lines of evidence:

- Hydro-geomechanics
- Water chemistry & isotope tracers

David, K., Timms, W., Baker, A.(2015). Direct stable isotope porewater equilibration and identification of groundwater processes in heterogeneous sedimentary rock. *Science of the Total Environment*. 538, 1010 – 1023.

Industry in-kind data provided

High resolution isotope tracers on core samples

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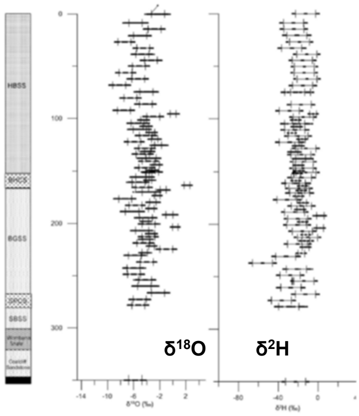
High resolution vertical profiles of stable isotopes Using the vapour equilibrium method

Meteoric water to depth, layered effects of sandstone

Lack of glaciation signal

David Timms et al 2017
doi:10.1016/j.scitotenv.2015.08.075.



Industry in-kind data provided

Water mixing and reaction models

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Quantifying flow and mixing of water that cannot be distinguished by other methods with the accuracy and confidence of multiple tracers and isotopes. This may be possible at very low volume water mixing (eg. 10% of river water + 90% of aquifer water).

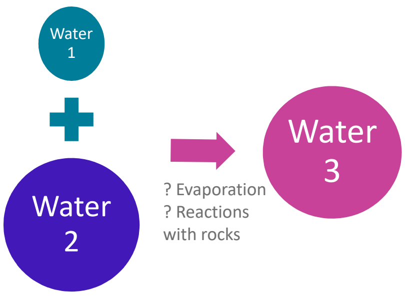
A multi-model, multi-scale approach will be used depending on available data and associated information (eg. water levels, flow rates, permeability, geology).

Eg. spreadsheet based mixing calculations – simple 2 or 3 water

Eg. Analytical models for multiple water tracers, evaporation and mixing

Eg. USGS hydrogeochemical model (PHREEQC) for non-reactive and reactive tracers

These can be used in various ways to verify other models (eg. MODFLOW groundwater models or AWBM surface water models).



Example of tracers constraining model: Timms W; Acworth RI; Jankowski J, 2001, *IAH congress*
Turnadge and Smerdon, 2014; DOI: 10.1016/j.jhydrol.2014.10.056

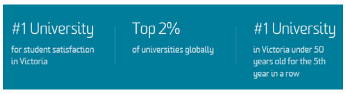
Opportunities for collaboration

A new research project is commencing on advanced pore pressures, including a new PhD student commencing soon, with collaborators in Germany and Australia

Are you/your company interested in collaborating?
We are seeking:

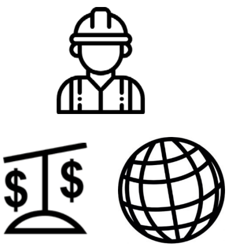
- Suitable sites with high frequency monitoring data and associated groundwater info available
- Modest investments that enable partners to leverage access to the latest techniques

Contact wendy.timms@deakin.edu.au



Who are we at Deakin Environmental engineering?

#EnviroEngDeakin



- Engineering projects for performance including economic and environmental.
- Designing the built environment and landscapes that are productive and sustainable.
- Evaluating and monitoring environmental performance
- Working in multi-disciplinary engineering and professional teams

Course Director:
Dr Ellen **Moon**

Prof Carol **Boyle**
A/Prof Lloyd **Chua**
Dr Jinzhe (James) **Gong**
Dr Yali (Lily) **Li**
Dr Nick **Milne**
Dr Mohjo **Rouzbehani**
Dr Svetlana **Stevanovic**
Prof Wendy **Timms**

Research Fellows:
Dr Bill **Howcroft**,
Dr Sudeep **Nair**

And over 70 engineering staff including technical staff:
Candice **Chan**, Leanne **Fargo**

Prof Wendy Timms

LinkedIn Google scholar

Dr Wendy Timms has over 25 years of professional experience in Australia, Canada and SE Asia, on water and waste issues in mining and agriculture. She has worked as an environmental engineer and hydrogeologists in consulting engineering, government, research and education.

- PhD (2001) Civil & Enviro Eng., UNSW Sydney
- BSc (1996) Geology, hydrology, ANU/Uni Newc.
- Member, Engineers Australia
- Vice President, Int. Assoc. of Hydrogeologists
- Expert boards providing technical advice to Federal Minister for Environment (water trigger – IESC and ARRTC panels)
- Over 200 technical reports including 45+ journal papers, 470+ citations
- Graduated several PhD students

CI on several Australian Research Council projects including founding CI for $3.5M aquitards research. Currently the lead CI delivering $673K worth projects to industry and government, including a new Cat 1 grant on water tracers (2019-2020).

Wendy teaches in water & waste engineering design and geotechnical engineering. She is also Course Director for Masters of Engineering.

Wendy's teaching is practice & research based with professional experience in :

• ***water & energy sustainability***, local & global
• ***porous earth engineering*** - soil water, consolidation and subsidence
•***mine water management*** – voids, water quality
• ***groundwater*** – hydraulic & geochemical interactions in aquifers and aquitard systems
•***waste sequestration*** with low permeability barriers (aquitards and/or engineered systems)

Wendy's research combines site based and in situ methods, with laboratory experimentation and numerical modelling using various codes.

Some downloads available here:
https://www.researchgate.net/profile/Wendy_Timms

Thanks, your comments, questions?