AUSTRALASIAN GROUNDWATER CONFERENCE

NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

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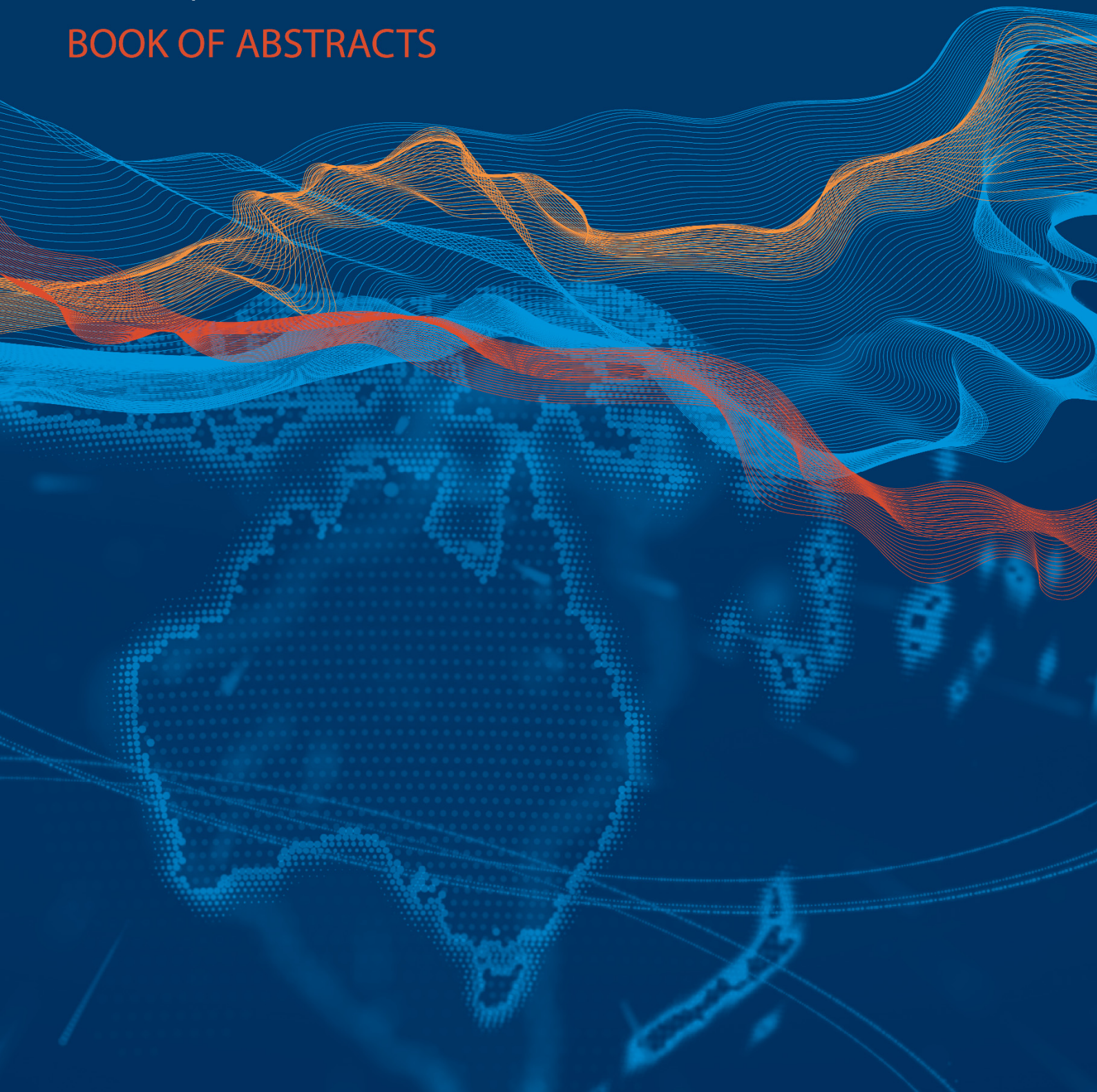
GROUNDWATER FUTURES SCIENCE TO PRACTICE

11-13TH JULY 2017
UNSW, SYDNEY

BOOK OF ABSTRACTS



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DAY 1: Tuesday, 11 July 2017

OPENING PLENARY

Opening Plenary Grand Challenges for Groundwater. *Prof Craig Simmons, Director, NCGRT*

Grand challenges for groundwater

Craig Simmons[1]
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Groundwater supplies half of the world's drinking water and nearly half of the water used for growing food. It is front and centre in critical contemporary issues about our environment, food and water security, coal seam gas and fracking, mining, energy and nuclear waste disposal. Groundwater depletion and pollution are major global problems. Climate change and population growth will place additional stress on already stretched groundwater resources.

This talk explores the challenges and opportunities for groundwater: spanning critical social, economic and environmental dimensions; to management; to policy; to science and research; to education and training and the vital links between them.

Current and foreseeable groundwater problems are interesting, important, demanding and complex. To advance and solve these problems will require novel fundamental scientific understanding including new paradigms; educational reforms; sophisticated management and policy; the necessary capacity and capability; and the integration of complex and interdisciplinary social and biophysical approaches, data, knowledge and information.

DAY 1: Tuesday, 11 July 2017

INVESTIGATIONS

Exploring for the future – new approaches to groundwater system mapping and characterisation

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1. Geoscience Australia, Canberra, ACT, Australia

Australia is the driest inhabited continent and the highest per capita user of water. As such, groundwater plays a critical role in national water security – both as an available water source in dry climates and during drought, as well as through its contribution to the Australian economy. In northern Australia, economic expansion has been limited in part by water availability: issues include limited surface dam sites; the seasonal nature of surface water; and high evaporation rates that rapidly deplete surface storages. Groundwater and water banking/aquifer storage may provide alternative water supply options, however there are major gaps in our knowledge of groundwater systems and resources.

The groundwater component of Geoscience Australia's new $100.5 million Exploring for the Future Programme will address these knowledge gaps, and underpin future opportunities for irrigated agriculture, mineral and energy development, and community water supply. Over the four years of the programme, a suite of pre-competitive data and information will be released to inform development and investment decisions in key regions, in collaboration with state/territory government agencies. Central to these new projects is the integration of hydrogeological and geophysical data with a range of new technologies including satellite, airborne and ground sensors and super-computing research infrastructure to explore, assess, monitor, and manage groundwater systems. This approach enables cost-effective mapping, assessment, characterisation and monitoring of groundwater systems, while also providing high quality data to parameterise groundwater numerical models and quantitative assessments of the uncertainties and confidence levels in these predictions.

Statewide space-time water table mapping: Victoria's water table over 30 years

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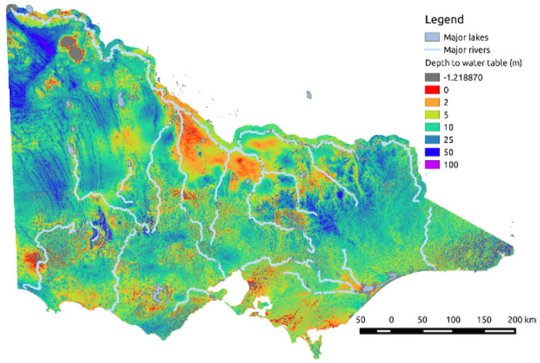
2. Agriculture Research and Development, Department of Economic Development, Jobs, Transport and Resources, Carlton, VIC, Australia
3. Groundwater Unit, Bureau of Meteorology, Melbourne, VIC, Australia

Groundwater level is the only widely monitored hydrological state variable and Australia has over 15,000 active monitoring bores. The data is primarily used for graphical hydrograph analysis and occasionally for groundwater model calibration. However, the data could potentially be used to inform regional subsurface and runoff processes and we argue that these opportunities have not been met; possibly because of the low frequency and sparsity of monitoring, hydrogeological and forcing complexities and groundwater level data being first and second order non-stationary over space and time. To realise some of these possibilities, herein advanced space and time statistical methods are presented and applied to map the water-table elevation across Victoria from 1985 to 2014.

The statistical methods involve (1) Markov Chain Monte Carlo time-series model calibration of every unconfined groundwater hydrograph in Victoria (n=10,362) using *HydroSight* (http://peterson-tim-j.github.io/HydroSight/, Peterson & Western, 2014) to produce hydrographs at monthly time-step; and (2) geostatistical spatial interpolation of the monthly groundwater level using our R package *GroundwaterMapper*. The geostatistical interpolation comprises of numerous new methods to produce potentiometric surfaces that account for local topographic form, landuse, elevation and fixed-head conditions (e.g ocean) and that are smoother than the land surface. Furthermore, variograms can be anisotropic and all kriging parameters are set by minimising a cross-validation likelihood function coupled to a mixed data-type global calibration scheme.

In applying the methods, water-table maps were produced for all of Victoria for each month from January 1985 to June 2014 (example below). The maps show complex surface-groundwater interactions, with the connection changing along reaches and over time. Additionally, regions are identified that were most severely impacted by the Millennium Drought and those that, by 2014, were yet to recover. In summary, our groundwater statistical tools open many opportunities for data-driven insights to regional groundwater dynamics, but many challenges remain.



1. *Peterson, T. J., and A. W. Western (2014), Nonlinear time-series modeling of unconfined groundwater head, Water Resour. Res., 50, 8330–8355, doi:10.1002/2013WR014800.*

SMART Aquifer Characterisation

Stewart Cameron[1], Zara Rawlinson[1], Rogier Westerhoff[1, 2], Uwe Morgenstern[3], Catherine Moore[3], Paul White[1]

1. GNS Science, Taupo, Waikato, New Zealand
2. Deltares, The Netherlands
3. GNS Science, Lower Hutt, New Zealand

Objectives: NZ is funding a joint NZ-EU research programme (SMART Aquifer Characterisation) to assemble and validate a suite of innovative methods for characterising the nation's groundwater systems, at the national and aquifer scales.

Focus of the research is on four key technical information gaps:

- Refining groundwater volume estimation
- Determination of aquifer hydraulic properties
- Quantification of fluxes between GW&SW
- Groundwater age-dating

This essential information, needed to effectively manage NZ groundwater resources, is lacking because traditional methods for aquifer mapping and characterisation are time-consuming, costly and ill-suited to large-scale application. The programme emphasis techniques that use passive data sources, which rely on existing data sources, or new measurements that can be made over large areas with reduced cost.

Methodology: The programme trialled methodologies in geophysics, satellite remote sensing, temperature-sensing and novel age-tracers. Validation via multiple methods applied in selected case study areas and ground-truthing. A framework was developed for quantifying uncertainty in each method, and optimising combinations of traditional and SMART. Techniques were established to synthesise and visualise the datasets. A web portal and harmonised 3D groundwater database was developed to meet stakeholder needs for open access, ease of use, and interoperability with existing database systems.

Results: Highlights to date include:

- Satellite derived nation-wide long-term time series of groundwater recharge;
- Novel groundwater age tracers lead to better insight into groundwater flow;
- Temperature sensing techniques map groundwater-surface water interaction on multiple spatial scales;
- Reinterpretation of helicopter geophysical data to map aquifer-relevant lithologies across Otago;
- Standardised data transfer and communication protocols increases efficiency of data use.

Conclusions: A key component of the SAC programme is effective communication with water managers to ensure uptake of methodologies and results. This presentation also discusses how NZ end-users and stakeholders have been involved throughout the programme and the avenues used to ensure research is relevant and utilized.

Groundwater resource analysis using the information contained in sub-diel hydraulic head variation

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The advent of accurate and stable groundwater logging systems makes possible the resolution of the fine detail in the hydraulic head record at a time-scale not possible given manual observation. The necessity to correct pumping-test data for atmospheric pressure loading, or coastal groundwater observations for ocean tide loading, has long been recognised. However, the recognition of the important groundwater resource information contained in the diel and sub-diel responses to atmospheric pressure and earth tide loading has been far more recent. The atmospheric pressure varies over a range of frequencies from the approximate week-long response to mesoscale movements of high and low pressure (<0.1 cycles per day), to diel and sub-diel (1 and 2 cpd) responses to changes in temperature in the upper atmosphere caused by the rotation of the earth. These pressure changes impact on heads measured in a confined or semi-confined aquifer but not on an unconfined aquifer. Their recognition is therefore fundamentally important in the allocation of storage values into a groundwater model.

The mesoscale processes are of larger amplitude than the sub-diel response and are easily observable. The ratio of the average hydraulic head change to the average amplitude of the atmospheric pressure change is a measure of the barometric efficiency, from which aquifer storage can be determined. However, the variation in frequency of the mesoscale processes precludes accurate barometric efficiency determination. By contrast, the diel and sub-diel responses are far more consistent and occur at a narrow frequency band that leads to accurate analysis using standard Fourier techniques. In this paper, we will give a review of the interpretation process and demonstrate some of the important groundwater system response data that can be determined using these techniques. The methods provide an important new approach to resolving aquifer storage in complex deep semi-confined sedimentary sequences.

Novel methods in groundwater assessment and monitoring through an efficient integration of remote sensing (RS) techniques

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Extractive industries can lead to alteration of the natural groundwater regime, groundwater interaction with surface water and its contribution to environmental water demands by groundwater dependent ecosystems (GDEs) and other groundwater related assets. The assessment of such an impact is challenging, particularly when changes in the natural water regime can be caused by unrelated factors, i.e., climatic variability or other water uses. The remote sensing (RS) historical data can be used to investigate relationships between groundwater levels or fluxes, inundation (or standing waters), vegetation dynamics in the past, prior to any operations.

Significant and valuable information for groundwater systems characterisation can be derived from land surface analysis. Groundwater interacts with the surface through processes such as recharge and discharge. This interaction with the surface influences groundwater balance and defines groundwater environmental functions. Characterisation of groundwater discharge also enables evaluation of hydrogeological pathways (e.g. faults) and discharge mechanisms (e.g. springs or groundwater dependent ecosystems, GDEs).

Remote sensing provides a unique opportunity to understand spatio-temporal dynamics of these processes and to estimate the fluxes. Two particular advantages of RS techniques are the availability of historical data (over 40 years) and the ability to monitor specific surface objects of interest over large areas at low cost. This is particularly valuable in remote and data poor areas.

Remote sensing technologies are best used where their outputs can be validated by on-ground measurements. The results provide important and independent information for hydrogeological analysis, helping to derive a better conceptual groundwater, to define the groundwater fluxes in groundwater discharge zones and to identify the importance of some geological forms (surface expression of faults or stratigraphical boundaries).

A special Groundwater Systems Monitoring Tools (GSMT) has been developed and tested for a number of projects in Pilbara (WA), Namoi (NSW) and Northern Australia.

Hydrogeology of West Ambae, Vanuatu as inferred by geo-electrical resistivity survey

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1. Water and Sanitation Programme, Geoscience Division, Pacific Community, Fiji Islands
2. Department of Water Resources, Vanuatu

As part of the resilience-building component of SPC's recovery support for Tropical Cyclone Pam funded by KfW and in collaboration with Vanuatu's Department of Water Resources, geophysical surveys were carried out using electrical resistivity in the N'dui and Walaha districts of West Ambae, Vanuatu, to assist with identifying fresh groundwater resources potential and optimal drill targets. In the absence of drilling and subsurface information in general, survey locations were selected based on surficial features including eruptive cones and fissures, and lineaments with the potential to cause high-elevation groundwater impoundment. In addition, geological maps were used to infer locations where groundwater may occur at relatively shallow depth along contacts between lava flows of different age. Ten geo-electrical transects were performed (> 5 km total length) allowing for the 2D representation of the spatial distribution of electrical resistivity up to 90 m depth. The interpretations suggest a limited presence of localized aquifers, either impounded within fractured basalt or perched due to the presence of impervious formations like ash or tuff layers between lava flows. The presence of springs at higher elevations supports the conceptual model of perched aquifer systems while the existence of brackish water springs along the coast suggests that infiltrating rainwater finds its way through the fissured basaltic lava flows and highly porous scoriae and eventually discharges into the sea. The small number and limited extent of identified potential targets highlights the value of performing detailed resistivity surveys prior to any drilling operations to minimize costs and risks associated with "wildcat" drilling.

National and consistent daily deep drainage data from the Australian Water Resources Assessment (AWRA) model

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Reliable estimates of water availability across Australia are required for historical understanding, current status evaluation and planning purposes. These estimates must be made for the majority of Australia based on limited or no observations. This presentation introduces Australian Water Resources Assessment Landscape (AWRA-L) model, towards use for water availability assessments with a particular focus here on groundwater.

AWRA-L is a one dimensional, 0.05° grid based daily water balance model over the continent that has semi-distributed representation of the soil, groundwater and surface water stores developed by CSIRO and the Bureau of Meteorology, and now run operationally within the Bureau. The Australian Landscape Water Balance website (www.bom.gov.au/water/landscape) — provides access to AWRA-L modelled soil moisture, runoff, evapotranspiration, deep drainage and precipitation with daily gridded outputs available from 1911 until the present. Further, AWRA-L has also been released as a community modelling system (https://github.com/awracms/awra_cms) so the public, researchers and organisations can now access, run and alter the model and suggest changes. This means AWRA can be used for different applications, such as local and regional area applications using locally relevant climate, soil or vegetation properties.

We present evaluation of AWRA-L - focused on comparison of deep drainage to recharge estimates collated nationally. AWRA-L performs reasonably for deep drainage according to evaluation against a national dataset. Further, we compare the deep drainage output by AWRA-L to other available methods applied within the Murray-Darling Basin; and show where AWRA-L falls within the range of methods compared described in light of the assessment against recharge estimates. Future developments of AWRA-L are also discussed.

The groundwater community can now easily visualise, investigate and download up-to-date daily water balance information including deep drainage to further inform groundwater modelling activities. Overall this modelling system provides a valuable addition to groundwater availability assessment across Australia.

DAY 1: Tuesday, 11 July 2017

MANAGEMENT

Implementation of the Murray-Darling Basin Plan: adaptive management and Plan amendments

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1. Murray Darling Basin Authority, Canberra, ACT, Australia

The Basin Plan was gazetted by the Minister for Water in November 2012. In November 2016, the first round of amendments of the Basin Plan were released for public consultation. The amendments were grouped into three categories: relating to the Northern Basin Review, relating to groundwater and other minor practical changes. The groundwater amendments focussed on baseline diversion limit (BDL) and sustainable diversion limit (SDL) changes, the compliance methodology, local management rules and adjustments to review provisions, water resource plan (WRP) area boundaries and SDL resource unit boundary definitions.

The Basin Plan requires that formal reviews be undertaken of the SDLs in three groundwater areas. This adaptive management approach ensured that the most appropriate recharge and SDL calculations were incorporated. The reviews were to be undertaken by expert review panels and found that the SDLs in these areas could be increased "once assurances have been given by the relevant state to demonstrate that the resources will be managed by state policies and plans so as to limit impacts to acceptable levels." The Basin Plan amendments incorporate these findings.

The amendments also include a proposed change to the methodology for assessing compliance with SDLs. The proposal states that a 10-year rolling average compliance method be used for groundwater SDL resource units. Non-compliance will occur after 1 July 2028 if the average annual take over the 10 year period ending with that water year is greater than the average annual permitted take over the same period and the state does not have a reasonable excuse.

A number of other technical and administrative groundwater issues have also been identified and included in the proposed amendments. These have been requested by NSW, Vic and Qld and are aimed at ensuring alignment with state water management plans to reduce complexity and administrative burden.

Reporting groundwater use under the Murray-Darling Basin Plan

Tariq Rana[1], Peter Hyde[1], Kristanne Mahony[1]
1. Murray-Darling Basin Authority, Canberra, ACT, Australia

Robust water accounting and compliance in any groundwater system ensures that the volume of water actually taken does not exceed the volume of water that is permitted to be taken. This protects investment by governments, corporations and individuals and increases certainty and security for all water uses.

The Murray–Darling Basin Plan (Basin Plan), adopted in November 2012, represents a significant milestone in groundwater management in Australia. It is the first time that a limit of 3,334 GL/y on groundwater use has been established across the Basin. This limit is expressed through the application of sustainable diversion limits (SDLs). The Basin Plan prescribes 22 water resource plan areas and 81 SDL resource units relating to groundwater. Each SDL resource unit has a separate SDL to which the states must manage extraction.

Because the Basin Plan has not yet been fully implemented, groundwater use accounting and compliance in the MDB is in transition. To support compliance with the SDLs after 2019, section 71 of the *Water Act* 2007 (*Cwlth*) establishes new groundwater use reporting requirements. Basin states and the Commonwealth Environmental Water Holder (CEWH) are now required to undertake monitoring and reporting of annual water availability and use in accordance with these arrangements.

Given requirements for reporting against all forms of groundwater take, the Authority and Basin states have identified the transition period as an important opportunity to establish and agree, trial arrangements for calculating and reporting actual and permitted take in ways that will support SDL compliance from the 2019/20 water year onward. This will help to ensure that there is continued confidence in the security of water entitlements and the effective operation of water sharing arrangements and trade through the water market.

Australian aquifer boundary alignment with National Aquifer Framework

Liam Murphy[1], Brendan Dimech[1], Elisabetta Carrara[1]
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Objectives: The Bureau's "Australian Groundwater Insight" currently displays the extent of all major aquifers in Australia, grouped by Upper (shallowest), Middle and Lower (deepest). The purpose of this aggregation is to convey the 3D nature of aquifers to non-groundwater experts. Aquifers are categorised as belonging to Upper, Middle or Lower horizons in accordance with the methodology initially established with the Victorian Aquifer framework, and further modified in reference to their stratigraphic horizon position.

The aim of this work is to align the existing aquifer boundaries and their aggregation with the National Aquifer Framework (NAF) and produce a hydrostratigraphic table to show what Hydrogeological Units are included in each group. This data conveys the relative sequence of layers in a simplified way. This will also improve the consistency of the Bureau's groundwater products.

Design and Methodology: Australia was first broken up into several major provinces based on Geoscience Australia Provence layer. Nine provinces were identified across Australia and were separated by basement highs.

Secondly a simplified hydrostratigraphic table was created to display how Hydrogeological Units are grouped. The table further divides the 9 provinces into 24 basins (and sub basins where needed) and basement highs. This summarises how the NAF Hydrogeological Units are grouped into Upper/Middle/Lower, and it also shows the relevant NAF Hydrogeological Complex's which provides information about the age, depositional environment and rock type.

Conclusion: The new aquifer boundary layer will support a better understanding of the 3D nature of groundwater to non-groundwater experts.

The table will also provide stakeholders with a consistent framework when working with aquifers across Australia and it will also provide a valuable link to the National Aquifer Framework.

Accounting for and managing the impacts of plantation forests on regional groundwater resources

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4. Department of Environment, Water and Natural Resources, Adelaide, SA, Australia

In the South East of South Australia groundwater management now incorporates 150,000 ha of plantation forestry as a licensed water user; accounting for 30 per cent of all licensed allocations. This is the first time that forestry has been required to hold a water licence to offset its hydrological impacts and this has been acknowledged by the United Nations Association with an *Excellence in Water Management Award* in 2016.

It is impractical to measure plantation impacts on groundwater at a commercial scale, whether in terms of recharge, or extraction from shallow water-tables. Therefore, there is a need for a robust model to account for forest impacts at a sub-regional scale. In this study, we evaluated the water accounting methodology adopted by the regional water allocation plan. The model accounts for forest impacts on groundwater recharge, and extraction where the water-table is shallow, using biophysical principles and scientific observations.

The forest groundwater accounting methodology was tested by calculating an annual water-mass-balance for softwood and hardwood plantations, with various depths to the water table, and comparing this calculation against 40-years of observed changes in groundwater storage, indicated by the changes in groundwater level. Sites, each of 5000 ha, where plantation forestry is the main land use were assessed for the study using a profile of the plantation forest estate from industry data.

The calculated annual net changes in groundwater storage compared well with the actual observed changes in groundwater storage. These results indicate that the adopted water accounting method can accurately estimate the annual net impacts of plantation forests on groundwater resources, concluding that the forest water accounting model is fit for the intended purpose of estimating, for management purposes, the impacts of the regional plantation forest estate on groundwater resources.

Fishermans Bend: regional-scale groundwater assessment and regulatory considerations

Anne Northway[1], Eleanor Pritchard[1], Ernie Sanchez[1]
1. EPA Victoria, Carlton, VIC, Australia

Fishermans Bend is Australia's largest urban renewal project, covering about 485 hectares in central Melbourne. The Environment Protection Authority Victoria (EPA) aids the cross-government Fishermans Bend Taskforce. As part of this, EPA oversaw a groundwater study across the initial area of Fishermans Bend (part 1), and is overseeing part 2 in the Employment Precinct.

This presentation will discuss key elements of Victoria's regulatory process for the groundwater study, the findings of the assessment and how EPA is using the results to inform the community and make regulatory decisions.

The presentation will discuss the objectives of the groundwater study: determine the district-wide baseline groundwater quality, particularly focusing on the shallow groundwater table in contact with fill material; confirm the protected and precluded beneficial uses of groundwater across the district; understand the potential risk of groundwater contamination to surface water receptors; and, how these were met.

We will discuss the results of the groundwater study in Fishermans Bend. Key factors in the regulatory framework that are considered as part of the risk-based decision making by EPA include: the condition of groundwater, and the ability of EPA to identify a groundwater quality restricted use zone (GQRUZ). We will discuss the probability of realising the beneficial uses, land uses in the area, potential impact to the nearest surface water receptors, and consultation with affected stakeholders.

The Fishermans Bend groundwater study and application of the regulatory framework has aided the regulator in understanding the current condition of groundwater at a regional scale. We will discuss how EPA will use the groundwater quality information obtained to make robust and timely regulatory decisions, how it will be able to be used by environmental consultants and developers to aid in site remediation and provide information to the community.

A comparison of French and Australian policies for sustainable groundwater management

Steve Barnett[1]
1. Department of Environment, Water and Natural Resources, *Adelaide, SA, Australia*

Following the 43rd International Congress of the International Association of Hydrogeologists which was held in Montpellier (France) in September 2016, a two day French-Australia Workshop on Groundwater Management took place with 30 French attendees and 13 Australian attendees from SA, NSW, WA, Vic, BoM, MDBA and ANU.

Case studies were presented on various aspects of groundwater management from both countries, and further discussions allowed a comparative analysis to be conducted by the French and Australian water professionals, supported by a small group of academics. This presentation will identify some of the similarities in management philosophy and technical methodologies, but also fundamental differences in management approaches which are mainly related to the population, climate, the role of the State and the community and also market mechanisms. Some topics for future collaboration are also suggested.

Managing groundwater resources in the absence of numerical models

Saskia Noorduijn[1], Peter Cook[1], Craig Simmons[1]
1. School of the Environment, Flinders University, Adelaide, SA, Australia

Numerical groundwater models are frequently used to inform the groundwater planning process, and can be used to predict potential impacts of different water allocation scenarios or even of individual license applications. However, limited data availability, cost or apparent necessity means that numerical models are not always available to aid in decision-making. In these model deficient areas, a simple, widely used approach employs groundwater extraction limits on a proportion of the estimated recharge. This may not always be appropriate for ensuring sustainability of the resource and ecosystems that depend upon it. The objectives of this review are to provide groundwater managers with an outline of the different approaches available, which are not reliant upon numerical models, and how they can be applied to help protect areas of interest within the environments such as lakes, rivers, and groundwater dependent ecosystems.

A number of different considerations need to be identified to develop a robust, sustainable groundwater management plan. For example, different approaches operate on different time frames such that strategies that work on one time frame might fail completely on other. Therefore, the period over which different groundwater allocations apply can affect the resources/assets and govern the response and possible adaptation within the environment. This review will highlight some key points to aid groundwater managers in selecting appropriate approaches dependent on the identified environmental receptors. Current management strategies (such as buffer zones, groundwater trigger levels, and hybrid approaches) are reviewed to determine their advantage and disadvantages based on their ability to predict changes in groundwater storage, ecosystem protection, and temporal variability in groundwater levels. Furthermore, guidance in the application of alternative, simple, scientifically informed approaches are provided.

DAY 1: Tuesday, 11 July 2017

MAR / STORMWATER MANAGEMENT

Utilising a fractured aquifer for storm water management at the Ernest Henry underground mine

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2. Mineright, Cairns, QLD, Australia

3. Ernest Henry Mining, Cloncurry, QLD, Australia

The Ernest Henry Mining (EHM) sublevel cave provides a hydraulic connection between the pit and the underground (UG) mine. This connection results in the potential of water inflows into the UG workings during major rain events.

An UG reservoir and pumping system has been installed to mitigate the risks from storm water inflows. Half of the UG reservoir volume is located in hydraulically conductive and fractured ground, which results in recharge to the mine aquifer during periods of water storage. To manage the additional strain that this recharge puts on the UG pumping system an optimization of the reservoir fill strategy and pumping sequence was carried out.

Prior to the 2015/16 wet season the pumping and reservoir system was tested by filling the leaking section of the reservoir with water from the active dewatering system. The reservoir was filled at a rate of 150 to 230 l/s for seven days and water levels in the reservoir as well as in the adjacent fractured aquifer were monitored. Detailed monitoring of water levels and pumping volumes allowed to quantify water loss from the reservoir and to determine recharge times and storage volumes in the fractured aquifer.

Water loss from the reservoir increased linearly with water level in the reservoir and reached a total loss of 180 l/s at a water level of 35 m. The first water level increase in the fractured aquifer was observed 41 hours after water was filled into the reservoir. The water loss into the fractured aquifer allows to utilize the fracture volume as additional storm water storage during rain events, which provides an estimated 50 ML of additional water storage. The test results allowed to develop optimized reservoir fill strategies and pumping schedules for major rain events.

Implementing a successful Managed Aquifer Recharge system

Russell Martin[1]
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Storm water harvesting and the subsequent storage of water under ground using Managed Aquifer Recharge (MAR) methodologies to achieve water supply sustainability and security is developing as an important alternative to meet urban, industrial, agricultural, and environmental water needs. Aquifer storage and recovery (ASR) is the most common MAR method applied throughout Australia. Currently, there are approximately 110 ASR wellfields and over 230 ASR wells operating across Australia. Implementation, design and operation of a successful and sustainable MAR system can face many challenges such as well design, clogging, recovery efficiency, poor design and geochemical reactions. Many of these challenges have been encountered and resolved by experienced practitioners in this specialised area of hydrogeology and the success rate of installed ASR systems to date has been high. There are still numerous challenges to be addressed and additional methodologies to be applied in the various hydrogeological settings found throughout Australia. Increasingly however; there have been several instances in the past few years where installed schemes have ultimately presented the operator with a system that underperforms or requires significant design modification post- construction to meet the original objectives of the project. Poor implementation or failure of ASR systems presents a potential threat to the ongoing uptake of this methodology as a resource management option. This paper draws upon recent case studies and a wide diversity of ASR experience gained over the past 30 years to present some of the more important technological aspects and other lessons learned that would be helpful for those considering starting a new ASR system or to enhance performance of an existing ASR system.

Factors affecting Managed Aquifer Recharge (MAR) scheme costs

Sunail Hasnain[1], Andrew Ross[1]
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Managed aquifer recharge (MAR) is an important technique for improving groundwater recharge and maintaining aquifer levels. There are many examples from around the world that demonstrate the advantages of managed aquifer recharge. Despite the numerous benefits and demonstrated advantages of MAR uptake has been lower than expected. The financial and economic performance of MAR is a key determinant of its global uptake. There are few studies of the financial characteristics and performance of different kinds of MAR schemes. This study contains an analysis of financial data from 22 MAR schemes from 5 countries. Although MAR schemes are highly heterogeneous it is possible to draw some conclusions about factors that affect the costs of storing water underground and recovering it for use. The costs of MAR schemes vary substantially. Schemes using natural infiltration and spreading basins using untreated water are relatively cheap. Schemes using wells, bores and expensive infrastructure are relatively costly. When water treatment is needed this involves significant extra costs. Other key factors that affect MAR scheme costs include scheme objectives and scale, frequency of utilisation of the scheme, hydrogeological conditions, and the source and end use of water stored underground. Priorities for further research include additional disaggregation of capital and operating costs, collection of more data on socio-economic, environmental, legal and institutional factors affecting the economics of MAR and inclusion of a wider range of studies including from developing countries.

Feasibility of MAR and CWU for irrigation in the Pilbara

Greg Hoxley[1], Chris Schelfout[2], Kate Dowsley[1], Rick Evans[1], Richard George[2]
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The Pilbara region of Northern Australia has good quality groundwater resources associated with alluvial aquifers. These aquifer are not currently used for irrigation in part because of concerns over the long term sustainability of the aquifer. Surface water in the Pilbara is dominated by short, high flow periods. Whilst surface water dam sites can be found, very high evaporation rates coupled with the short flow period make surface water storage unattractive. Groundwater storage has the potential to enable the augmentation of the existing aquifer resources that could boost the available water for irrigation. This study has assessed the feasibility for Managed Aquifer Recharge in five areas in the Pilbara. The irrigation scenario that has been used is to augment beef herd preservation through the use of mosaic irrigation. At two of the five sites the potential to harvest and use water from mine de-watering is also considered. The study has selected a preferred site and a reserve for field studies and detailed evaluation.

Fortescue Metals Group's Papa Waringka - dewatering and Managed Aquifer Recharge (MAR) scheme

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Fortescue's Chichester Hub is an iron ore operation located within the Pilbara region of Western Australia adjacent to the Fortescue Marsh. The Marsh is a 1000km^2 evaporation basin comprised of a complex array of alluvial aquifers and is a wetland of national significance. Given this significance, its proximity to the mine, the complex hydrogeology, and the hypersaline quality of groundwater; stringent water management conditions were applied by both State and Federal regulators. The *Papa Waringka* (*Nyipali language for water in the ground*) dewatering and MAR schemes employs a complex, integrated, multiple water quality solution to enable below watertable mining whilst mitigating environmental impacts on the Marsh and ensuring regulatory compliance. All surplus water is returned to the appropriate aquifer systems via groundwater injection for either future operational supply if brackish, or if saline to maintain pre-mining water levels in the vicinity of the Fortescue Marsh. As far as the authors can ascertain, the *Papa Waringka scheme* represents one of the world's largest dewatering and MAR schemes and by all accounts, Australia's largest. *Since operations commenced in 2008 the Papa Waringka scheme has:*

- *Dewatered 575GL of water;*
- *Injected 432GL of saline water;*
- *Injected 26GL of brackish water;*
- *Recovered 24GL of previously injected brackish water.*

The *Papa Waringka scheme* has been awarded numerous awards the most recent being the International Water Association (IAW) award for innovation (2012). Since winning this award, the *scheme* has grown fivefold and has been used multiple times as a leading practice case study example in water management, most recently in the *"Leading Practice Sustainable Development Program for the Mining Industry"* and the Department of Water, "*Water for Growth – Mining* document". The authors believe the *Papa Waringka* Scheme is an excellent case study on how to balance the requirement for continued economic development whilst avoiding environmental impacts.

Bayesian framework for benefit-cost analysis of clogging investigations at ASR sites

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Cost-conscious developers of any new ASR project may be reluctant to invest time and cost to undertake investigations to determine whether the level of treatment intended for the source water will be adequate to prevent irreversible clogging in the injection well. So a Bayesian approach was developed to determine the benefit cost ratio of undertaking such investigations before undertaking them, using assumed reliability of investigations. This gives transparent outcomes based on the views held by decision makers.

At three Australian ASR sites, two stormwater and one treated sewage effluent, the projected confidence of a successful outcome for a given water type was qualitatively defined based on experiences at each phase of project investigations. A Bayesian analysis of laboratory column clogging studies was undertaken and embedded in an analysis of expected benefits and costs. Furthermore, the effect of clogging on operational costs including reduced volumes recharged and well rehabilitation for accute and chronic clogging were defined using analytical equations.

Benefit-cost ratios were determined for a set of assumed experimental reliabilities (10% false positives and 20% false negatives) for an applied example project. The results showed that if the results of the clogging investigations were used to make water treatment decisions, expected benefits significantly exceeded costs regardless of whether the clogging investigation predicted clogging or no clogging.

Although this Bayesian approach is based on assumed experimental reliability, it does show how clogging investigations can be highly valued in establishing viable projects and in avoiding losses, and lead to more confident decisions. This work has been documented in Dillon *et al* (2016) but has not yet been presented at an Australian conference.

1. *Dillon, P., Vanderzalm, J., Page, D., Barry, K., Gonzalez, D., Muthukaruppan, M. and Hudson, M. (2016). Analysis of ASR clogging investigations at three Australian ASR sites in a Bayesian context. Open Access Journal "Water" 8(10), 442 (17p); doi: 10.3390/w8100442. Special Issue "Water Quality Aspects of Managed Aquifer Recharge" " (published 12 Oct 2016) PDF Version: http://www.mdpi.com/2073-4441/8/10/442/*

Fluoride and phosphate release from insitu carbonate-fluorapatite during trial Managed Aquifer Recharge injection of recycled deionised wastewater

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Managed aquifer recharge (MAR) of purified wastewater can create geochemical disequilibrium which may trigger various water-rock interactions, including the mobilisation of geogenic fluoride. A comprehensive MAR trial has been conducted to investigate the feasibility of recharging recycled, deionised wastewater into the Cretaceous silici-clastic Leederville aquifer of the Perth Basin, Western Australia. During the injection trial, simultaneous pulses of fluoride (up to 1.1 mg/L) and phosphate (up to 1.7 mg/L) were observed to occur rapidly upon breakthrough of the deionised injectate. As fluoride concentrations above 1.5 mg/L are considered detrimental to human health it is important to determine the geochemical mechanisms causing the fluoride release.

Saturation indices for a suite of phosphate and fluoride bearing minerals performed on comprehensive pre-injection groundwater analyses indicated that the fluorapatite-water interface layer of dicalcium phosphate composition ($CaHPO_4.nH_2O$) [1] was the closest phase to saturation. Other fluoride-bearing minerals, such as fluorite, were significantly undersaturated and presumably absent. Phosphatic nodules sourced from Leederville aquifer core material were analysed and found to contain significant carbonate-fluorapatite (CFA =$Ca_{10}(PO_4)_5(CO_3F)F_2$), a variety of fluorapatite which is by far the most common autochthonous phosphate mineral in sedimentary environments [2]. Anaerobic batch experiments with powdered CFA rich nodules produced a similar release pattern for fluoride and phosphate to that observed during the MAR field trial. Fluoride extraction experiments with Leederville sediments of low phosphate content yielded minimal fluoride release. The observed fluoride and phosphate pulses can be primarily attributed to incongruous dissolution of CFA mediated by calcium preferential removal onto exchange sites under low ionic strength conditions. Elevated fluoride and phosphate concentrations were found to recede once a new equilibrium for Na-Ca exchange was established under low ionic strength conditions.

[1] Chaïrat, C., et al., GCA, 2007. 71(24): p. 5901-5912.
[2] Föllmi, K.B., Earth-Sci. Rev., 1996. 40(1–2): p. 55-124.

DAY 1: Tuesday, 11 July 2017

AFTERNOON PLENARY

Groundwater & Climate Change in Drylands: From Hominin Evolution to Future Human Resilience.
Dr Mark Cuthbert, Research Fellow & BGS Lecturer in Environmental Geoscience, School of Earth & Ocean Sciences, Cardiff University, UK

Groundwater and climate change in drylands: from hominin evolution to future human resilience

Mark Cuthbert[1]
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Drylands cover around 40% of the global landmass, support a population of around 2 billion people, 90% of whom live in developing countries, and support nearly 50% of the world's livestock and cultivated land. Groundwater is often a critically important water resource in such regions acting to 'buffer' the variability in climate and provide reliable freshwater both for humans and other ecology. Despite its importance, significant challenges are still faced in understanding and modelling dryland climate-groundwater interactions globally.

This talk will begin by outlining how the concept of 'groundwater response time' enables us to understand the relationship between climate variability and the presence of persistent sources of freshwater in global drylands. This idea will then be used to explore the role that groundwater hydro-refugia likely played in enabling human resilience to climate change over the past 2 million years since the origin of our own genus *Homo*.

Finally, recent progress in understanding climate-groundwater interactions in dryland environments will be presented to suggest how global modelling efforts can be improved to enable more robust future groundwater management and climate change resilience.

DAY 1: Tuesday, 11 July 2017

WATER QUALITY

The presence of magmatic CO2 in central Victorian basalt groundwater and its influence on hydrogeochemistry

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The Birch Creek catchment in central Victoria is covered predominantly by Pliocene – Quaternary Newer Volcanics basalt lavas with scattered eruption points; the lavas overlie Tertiary valley-fill sands and Palaeozoic bedrock. Groundwater within the catchment can be divided into 3 types. Type 1 groundwater is fresh (<600 uS/cm, < 60 mg/L Cl) and occurs close to eruption points where recharge is rapid; type 2 is more saline and its EC (900-1500 uS/cm), which is strongly correlated with the Cl concentration (60-280 mg/L), increases downgradient. This reflects the progressive input down the flow path of recharge that has been impacted by evapotranspiration during infiltration through the low permeability clay-rich soils on the basalt. Type 3 groundwater is found in 3 bores located within 1 km of each other, and has quite different chemistry, with relatively high salinity (900-1500 uS/cm) but low Cl levels (<50 mg/L), so the high salinity is not due to evapotranspiration, in contrast to Type 2 groundwater. Type 3 groundwater also has high PCO_2 ($10^{-0.6}$ to $10^{-1.8}$) and enriched $del^{13}C$ (>-10), similar to the naturally effervescent Hepburn mineral springs located ~15 km east of Birch Creek. The Hepburn spring water contains high levels of magmatic CO_2, presumably derived from an underground reservoir emplaced during eruption of the Newer Volcanics, and type 3 groundwater has a component of CO_2 from the same source. The input of CO_2 made type 3 groundwater more acidic, increasing the weathering of olivine and plagioclase in the basalt and releasing substantial amounts of Mg^{2+} and Na^{2+} into this groundwater, accounting for its relatively high salinity but low Cl concentration. Therefore, magmatic CO_2 is more widespread in central Victoria than previously realised, and its distinctive hydrochemical signature (high salinity but low Cl) can be used to identify its presence in groundwater throughout Victoria.

Assessing aquifer effectiveness as a natural treatment barrier for recycled water

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3. Water Corporation, Leederville, WA, Australia

Using aquifers to store and treat recycled water provides a cost effective solution for management and optimal use of water resources, a necessity in light of predicted population growth and climate change. Operational wastewater disposal schemes provide a unique opportunity to develop the scientific understanding of the treatment capacity of the aquifers. Analysis of long-term datasets from these schemes and extrapolation to managed aquifer recharge schemes can facilitate future innovations in water recycling.

Eighteen wastewater infiltration sites, constructed over sand or sand/limestone, were used to evaluate the aquifer treatment performance. Water quality data was analysed to assess the removal efficiency for nitrogen, phosphorus and *Escherichia coli* using a probabilistic modelling approach. The treated wastewater (input) and groundwater (output) quality were considered as stochastic variables represented by probability density functions (PDFs). These input and output PDFs were used to derive a theoretical aquifer removal efficiency PDF for nitrogen, phosphorus and *E. coli*.

Site specific characteristics influenced removal efficiency, including wastewater treatment type, soil and aquifer characteristics and operational practices. Despite such influences, median total phosphorus removal efficiencies were typically >90%. Downgradient concentrations of phosphorus were comparable to background groundwater quality, for bores within 700 m of the infiltration basin. While overall the median total nitrogen removal efficiency was 80%, nitrogen attenuation between sites was more variable than for phosphorus. The efficiency of nitrogen removal was controlled by the propensity for denitrification at selected sites. The probabilistic modelling approach was limited for *E. coli* due to the low number detections in groundwater despite the high concentrations in treated wastewater.

The probabilistic modelling approach was effective in calculating the attenuation of nitrogen and phosphorus within aquifers across eighteen different wastewater infiltration sites. This approach was demonstrated as a useful management tool to assess operational performance of the aquifer treatment barrier in water recycling.

Are we over-analysing water when assessing project related impacts?

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Are the project specific objectives of water quality monitoring sometimes lost in the large amounts of data collected? Are we spending too much time and money characterising the water quality where we could undertake risk-based assessments and only monitor for analytes that are an indication of a potential project related risk?

Case studies where extensive suites of water quality analytes are monitored during operational water quality monitoring programs are presented and discussed. But, has an accurate assessment of the receiving environment's sensitivity been completed when selecting the analytical suite? And what does an exceedance of a trigger value mean on the receiving environment?

How can we design risk-based monitoring that is appropriate to monitor the potential impacts from the project and include a targeted analytical suite optimised for impact assessment?

Extensive suites of analytes are often expected by regulators and clients based on previous assessed projects, but reduced analytical suites may be more appropriate.

Analytes that can in some instances be made redundant are proposed.

When designing an operational water quality management program, we need to consider a targeted monitoring approach focussing on potential risks from the project, while meeting clients' and regulator's expectations… "Less is more"

Use of control charts for groundwater quality monitoring and assessment – the Queensland (Australia) experience

John Broughton[1], Tim Anderson[1]
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The purpose of monitoring is to detect impacts associated with the monitored activity. Where an impact occurs, monitoring should provide early detection, thus allowing for early corrective action. Groundwater quality monitoring programs developed for compliance assessment as part of mining licencing requirements in Queensland are rarely this useful. Problems such as poor data collection and insufficient quality control can be easily remedied. More significant issues are the representativeness of compared bores used by inter-bore monitoring approaches and the high false-positive rate of the compliance assessment. A control chart monitoring approach that addresses these issues is presented here.

This presentation describes the adaptation of existing control chart groundwater quality monitoring approaches to meet the environment management and regulatory requirements of mining operations in Queensland. The adapted approach has been operational at a major Queensland mine for two years and has proven effective in detecting situations requiring management intervention and in reducing false-positives that would otherwise be generated by traditional approaches.

The approach has two key advantages. Firstly, it uses an intra-bore data comparison, rather than comparing data from 'compliance' and 'reference' bores, negating the issue of representativeness. Secondly, compliance assessment for the approach uses the frequency and magnitude of monitoring values to define events, rather than just single values. This reduces false-positives. A further innovation is the use of percentiles to set control limits.

In parallel with development of the technical aspects, the regulatory context for the use of control charts in licences was negotiated with the State. The licence conditions combined detection of groundwater quality changes and protection of environmental values into an outcome that was acceptable to the mining operation and the regulator.

If suitability applied, the approach has the potential to increase the effectiveness of groundwater quality monitoring and improve regulatory and environmental outcomes at mining operations.

Where do the methanogens live? New insights into the origin of methane in the Condamine River alluvial aquifer

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There is considerable debate about the origin of methane (CH_4) in aquifers surrounding coal seam and shale gas exploration and production. Numerous processes control the natural occurrence of CH_4 in groundwater. To determine the origins of CH_4 in an aquifer both the geochemical and microbial community need to be characterised, however this is rarely done. We use geochemical and microbiological data, along with measurements of CH_4 isotopic composition ($\delta^{13}C\text{-}CH_4$), to determine the processes acting upon CH_4 in the Condamine River Alluvial Aquifer, a freshwater aquifer that directly overlies coal measures targeted for coal seam gas production in Australia.

Groundwater samples for geochemical and microbiological analyses were collected from private irrigation boreholes in the Condamine Catchment. The groundwater was analysed for the major ions, water stable isotopes (δ^2H and $\delta^{18}O$), the isotopic composition of dissolved organic carbon ($\delta^{13}C_{DOC}$) and dissolved inorganic carbon ($\delta^{13}C_{DIC}$). Quantitative real-time PCR was used to determine abundances of bacterial and archaeal 16S rRNA gene targets and functional gene targets in the groundwater.

Measurements of CH_4 concentration and isotopic composition suggest that there is biogenic CH_4 in the aquifer, however microbial community analysis indicates that there are no methanogenic archaea in the groundwater. In addition, geochemical data, particularly the isotopes of DIC and, as well as the concentration of SO_4^{2-}, indicate limited potential for methanogenesis *in situ*. Microbial community analysis also showed that aerobic oxidation of CH_4 is occurring in the alluvial aquifer despite the absence of a microbial pathway to produce the CH_4.

The combination of microbiological and geochemical indicators suggests that the most likely source of CH_4, where it was present in the deeper freshwater aquifer, is the upward migration of CH_4 from the underlying coal measures.

Interdisciplinary insights into the Lake Eyre Basin

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Interdisciplinary approaches to solving environmental and water resource science problems is the *modus operandi* of the Science Group within the South Australian Government Department of Environment Water and Natural Resources. This presentation provides two examples of where multiple science disciplines have come together to improve our understanding of the water sources that supports ecological communities in the Far North of South Australia.

Under the Lake Eyre Basin Water Knowledge Project, 1) the source of groundwater supporting ecologically diverse springs in two regions of SA was investigated using hydrogeological techniques combined with land-based geophysical surveys and ecological assessments and 2) the distribution and characteristics of water supporting riparian landscapes and the dependency of those ecosystems on that water source was investigated using hydrogeological and hydrological techniques, remote sensing and hydro-ecological assessments.

In these studies, we were able to investigate key knowledge gaps to provide a transparent and knowledge based vulnerability assessment on relevant spring and riparian environments. Fingerprinting water sources for vulnerable ecosystems, and ecological surveys to assess ecosystem health, significance and groundwater dependence allowed detailed conceptual hydro-ecological models to be generated for these environments.

A core challenge and focus of these studies was communication, an important component being the development of conceptual hydro-ecological models. These models explain the function and possible interactions between groundwater and groundwater dependant ecosystems and in particular provide a framework to explain how groundwater extraction may or may not impact the ecosystem.

Key outcomes included:

- The discovery of non-Great Artesian Basin (GAB) groundwater contributing significantly to certain spring systems, and
- Far North SA riparian environments are not completely dependent on shallow groundwater, but are capable of accessing water from a variety of sources. With further evidence showing trees move soil moisture around the root system, thus optimising the distribution and use of soil moisture.

A systems integration approach to estimating water quality - letting the water tell the story

Clinton Rissmann[1], Alexandra Badenhop

1. University of Canterbury/Lincoln University, Invercargill, Southland, New Zealand

Water quality decline is evident in areas of farming intensification in the Southland region of New Zealand. However, regardless of similar landuse pressures, there is significant spatial variation in water quality outcomes. To optimise water management expenditure, the accumulation and transport of farm contaminants through soil, groundwater, and into streams and rivers must be understood. This work utilises a systems integration approach to explain the spatial variability in the hydrochemical and water quality signatures of freshwaters. Precipitation (rain, hail and snow), soil, soil water, ground- and surface water samples were analysed and cross-referenced against existing spatial frameworks of topography, geomorphology, hydrology, hydrogeology and soils. This included classifying waters with common origins and identification of the controls or 'drivers' over water composition. Four key drivers of surface water and shallow groundwater composition were identified and mapped for the Southland region: (i) precipitation source; (ii) water source and recharge mechanism; (iii) combined soil and geological reduction potential, and; (iv) geomorphic surface age and substrate (rock and sediment) composition. Maps for each driver layer spatially depict driver gradients across the region that influence different aspects of water composition and quality. Each driver layer is a distillation of (multiple) critical characteristics of pre-existing spatial frameworks (e.g. soils maps, Q-Map, REC, DEM, hydrogeology). We demonstrate that: (i) through combination of each of the key spatial drivers it is possible to estimate the steady-state water composition of regional surface waters and shallow unconfined groundwaters with a high degree of confidence, and; (ii) that unique assemblages of driver layers can be used as a basis for targeted land use management to improve water quality.

DAY 1: Tuesday, 11 July 2017

CLIMATE CHANGE

Sustainable management of the Gascoyne River alluvial aquifer through a period of climate variability

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The sustainable management of the Gascoyne River alluvial aquifer is essential to maintain horticultural production from Carnarvon, Western Australian. Carnarvon is a major horticultural area with a mild climate and a supply of fresh water within the alluvial aquifer. The average Carnarvon rainfall is about 200 mm/yr with horticulture reliant upon irrigated water obtained from the Gascoyne River alluvial aquifer. The Gascoyne River is an ephemeral river that is predominately dry with an extensive fresh water alluvial aquifer recharged during sporadic and infrequent river flow events. Irrigation demand from the alluvial aquifer is about 12 GL/year with requirement for high quality water of less than 455 mg/L of total dissolved solids [TDS]. It is estimated that the banana crop suffers a 30 % decline in production as groundwater salinity increases from 455 to 770 mg/L TDS. Government intervention to limit abstraction and reduce groundwater salinisation occurred in the 1960's as a consequence of significant degradation in groundwater quality. Current groundwater management is based upon the measurement of groundwater salinity and level that is used to estimate aquifer storage and restrict the production of groundwater with salinity greater than 1000 mg/L TDS. This process utilises a range of tools that include a groundwater storage volume calculator, groundwater salinity contouring and groundwater models. The sustainable management of the alluvial aquifer has become more complex with changes in river flow cycles that have coincided with increased climate variability since the mid – 1970's. The groundwater model has been revised on a regular basis to provide groundwater storage and quality predictions. Groundwater management issues are an increasing priority due to expansion of the horticultural area with increasing demand, changes in crops and land tenure and increasing climatic variability combined with State provisions to recoup unused groundwater licences and implementation of groundwater entitlement trading.

Improving our understanding of groundwater resources in the Albany groundwater area to meet the challenges of a drying climate

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The Albany Groundwater Area covers an area of 2015 km^2 and is an important urban and agricultural development area on the south coast of Western Australia. It is facing severe climate effects with a 40-year drying trend projected to continue. Groundwater supplies over 80 per cent of drinking water to Albany and surrounding towns. As alternative drinking water supplies in the region are scarce, careful management of this limited groundwater resource is essential.

The Department of Water has recently completed an investigation into the Albany Groundwater Area that was initiated to help secure water supply into the future. Prior to this investigation, resources were near or at full allocation raising concerns on groundwater availability for future growth. In addition, important values including groundwater dependent ecosystems require protection and seawater intrusion from pumping near the coastline is a threat to water quality.

The key outputs of the project for the Albany Groundwater Area included developing a 3D conceptual model incorporating airborne electromagnetic data (AEM), groundwater chemistry, isotope sampling and hydrograph evaluation. AEM data was used to map the sea water interface along the southern coastline and a combination of AEM and chemistry data was used to map the interface along Princess Royal Harbour. The conceptual model was used to build a numerical groundwater flow and density model capable of simulating groundwater systems under varying projected future climate scenarios and pumping regimes.

Outcomes of the investigation show that additional water is available for use without significant impacts. This investigation indicates that recharge from future 2030 and 2050 dry climate projections is between 18 and 13 GL per year respectively, an increase on the current estimates of 9 GL per year. Our knowledge of the groundwater systems has been greatly improved which will secure water supply to Albany for up to 20 years.

Increased groundwater salinity resulting from pyrite oxidation exacerbated by climate change in a aquifer used for irrigation at Myalup, WA

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Irrigated horticulture, worth $62m annually, abstracts 14 GL/y from the superficial coastal limestone aquifer in the Myalup area, north of Bunbury WA. Salinity has been increasing in the aquifer. Previously it was thought to have resulted from; evaporation and recycling of irrigation return water, the application of fertiliser and/ or saltwater intrusion, however the relative role of these processes, or other potential processes, has not been assessed.

Licensee water quality data from 140 irrigated sites, collected since 2009, plus groundwater samples from an additional 61 targeted sites, with more comprehensive chemistry data were analysed to identify the sources of salinity and temporal trends.

Results showed aquifer salinity ranged from 400 to 5800 mg/L (median 1000 mg/L) similar to the historic median value. The chemical composition of groundwater salinity was also spatially variable. Around 75% of licensee sites had chloride:sulfate ratios <2; a marker for pyrite oxidation. There were no relationships between sulfate and fertiliser markers, nitrate and potassium, leading to the conclusion that pyrite oxidation and not fertiliser was the source of high sulfate in the aquifer.

There was an increasing trend in salinity (TDS) in 29 out of 140 sites while 6 had a decreasing trend in salinity. Of those increasing, at over half (n=18) pyrite oxidation was the dominate process. Recirculation or upconing was the dominant process at a third (n=9) of the sites and saline groundwater intrusion at 2 sites (7%).

The increase in salinity was predominantly driven by pyrite oxidation due to declining watertables attributed to climate change with decreasing rainfall. The pyrite oxidation was predominately from wetlands to the east of the irrigation areas. The pyrite oxidation has gone unrecognised due to neutralisation of acidity by limestone and is potentially the first instance of increasing groundwater salinity caused by pyrite oxidation in the Australian context.

The role of agreed resource condition limits in communicating the implications of climate change for groundwater resources

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The requirement commonly placed on hydrogeologists to quantify 'sustainable' extraction limits for a groundwater resource implies there is a quantifiable amount of water that can be extracted from a resource without causing unacceptable change in its condition over a given timescale. A central task for hydrogeologists responding to this requirement is to provide the technical information needed by stakeholders and environmental regulators to reach agreement on what are the limits of 'acceptable change' to the condition of the resource, whether these be changes in groundwater levels, salinity, discharges to the surface environment, or other groundwater condition indicators.

In the drying and warming climate projected for southern Australia, a change to the condition of some groundwater resources can be expected even in the absence of groundwater extractions. The likely impacts of climate change are therefore an important consideration in the assessment of groundwater extraction limits that aim to maintain the condition of a groundwater resource within agreed limits. The SA Department of Environment, Water and Natural Resources has incorporated projections of climate change and consequent groundwater impacts into the technical assessment of extraction limits for a number of groundwater resources. By incorporating projected regional climate change into predictive model scenarios, we have been able to communicate to stakeholders the relative risks of exceeding agreed resource condition limits under a range of extraction scenarios, with and without the impacts of climate change. By communicating the projected changes with reference to agreed resource condition limits, we have been able to convey an improved understanding firstly of the potential impact of climate change on water availability, but perhaps more importantly, of the need for water users and resource managers to reach collective agreement and compromise on their expectations of the future condition of the resources and environment to which they are accustomed.

A framework of simulation coupled optimization model incorporating climate change and landscape dynamics for sustainable groundwater development

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The world is facing severe challenges in meeting growing water demand due to increased population, intensified agriculture, dramatic changes in land use and climate change. This widens the demand-supply gap which in turn puts relentless pressure on the groundwater systems to bridge the gap. The exorbitant exploitation of groundwater has caused alarming rate of decline in groundwater level in many areas, particularly in arid and semi-arid regions where surface water is scarce and tubewell irrigation is practiced for agricultural productivity. The objective of this paper is to present a framework of simulation coupled optimization model for the comprehensive evaluation of the groundwater system to the imposed forcing stresses expressed as hydraulic, climatic and landscape stresses in order to arrive at the strategic regulatory plans of optimal pumping, groundwater withdrawal permits and well installation permits. It combines a numerical groundwater flow simulation model with an optimization model using internally linked resource matrix or embedding technique, a climate change effect simulator and a landscape change effect simulator. The groundwater flow simulation is carried out using a finite difference numerical model and the optimization model is solved using simplex algorithm for linear optimization model and exterior penalty function method linked pattern search algorithm for nonlinear optimization model. The developed modeling framework has been applied to two study areas, namely, Delhi aquifer system located in India and Aynalem aquifer system located in Ethiopia. Results reveal that the current groundwater withdrawal is more than the optimal pumping, indicating overexploitation of groundwater from several wells in the study areas. It is imperative to put regulations on pumping rates and installation of new wells to check the decline of groundwater table in critical areas and to ensure long term sustainability as the current pumping practice may not be secure on long run unless precautionary measures are taken.

Quantifying recharge from ephemeral stream check dams in a hard rock area with sparse data

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An ACIAR project (MARVI) was established to evaluate village level interventions, including managed aquifer recharge in sustaining rural livelihoods in hardrock areas of Rajasthan and Gujarat in drought prone NW India (Maheshwari *et al* 2014). The subject of this paper is the description of a method and results obtained from evaluation of recharge from four check dams over 3 years.

At each checkdam a topographic survey was used to produce area- and volume – elevation curves, a gaugeboard was installed and daily readings taken when the checkdam contained water and rainfall was recorded daily at raingauges, and groundwater levels recorded daily in nearby wells. The water balance was structured so as to minimise the error in recharge estimation. Some basins were scraped and the impact on recharge rate was recorded. Data were acquired by farmers trained and analyses were undertaken by the lead author, PhD student at Maharana Pratap University of Agriculture and Technology in Udaipur.

Recharge rates and annual values were determined and related to catchment runoff and groundwater use for irrigation. Approximately 18% of the groundwater used for irrigation was recharged from check dams. Scraping of check dams in the dry season was found to have an effect on the recharge effectiveness of checkdams and manual and mechanical scraping resulted in quite different outcomes.

This research has produced a template for evaluating recharge dam effectiveness with minimal data that can be collected by farmers using smart phones, including quality assurance. It enables benefit-cost analysis of programs for recharge enhancement and maintenance, and is opening prospects for development of further apps to allow upscaling of this work in India and elsewhere.

1. *Maheshwari, B., M. Varua, J. Ward, R. Packham, P. Chinnasamy, Y. Dashora, S. Dave, P. Soni , P. Dillon, R. Purohit, Hakimuddin, T. Shah, S. Oza , P. Singh, S. Prathapar , A. Patel , Y. Jadeja, B. Thaker, R. Kookana, H. Grewal, K. Yadav, H. Mittal , M. Chew , P. Rao (2014). The role of transdisciplinary approach and community participation in village scale groundwater management: Insights from Gujarat and Rajasthan, India. Int Open Access J Water, 6(6) 3386-3408. http://www.mdpi.com/journal/water/special_issues/MAR*

Groundwater organic matter: carbon source or sink?

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The natural environment plays a critical role in offsetting the anthropogenic carbon emissions. Despite the size of the global groundwater store the processes controlling the concentration and characteristics of organic matter in groundwater are poorly understood. Through a survey of global carbon concentrations, it is apparent that groundwater carbon concentrations are significantly lower than terrestrial (soil, sediment and river) concentrations. This indicates that terrestrial OM is biologically processed (and a potential source of inorganic carbon) or sorbed to mineral surfaces (a sink of carbon). This will be explored through an ARC Discovery research project which will investigate factors that determine groundwater organic matter concentration, how important is groundwater to the terrestrial carbon budget and under what conditions where groundwater is a carbon source or sink. This project is bringing together geochemists, ecologists, hydrologists and anyone with an interest in organic matter in groundwater. Specifically, the amount of colloid and dissolved organic matter present will be quantified, the rate and extent of biological processing, desorption and sorption will be investigated and the relative importance of each process to be determined. The processes that control organic matter in groundwater will be investigated at a range of field sites with differing surface soil, land cover, recharge type and hydrological properties. Preliminary results from various field sites has shown that sedimentary organic matter is mobilised as water flows through the hyporheic zone. The results from this project will provide guidelines for the management of groundwater resource as part of the carbon economy.

DAY 1: Tuesday, 11 July 2017

SURFACE WATER - GROUNDWATER

Addressing groundwater inflows to rivers during high flow events (the "old water paradox") using tritium

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In many catchments, changes in stream geochemistry during high streamflows following rainfall events implies little dilution of groundwater inflows by event water. Rather, much of the water contributing to the high streamflows appears to be older water from within the catchment (the "old water paradox"). However, it is unclear whether this represents water displaced from shallow stores in the soils or regolith or older regional groundwater.

Here we use tritium, major ions and stable isotopes to assess sources of water during high streamflows in streams from the Latrobe and Yarra catchments (SE Australia). Most major ion concentrations do not vary systematically with streamflow. However, nitrate concentrations increase and silica concentrations decrease during the events and there are small but systematic changes in stable isotope ratios. Tritium activities increased from 1.4 TU to up to 2.4 TU close to the peak in streamflow and then decline over several days to pre-high flow values. The peak tritium activities are lower than those of the rainfall that generated the high flow events (~3 TU) but within the range of tritium activities commonly recorded in soil water in SE Australia (2.0 to 2.6 TU). The combined geochemical data imply significant water input to these streams during high streamflows from shallower stores with residence times of <5 years rather than deeper regional groundwater.

Catchments contain multiple stores of water (old regional groundwater, younger shallow groundwater, soil water, interflow). Thus, a multi-tracer approach is required to apportion the contribution of water from these stores during high streamflows. Tritium provides the opportunity to directly assess how the average residence time of water varies across high streamflow events and through this address the old water paradox. Understanding the changing sources of water during high streamflows is important for catchment water balances, flood forecasting, and predicting contaminant transport.

Remapping and validation of gaining steams in the Surat Basin – an integral part of understanding impacts on environmental values

Jit Khor[1], Steve Flook[1]
1. Office of Groundwater Impact Assessment, Brisbane, QLD, Australia

Increased confidence in the mapping of gaining streams in the Surat Basin is essential for improving conceptual understanding of surface-groundwater interaction and for assessing impacts from groundwater development on associated environmental values. The Office of Groundwater Impact Assessment (OGIA) has initiated a project to remap gaining streams in the Surat Basin using new data generated since the last assessment in 2005.

OGIA is responsible for the assessment of cumulative groundwater impacts from petroleum and gas (P&G) activities in the Surat Cumulative Management Area (CMA). OGIA's assessment includes regional groundwater flow modelling and the development of monitoring requirements for aquifers and groundwater dependent ecosystems (GDEs) – specifically, springs and gaining section of streams ('watercourse springs'). In the Surat Basin, gaining streams often result from the dissection of an outcropping aquifer by surface water flows, resulting in the watertable being intersected by the streambed.

At a regional scale, this project uses multiple data sources to identify areas where gaining streams potentially exist. This included the development of a methodology to generate watertable mapping by integrating bore data and a digital elevation model, and assessing other new datasets such as the Queensland GDE mapping. The output from this process is a revised map of potentially gaining reaches in the Surat Basin.

A risk based approach was applied to identify sites for field validation. Outputs from impact assessment were used to prioritise sites for field investigation. Surface water and groundwater data was collected including groundwater pressure, major ion chemistry, isotope analysis (^{222}Rn) and field observations at two field sites.

The outcomes from this project improve the conceptual understanding of surface-groundwater connectivity in the Surat Basin and provides a basis for the establishment of appropriate management strategies for gaining streams in the next iteration of the Surat UWIR.

The mode of occurrence of small surface water bodies in the Pilbara Region, Western Australia

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Surface water pool expressions are ubiquitous across the Pilbara Region of Western Australia. These features and the systems supporting them commonly hold significant environmental value as a refuge for flora and fauna (including subterranean). Furthermore, from a cultural and heritage perspective they often hold special value as important meeting places for traditional owners, or places of significance referred to within Indigenous mythology.

Historically, research in the Pilbara Region relating to the nature and origin of surface water bodies has predominantly focused on large systems such as the Fortescue Marsh. Despite the prevalence of the much smaller water bodies, little is understood in relation to the flow dynamics that sustain them. The study sets out to characterise small surface water bodies in the Pilbara by applying a multifaceted understanding of the hydrological cycle.

Findings confirm the strong link between permanency and hydraulic connection to the fractured rock aquifer. Furthermore, understanding aquifer storage and the relationship between stream flow, and recharge dynamics associated with episodic rainfall events is essential to the ongoing management of these important features.

A simple Excel tool for quantifying surface water-groundwater exchange using temperature

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Understanding the fluid exchange between groundwater and surface water is important for effective water resource management. However, groundwater-surface water (gw-sw) interactions also control important ecological variables including water temperature stability, spatial thermal diversity, nutrient availability, and other biogeochemical aspects of water quality. Thus, understanding gw-sw exchange is also important for ecologists who study the health of aquatic habitat in streams, springs, estuaries, lakes and wetlands.

A number of methods exist for quantifying gw-sw exchange rates, but these have predominantly been applied by physical scientists (e.g. hydrogeologists). If methods to quantify gw-sw exchange are to be more widely utilised by other disciplines of aquatic science, it is important that the approaches and associated tools can readily and appropriately applied by non-experts. Here we describe FLUX-LM, a simple Excel spreadsheet tool for quantifying vertical gw-sw flux using measured sediment temperature gradients.

Inputs for FLUX-LM include a temperature-depth profile of the stream or lakebed sediment and some basic thermal properties. FLUX-LM either applies a classic single-layer analytical solution, or a newer multi-layer analytical solution and enables the user to automatically produce an optimal vertical water flux estimate using a clickable ‘solve’ button.

The primary limitation of FLUX-LM is that it assumes steady state temperatures. This condition is violated in shallow portions of the streambed in cases of downwelling, as temperatures vary due the downward propagation of diurnal temperature variations in the surface water. However, upwelling of groundwater to surface water limits diurnal signal propagation to the upper few centimetres of bed sediments, making the FLUX-LM an appropriate tool for the quantification of upward water flux.

We present an example of the tool applied to research regarding native cold water fish spawning habitat in a layered streambed system of contrasting thermal properties. Further potential applications of FLUX-LM will also be discussed.

The role of surface-groundwater interactions in salt delivery from a small upland salt scald in Central west NSW

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The objectives of this research was to better understand the processes that mobilise and transport salt from the land to the stream and the role groundwater has, if any, in the process. Dryland salinity is attributed to the removal of deep rooted vegetation, salt is mobilised from deep in the soil and transported to the soil surface and/or into waterways by rising groundwater. Recent research has challenged that paradigm and indicates that changes are mainly due to climate influences; as well stream EC follows an oscillating path of rising during wet periods and falling during dry periods.

Method: Two plots (one revegetated) of 1 ha in size were established on a saline scald in central NSW, climate, groundwater and surface runoff from September 2003 to present were measured.

Results: A change point analysis was performed on the event mean concentration (EMC) of the runoff water. Change points were detected in 2006, 2012, 2013 and 2014. There was a high EMC of around 4 kg/mm from 2003 to 2006, then a low EMC of 0.4 kg/mm from 2006-2012, then a reversion to a high EMC 4 kg/mm, and then a return to an EMC of 0.4 kg/ha. These periods of high EMC coincided with periods of groundwater that within 1.5 m of the ground surface while the periods of low EMC runoff water coincided with ground water being below 1.5m.

Conclusion: The watertable elevation is the primary driver of salt export coupled with surface runoff events. Only when the watertable is within a critical distance from the soil surface are significant amounts of salt exported. If scaled up, this phenomenon is capable of providing a causal mechanism for the larger-scale observations, particularly the oscillation in stream EC reported particularly in the 2009 NSW Salinity Audit.

Using stable isotope with hydrometric data to understand river-aquifer interactions in a semi-arid environment stressed by groundwater abstraction

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Profound changes are occurring to hydrological processes in semi-arid environments. For water resources to be managed sustainably these changes and their drivers need to be understood. This study focusses on the anthropogenic alteration of river-aquifer interactions in the Murray Darling Basin, Australia. Field investigations were carried out on a floodplain of the Namoi River. Naturally occurring stable isotopes of water in combination with hydrometric data were used to understand the river-aquifer interactions. Two end-members are established: a regional isotopically depleted groundwater signature, and an evaporatively enriched river water signature. Water at depth in the aquifer and away from the river has the depleted signature indicative of water originating from rainfall, while water in the upper aquifer and close to the river has elevated δ18O values indicative of water originating from the river. The hydrometric data suggest that groundwater flow towards the river in the upper aquifer has reduced in magnitude while flow in the lower aquifer has reversed in direction since development. It is found that when there is no river flow or groundwater abstraction there is little interaction, while when there is river flow or abstraction recharge from the river is induced. It is further found that the river is complexly connected to groundwater abstraction. Abstraction from the lower aquifer is causing extensive declines in groundwater levels in that aquifer, which in turn is causing an increased vertical leakage of water from the upper to the lower aquifer. This leakage is causing declines in groundwater levels in upper aquifer and thus an increased lateral infiltration of river water to the upper aquifer during flow events. The study illustrates that conventional concepts for surface water groundwater interactions can be too simplistic and that a solid understanding of the site geology is a perquisite for better understanding of the interaction processes.

Seasonality of groundwater discharge to streams: implications for water management in Australia

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An understanding of the interaction between groundwater and surface water systems is fundamental to the effective management of water resources. Importantly, groundwater discharge to streams often accounts for a significant proportion of total streamflow, particularly during low-rainfall periods. This study has applied a consistent approach to classifying streams and assessing groundwater discharge to streams in order to characterise streamflow and baseflow patterns in different geographic regions across Australia.

Historical streamflow data for 233 Australian stream gauges were analysed. Long-term and seasonal (high-flow and low-flow) baseflow indices (BFI) were determined using the Lyne and Hollick recursive digital filter to quantify the relative baseflow component of streamflow. Classifying streams into perenniality and seasonality groups highlights distinct characteristics of baseflow regarding timing, magnitude and variability.

Five distinct perenniality groups were identified by hierarchical clustering of percentage flow days. Non-perennial streams (flow < 90% of the time) have a long-term mean BFI of 0.25 while perennial streams (flow > 90% of the time) have a long-term mean BFI of 0.46.

Two overarching seasonal flow regimes (Summer or Winter-dominant) or eight sub-groups were distinguished by hierarchical clustering of mean monthly streamflow data. Streams within each of the seasonal flow regimes have a characteristic streamflow and baseflow pattern. All streams assessed in Northern Australia are Summer-dominant; a number of these streams have sustained baseflow throughout the dry season. Winter-dominant streams predominate in the southern half of Australia. The timing and relative discharge of groundwater to streams vary between seasonal flow regimes due to differences in the dominant sources of water to the stream at different times of the year.

Knowledge of stream perenniality, seasonal streamflow regimes and the respective streamflow and baseflow relationships is important from a water management perspective, particularly for conjunctive use of groundwater and surface water resources.

DAY 2: Wednesday, 12 July 2017

PLENARY

Groundwater and Energy: Perspectives from the Mining Industry. *Chris McCombe, Senior Adviser – Environment, Minerals Council of Australia*

Abstract not supplied.

DAY 2: Wednesday, 12 July 2017

MODELLING

Keynote: Empowering the flexibility and solution efficiency of an overland model and a groundwater model into a new integrated modelling tool. *Fabien Cornaton, DHI WASY.*
Worth of radon, electrical conductivity, and carbon-14 for the estimation of streamaquifer exchange using a regional-scale groundwater model (Campaspe River). *Daniel Partington, Flinders University.*
Accounting for conceptual and parametric contributions to the total uncertainty of streamflow depletion predictions in Northern Australia. *Chris Turnadge, CSIRO.*
Does resolution in surface water representation in groundwater models affect nitrate transport and removal in a coupled groundwater: surface water system? *Trine Enemark, CSRIO.*
Does macroscopic dispersion exist in heterogeneous Darcy Flow? *Daniel Lester, RMIT University.*
A new way to model non local constituent transport in subsurface: rate of mass exchange between mobile and immobilezones depends on immobile-age. *Kaveh Zamani, UNSW.*
Effect of turbulent flow on heat transfer in a real fracture. *Hamid Roshan, UNSW.*
A family of calibrated models. *Roger Cranswick, Department of Environment, Water and Natural Resources SA.*
Is model calibration alone good enough? A case study of the Chowilla Floodplain modelling demonstrates the benefits of model post-audits. *Chris Li, Department of Environment, Water and Natural Resources.*
Transferring regional calibrated groundwater model to local model for engineering design using MODFLOW USG. *Xuyan Wang, Klohn.*

Empowering the flexibility and solution efficiency of an overland model and a groundwater model into a new integrated modelling tool

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Surface and subsurface flow systems are unified continua that often need to efficiently operate together in a water resource distributed modelling framework. Watershed modelling studies targeting surface water flood and storm events, or groundwater flooding events involving complex, strong surface water - groundwater interactions require access to powerful, physically-based simulation tools.

A new integrated model has been designed by allowing the two state-of-the-art groundwater model FEFLOW and surface water model MIKE 21 Flow Model FM to communicate into a single, dynamically coupled modelling system. The tool features the ability to model coupled variably-saturated and overland flows, as well as coupled heat transfer and salinity transport, by taking advantage of optimal parallelization based on hybrid OpenMP, MPI, and multi-GPU programming models. The contrasted flow dynamics of the surface and subsurface environments operate in an efficient manner using unstructured, flexible non-conforming meshes for the two continua. An area-weighted interpolation strategy allows the joint use of process-tuned meshes with optimal resolution, while a sub-timing approach with independent dynamical stepsize control supports the continua dynamics coupling and synchronization.

The tool is applied in the lower Havel polder region (Germany), a place flooded by a complex weir group and used as a retention area to reduce peak discharges in the lower Elbe region part. Recent flooding events initiated modelling work efforts in order to optimize the polder and the weirs, and support renaturation planning including reconnection of old river branches and removal of dike protections. With the new integrated model it is now possible to analyze these interaction processes with much more details.

Worth of radon, electrical conductivity, and carbon-14 for the estimation of stream-aquifer exchange using a regional-scale groundwater model (Campaspe River)

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2. GNS Science, Wellington, New Zealand

Knowledge of the exchange between streams and underlying aquifers is required for management in systems where both surface water and groundwater are exploited and also well connected. In northern Victoria, the Campaspe River catchment (within the Murray Darling Basin), downstream of Lake Eppalock, is one such catchment in which it is necessary to quantify the impact of changes to allocations/extractions of surface water and groundwater on stream-aquifer exchange. The primary tool for assisting such quantification is a numerical model of the system that is constrained by field observations of groundwater head and stream stage. However, quantifying stream-aquifer exchange is notoriously difficult, and so any data (type, frequency, location) that may reduce the uncertainty in model predictions is desirable. The aim of this study is to quantify the reduction in uncertainty of simulated stream-aquifer exchange rates over a variety of spatial and temporal scales through the acquisition of innovative data beyond traditional groundwater head and stream stage data. In particular, carbon-14 (C-14), radon, and electrical conductivity data that were collected within the study area are investigated in terms of their “worth”, defined here as their ability to reduce stream-aquifer exchange predictive uncertainty.

Utilising the parameter estimation (PEST) software suite, the traditional and innovative data supported the calibration of a regional-scale groundwater flow (MODFLOW-NWT) and transport (MT3D-USGS) model. The calibration-constrained model has been used to test the extent to which these innovative data provide a reduction or otherwise in uncertainty for predictions of stream-aquifer exchange. Analysis of modelled stream-aquifer exchange was carried out at reach and whole of river spatial scales, and for each of these, at annual, seasonal, and monthly temporal scales.

Accounting for conceptual and parametric contributions to the total uncertainty of streamflow depletion predictions in Northern Australia

Chris Turnadge[1], Andrew Taylor[1]
1. CSIRO, Glen Osmond, SA, Australia

The Northern Australia Water Resource Assessment (to conclude in June 2018) will provide a range of information to facilitate economic development in three regions located across northern Australia. Such information includes evaluations of the scale and opportunities for groundwater resource development whilst recognising the potential environmental, social, cultural and economic benefits, impacts and risks of increased future usage. In areas where groundwater baseflow sustains groundwater-dependent ecosystems, a key limitation on the potential for groundwater extraction is the risk of streamflow depletion. This is defined as the fraction of extracted water that would otherwise discharge to a stream at a given time after the onset of (typically continuous) groundwater extraction.

The potential for streamflow depletion by groundwater extraction has historically been estimated using analytical solutions and/or using deterministic numerical models. In the present study, numerical solutions were incorporated in a Monte Carlo framework in order to account for both conceptual and parametric sources of uncertainty. Sources of conceptual uncertainty assessed included variations in hydrostratigraphy, including the presence of a surficial aquitard or multiple aquifers, as well as variations in bore penetration depth and screen extent. Sources of parametric uncertainty assessed included hydrogeological properties, streambed conductance, and rates of extraction. Numerical solutions enabled testing each of these assumptions, as well as providing the ability to simulate discontinuous extraction regimes. Furthermore, numerical solutions also provided the ability to predict cumulative streamflow depletion over the duration of extraction.

Global sensitivity analysis metrics and simple scatterplot analyses were used to identify model parameters to which predictions of streamflow depletion were most sensitive. This research serves as a practical demonstration of best-practice methods for the estimation of streamflow depletion uncertainty. The methodology will support transparent, comprehensive and robust groundwater allocation policy where groundwater extraction occurs (or is proposed to occur) in the vicinity of groundwater-fed streams.

Does resolution in surface water representation in groundwater models affect nitrate transport and removal in a coupled groundwater-surface water system?

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For the efficient regulation of agricultural practices aimed at minimising nitrate influxes to streams, it is essential to identify potential zones where nitrate is naturally removed by denitrification prior to reaching the stream network. Large-scale distributed hydrological models used for this purpose often do not include lakes and smaller stream tributaries. This study investigates the influence of the resolution of the surface water system representation on simulated flow, nitrate transport and potential for removal by denitrification in groundwater.

A regional (160 km^2) 3D numerical groundwater model is set up including a lake-rich area in Western Denmark. Four scenarios with different spatial resolution of the surface water system are evaluated. The most complex model in regards to the surface water system has a 56-km stream network and 13 lakes, while the simplest model only represents 19 km of the stream network and none of the lakes. When the surface water system is not fully represented in a groundwater model, the option for removing water to match the observed water table is either to incorporate drains or increase the aquifer hydraulic conductivity. The four groundwater-surface water flow systems were evaluated using particle tracking. The fraction of the total travel time that the particles spend below the groundwater redox boundary prior to discharging to the surface water, was recorded to determine the potential for denitrification (due to pyrite oxidation).

When removing surface water bodies and increasing hydraulic conductivity, capture zones increase and the potential for removing nitrate decrease. Regulations on agriculture based on such models would therefore affect a large area but not necessarily reduce environmental impact. Including drains instead of parts of the surface water system has the opposite effect on the capture zone, which would potentially lead to inefficient regulations.

Does macroscopic dispersion exist in heterogeneous Darcy Flow?

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It is well known that transverse macroscopic dispersion cannot occur in two-dimensional (2D) steady heterogeneous Darcy flow as the fluid streamlines are confined to a plane, and hence cannot diverge or converge without bound. Conversely, it is widely believed that such constraints do not apply to steady three-dimensional (3D) flow as the fluid streamlines can now wander without bound throughout 3D space. However, the special form of the isotropic Darcy flow equation imposes specific constraints upon fluid motion which are not immediately obvious. The pioneering work of Sposito [1] shows that steady 3D isotropic heterogeneous Darcy flow has identically zero helicity, defined as the product of fluid velocity and vorticity, hence fluid elements cannot make helical motions as they travel along streamlines.

We show a further consequence of this constraint is that fluid streamlines in 3D space are confined to an orthogonal set of material surfaces, and as these surfaces are topologically simple and flat (in the Gaussian sense), then the same constraints as for 2D flow apply locally to these surfaces. As such, macroscopic transverse dispersion cannot arise in steady isotropic Darcy flow. We show that the majority of Darcy flow numerical codes do not explicitly enforce the helicity-free condition, and so macroscopic transverse dispersion calculated by these methods is purely a numerical artefact. We develop an explicitly helicity-free Darcy solver and show that indeed it does recover zero macroscopic dispersion.

These results have significant implications for the study of transport and dispersion in steady Darcy flow, and indicate that caution must be exercised when designing and interpreting numerical simulations of transport in Darcy flow. Moreover, as macroscopic dispersion is a well-observed phenomenon in field studies and laboratory experiments, these results show that the isotropic Darcy flow equation has limitations for capturing dispersion phenomena.

1. *[1] Sposito G. Topological groundwater hydrodynamics, Advances in Water Resources 24, 793-801 (2001)*

A new way to model nonlocal constituent transport in subsurface: rate of mass exchange between mobile and immobilezones depends on immobile-age

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Solutes and suspended material often experience delays during exchange between phases one of which may be moving. Consequently transport often exhibits combined effects of advection/dispersion, and delays associated with exchange between phases. Such processes are ubiquitous and include transport in porous/fractured media, watersheds, rivers, forest canopies, urban infrastructure systems, and networks. Upscaling approaches often treat the transport and delay mechanisms together, yielding macroscopic “anomalous transport” models. When interaction with the immobile phase is responsible for the delays, it is not the transport that is anomalous, but the lack of it, due to delays. We model such exchanges with a simple generalization of first-order kinetics completely independent of transport. Specifically, we introduce a remobilization rate coefficient that depends on the time in immobile phase. Memory-function formulations of exchange (with or without transport) can be cast in this framework, and can represent practically all time-nonlocal mass balance models including multirate mass transfer and its equivalent counterparts in the continuous time random walk and time-fractional advection dispersion formalisms, as well as equilibrium exchange. Our model can address delayed single-/multievent remobilizations as in delay-differential equations and periodic remobilizations that may be useful in sediment transport modeling. It is also possible to link delay mechanisms with transport if so desired, or to superpose an additional source of nonlocality through the transport operator. This approach allows for mechanistic characterization of the mass transfer process with measurable parameters, and the full set of processes representable by these generalized kinetics is a new open question.

Effect of turbulent flow on heat transfer in a real fracture

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An understanding of heat transfer in fractured systems is vital in many engineering applications such as heat extraction from geothermal systems, thermal enhanced oil recovery and heat transport through karst systems. The heat transfer in fracture systems greatly depends on the rock and fluid thermal interactions, in particular the flow regime. The fluid flow in fracture systems is often considered laminar where the fracture flow is coupled with heat transfer to investigate the heat exchange between the matrix and fracture. However, it has been documented that the fluid flow approaches the turbulent regime in many natural systems. The effect of turbulent flow on heat transfer within the fracture system remains poorly understood.

To understand the implications of turbulent flow on the heat transfer in fracture systems, a coupled 3D turbulent flow and heat transfer model has been constructed based on realistic fracture properties. The variables controlling flow, such as fracture aperture, fluid velocity/flow regime and surface roughness, are varied to investigate the effect of turbulence flow on fluid-matrix heat exchange. The obtained results are then compared with that of a coupled laminar flow and heat transfer model commonly implemented in commercial numerical simulators.

The results of the numerical experiments showed that turbulent flow can considerably enhance the heat transfer in a fracture with surface roughness mainly due to flow localization. It was found that the fracture surface roughness, fracture flow and aperture are the key factors controlling the heat exchange between the matrix and fluid. The influence of the fracture aperture becomes more significant at relatively low Reynolds numbers (Re<10). Despite common expectation of an increasing difference in heat transfer with increasing Re, the difference in heat transfer between laminar and turbulent flow is more pronounced at relatively low Re.

A family of calibrated models

Roger Cranswick[1], Chris Li[1]
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It is increasingly feasible to develop multiple groundwater models with different conceptual assumptions, model structure and parameterisation, that are similarly well-calibrated in terms of hydrograph fitting, constraints imposed by expert knowledge and other measures. Such non-uniqueness is widely acknowledged in the groundwater industry but rarely explored in practice.

We present a case study from the Tatiara Prescribed Wells Area in South Australia, for which a small family of calibrated models have been developed. These collectively capture some of the uncertainty that we know exists within our model assumptions and are used to present a range of future projections of groundwater condition. These model assumptions commonly arise out of key decision points faced by the groundwater modeller. For example, what scaling factor should be applied to crop water requirements to provide estimates of historical groundwater extraction? The creation of a family of models (using a reasonable range of scaling factors) no longer narrows the model calibration and subsequent projections to those resulting from a single and uncertain model assumption. If carefully presented, a multi-model approach such as this can engender a broader appreciation among stakeholders, water managers and policy makers of both the sources, and implications of uncertainty in hydrogeological models.

Is model calibration alone good enough? A case study of the Chowilla Floodplain modelling demonstrates the benefits of model post-audits

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The Chowilla Floodplain is one of the most important floodplains in South Australia due to its ecological and cultural significance. However, due to River Murray regulation and the consequent reduced flood frequency, the floodplain suffers greatly from a lack of soil moisture and salt accumulation. To address this problem, a regulator has been constructed to enable the floodplain anabranch water levels to be temporarily raised, and large areas of the floodplain to be inundated. However, this will also raise the naturally-saline groundwater, and subsequently increase the saline groundwater discharge to the floodplain anabranches, ultimately to the River Murray. There are policy obligations for the salinity impact of such an action to be assessed via modelling.

A coupled surface water–groundwater modelling approach is used to simulate the salinity impact of regulator operations. The surface water model (MIKEFLOOD) estimates the changes in surface water levels and inundation areas caused by regulator operations. The outputs are then fed into the groundwater model (MODFLOW) to simulate the resulting groundwater discharge to the floodplain anabranches and River Murray. The groundwater model was constructed and calibrated in 2012, with the riverbed conductance being the most sensitive and uncertain parameter.

A number of regulator-operation trials have occurred in recent years, which enabled additional data such as salt load to be collected. This study uses these data to undertake a model post-audit, which proves to be beneficial as it further constrains the riverbed conductance, identifies processes that are not captured in the model, and allows the model's predictive capability to be assessed. It is recommended that when new data becomes available, model post-audits should be proactively carried out, especially on models used for management decisions, to provide additional insights and establish greater confidence in prediction outcomes.

Transferring regional calibrated groundwater model to local model for engineering design using MODFLOW USG

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A common approach for simulating dewatering/transport problems in mining and tunnelling engineering is to use a regionally calibrated groundwater model. MODFLOW's unstructured grid (USG) is a recent advancement that can allow the creation of unstructured grid to facilitate local refinement modelling groundwater problems such as these. Transferring the calibrated model boundaries from the regional mesh to the local refined grids with USG approach can result inconsistencies in the water budget and the mass balance. In this paper, the impact on water budget as a result of variation of grid, grid size and numerical approaches (upscaling, ghost node correction) is analysed. The examination in a local dewatering design showed that high uncertainty occurs if model boundaries are not transformed and assigned correctly. The paper further outlines effective methods to transfer a variety of model boundaries from larger scale regional groundwater model to local, refined grid model such that numerical uncertainties can be reduced.

DAY 2: Wednesday, 12 July 2017

COAL SEAM GAS

Keynote: Evaluating the deep groundwater attenuation potential for chemicals associated with coal seam gas extraction: a generic methodology. *Dirk Mallants, CSIRO.*
A qualitative assessment of the potential impacts of coal seam gas development on waterdependent assets in the Richmond river basin. *David Rassam, CSIRO.*
Multi-disciplinary GISERA research to inform risk assessment and management of water impacts of onshore gas development in New South Wales. *Sreekanth Janardhanan CSIRO.*
How much water is CSG development actually producing compared with early predictions? *Jim Underschultz, University of Queensland.*
Reinterpretation of wireline log data in the eastern Galilee Basin: stratigraphical and hydrogeological implications. James Hansen, *Department of Science, Information Technology and Innovation QLD.*
Proposed methodology to quantify methane in coal seam gas aquifers. *Grazia Gargiulo, Symbiolabs.*
Injection of treated coal seam gas co-produced water into deep aquifers: predicting long-term groundwater quality impacts. *Bhasker Rathi, CSIRO / University of Western Australia.*
Characterisation of fluid migration in aquitards using helium concentrations in quartz. *Dirk Mallants, CSIRO.*
Spatial and temporal scale influences on conceptual model development – examples from CSG water injection studies. *Ryan Morris, Origin Energy.*

Evaluating the deep groundwater attenuation potential for chemicals associated with coal seam gas extraction: a generic methodology

Dirk Mallants[1], Simon Apte[1], James Kear[1], Chris Turnadge[1], Sreekanth Janardhanan[1], Dennis Gonzalez[1], Mike Williams[1], Zuorong Chen[1], Rai Kookana[1], Andrew Taylor[1], Matthias Raiber[1], Jody Bruce[1], Henning Prommer[1], Merrin Adams[1]

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A generic methodology was developed for rapid screening of coal seam gas (CSG) chemicals (drilling, fracturing, and geogenic chemicals) to determine which chemicals are more likely to be hazardous when present in or mobilised from deeper groundwater environments. First, the method adopts existing rules for screening chemicals and lists of chemicals that have previously been rigorously assessed and found to be of low concern to the environment and/or human health. Next, the degree of attenuation (expressed as a dilution attenuation factor) that coal seam gas chemicals would experience prior to potentially reaching receptors was determined using a multiple lines of evidence approach. This involves i) spatial analyses of proximity (horizontal distance) between potential contaminant sources at CSG wells and receptor locations in the vicinity of those wells, including derivation of proximity-frequency relationships for several groups of receptors (ecologic, economic and socio-cultural), ii) chemical and or biological, geological (owing to chemical sorption onto organic and/or mineral phases) and flow-related (dilution/dispersion) attenuation information for CSG chemicals in deep groundwater, iii) conceptual models with plausible fate and transport release pathways, iv) solute particle tracking analysis to identify likely connectivity, travel distance and time between the coal seam formations being hydraulically stimulated and groundwater receptors, and v) simplified calculation tools that combined all the above information. An extensive literature survey provided robust data on chemical and or biological degradation of organic chemicals. Additional particle tracking-based pathway calculations were undertaken with an entire well field to capture possible cumulative effects from mass accumulating for the case of hydraulically stimulated wells. Application of this methodology facilitates prioritisation of chemicals for which more detailed risks assessments associated with potential deeper groundwater contamination are warranted. Our methods further provide a robust approach to inform management decisions around safe setback distances.

A qualitative assessment of the potential impacts of coal seam gas development on water-dependent assets in the Richmond river basin

David Rassam[1], Matthias Raiber[1], Justine Murray[1], Tao Cui[1], Mat Gilfedder[1]
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This work describes a qualitative assessment of the potential impacts of CSG development on water-dependent assets in the Richmond river basin. The integrated understanding of the geology, hydrogeology and surface-groundwater interactions underpinned the development of a groundwater model that provided a quantitative assessment of the hydrological changes resulting from CSG development in the Richmond river basin (part of the Clarence-Moreton bioregion). Conceptual models were developed to describe the causal pathways, the logical chain of events that link coal resource developments to water-dependent assets. A landscape classification system was developed to characterise the nature of water dependency among assets identified in the area. The assessment identified hazards associated with CSG that could potentially result in hydrological changes. Four major causal pathway groups were identified: (1) Subsurface depressurisation and dewatering, (2) Subsurface physical flow paths, (3) Surface water drainage, and (4) Operational water management.

Ecosystems in the Clarence-Moreton bioregion were classified into 35 landscape classes to enable a systematic analysis of potential impacts on, and risks to, the water-dependent assets. Landscape classes were aggregated into landscape groups based on whether they respond similarly to changes in groundwater and/or surface water.

The numerical groundwater model predicted drawdown, which was used to define a zone to 'rule-in' or 'rule-out' potential hydrological change. The zone is the area with at least a 5% chance of greater than 0.2 m drawdown due to additional coal resource development. This threshold is consistent with the most conservative minimal impact thresholds in NSW and Queensland State regulations within which potential impacts may need to be considered in an impact and risk analysis.

Based on this integrated conceptual understanding, an informed decision to classify various assets as either, being potentially 'impacted' or 'not impacted', is made.

Multi-disciplinary GISERA research to inform risk assessment and management of water impacts of onshore gas development in New South Wales

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5. Data61, CSIRO, Dutton Park, QLD, Australia

The Gas Industry Social and Environmental Research Alliance (GISERA) was set up as a partnership between CSIRO and the gas industry, and has been undertaking independent, transparent and trusted social and environmental research for communities in gas development regions since 2011. GISERA's aim is to provide scientific research and information on Australia's growing natural gas industry to community, government and industry alike through the use of industry, CSIRO and government funding independently allocated to research projects by a stakeholder dominated Regional Research Advisory Committee. GISERA has expanded currently undertaking social and environmental research in New South Wales.

Four independent but related water projects spanning multiple research disciplines have been scoped and designed in consultation with community, government and industry stakeholders. These projects investigate multiple processes on different scales to comprehensively assess potential risks to groundwater quantity and quality, and build on from previous research undertaken as part of Bioregional Assessments Programme. They undertake focused assessment of reservoir-scale processes, water quality risks from bore delamination, uncertainties in aquifer-scale flow and water balance changes, and monitoring strategies to minimise prediction uncertainties.

The outcomes of these projects are expected to provide quantitative assessment of risks that the community and other stakeholders have expressed concerns about. The GISERA communication strategy that encourages continuous and ongoing engagement ensures communication of the research outcomes to diverse stakeholders and inform policy and regulatory decision making.

How much water is CSG development actually producing compared with early predictions?

Jim Underschultz[1], Sue Vink[1]
1. University of Queensland, Brisbane, QLD, Australia

Coal Seam Gas development in Queensland is currently going through a transition from less than 300 bcf/yr (~315 PJ/yr) for domestic consumption to ~1400 bcf/yr (nearly 1500 PJ/yr) by late 2017 driven by LNG export contracts. Prior to this ramp up in production, industry, government and academia have been forecasting not only gas but associated water production for the various purposes of financial investment decisions and field development planning, prudent governance and regulatory planning, and estimation of potential environmental impacts for planning management, monitoring and mitigation strategies. During the course of resource development, prediction methodologies and modelling sophistication varies greatly as more data becomes available and uncertainty is reduced. In Queensland, now that 6 LNG trains are running there is now a substantial and growing data inventory to history match numerical models. Measured associated water production from CSG development (up to July 2015) equates to ~65GL/yr with combined operator forecasts defining a peak projected to occur for about 10 years at ~80 GL/yr, substantially less than earlier forecasts.

In this paper we review the historical forecasting of CSG water production in Queensland leading up to the development and operation of CSG for LNG export, and compare that to the current actual produced volumes now that the projects have come on stream.

Reinterpretation of wireline log data in the eastern Galilee Basin: stratigraphical and hydrogeological implications

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The Millennium drought and increased demand for water throughout Australia placed the water supply infrastructure of the day under considerable stress. In response the Bureau of Meteorology (BoM) was given the role of compiling and delivering Australia's water information under the conditions set out in the Federal Water Act 2007.

To achieve this the BoM developed the Australian Water Resource Information System (AWRIS) and the National Groundwater Information System (NGIS) to support AWRIS. Functionality of the NGIS relied on updating and compiling state and territory groundwater databases. Completeness of the data contained in these databases was critical in facilitation data migration to the NGIS and groundwater bores in the Galilee Basin were identified as a priority target for addressing data gaps.

To achieve this a stratigraphic framework was created using published wireline log interpretation information to map structure surfaces for the Galilee Basin. Assessment of these structure surfaces and wireline log interpretations identified numerous inconsistencies with the established basin stratigraphy, particularly for some recent exploration wells. This is partially attributed to the large number of interpretation sources, exploration relevance and an incomplete understanding of facies variability.

Systematic reinterpretation of the published wireline log data has been undertaken to validate and reassign inconsistent interpretations in the eastern Galilee Basin. Reinterpretation has resulted in shifting formation top picks vertically by up to 300m in some instances, leading to significant modification of some structure contour surfaces.

Uncertainty over the internal architecture of the Galilee Basin has significant implications for understanding the hydrogeology of aquifer systems and springs in the basin. Reinterpretation by a single operator has assisted in removing some of this uncertainty and provided a consistent dataset of interpretations. This is significant with regard to assessing potential impacts that proposed coal mining activities will have on these aquifer systems and springs.

Proposed methodology to quantify methane in coal seam gas aquifers

Grazia Gargiulo[1]
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The popularity of utilising Coal Seam Gas (CSG) is increasing throughout the world. Coal seam gas is primarily made up of methane gas and is found in coal seams at depths of 200m to 1000m below ground surface (BGS). The groundwater (hydrostatic pressure) holds the gas into the formation pore spaces. In order to release the gas, dewatering is used to allow the desorption of CSG from the formation, additionally hydraulic fracking can be used to stimulate and accelerate the flow of gas. However, there are some concerns associated with the extraction of CSG including the potential to introduce desorbed methane in the groundwater resources. In order to address these concerns it is necessary to monitor the aquifers to determine if the concentration of methane increases with the time.

An issue with testing the concentration of methane in groundwater from deep aquifers is that methane solubility in water is affected by the change in pressure. When the groundwater is brought up from the aquifer to the surface the change in pressure causes the methane to escape from the groundwater sample. Therefore, the current dissolved methane analysis performed in the water sample does not correctly quantify the total amount of methane present in the deep aquifer as the gas is released to the atmosphere once the sample is transported to the surface.

Injection of treated coal seam gas co-produced water into deep aquifers – predicting long-term groundwater quality impacts

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Coal Seam Gas production in the coming decades will involve disposal of large amounts of co-produced water into deep aquifers. Prior to the implementation of larger-scale injection schemes, it is important to perform field injection trials that generate sufficiently meaningful data sets to allow for the assessment of both the hydrological and geochemical impacts on the target aquifer. The present work illustrates the use of reactive transport modelling for data analysis from a field experiment where arsenic mobilisation was observed. This type of modelling study requires integration of multi-scale data and models with a relatively high parametric uncertainty. The parametric uncertainty, however, can lead to significant predictive uncertainty when the field-scale reactive transport model (RTM) is employed for the prediction of the long-term groundwater quality evolution.

Arsenic sorption behaviour was studied through laboratory experiments and modelled using a surface complexation approach. A field-scale RTM that incorporated the laboratory-derived model was used to simulate the injection trial and to predict the long-term fate of arsenic. Here, we propose a new practical procedure for better integration of laboratory and field-scale models in order to quantify predictive uncertainty. The approach alleviates a significant proportion of the computational effort required for uncertainty quantification. The results illustrate that both desorption and pyrite oxidation have likely contributed to arsenic mobilisation observed during the trial. The predictive simulations show that arsenic levels are likely to remain very low if the potential for pyrite oxidation is minimised through a complete deoxygenation of the injectant. The proposed modelling and predictive uncertainty quantification approach can be implemented for a wide range of groundwater studies that investigate the risks of metal(loid) or radionuclide contamination.

Characterisation of fluid migration in aquitards using helium concentrations in quartz

Stan Smith[1], Dirk Mallants[1], Emeline Mathouchanh[1]
1. CSIRO, Urrbrae, SA, Australia

This presentation provides an overview of a novel approach using noble gas tracers to derive formation-scale hydraulic conductivities of key aquitards in the Gunnedah Basin, New South Wales. Concentrations of helium in quartz were measured as proxy for helium in aquitard pore-water, and used to calibrate a fluid flow model encompassing a 500-m thick aquitard. Specifically this study:

- Measured a vertical profile of helium concentrations in the Watermark/Porcupine Formation aquitard sequence.
- Constrained rates of helium diffusion to ensure helium reached equilibrium between pore water and quartz.
- Simplified the diffusion modelling process to allow the quantitative assessment of helium equilibrium between pore water and quartz.
- Modelled the formation-scale transport, production and partitioning of helium between pore-water and solid phase (mainly quartz) in the aquitard sequence.
- Compared results to independent core-scale measurements of aquitard permeability.

Modelling suggests a vertical fluid velocity on the order of 0.002–0.02 mm/year (~10^{-13} - 10^{-12} m/s), which is very slow and indicative of diffusion-dominated transport, especially because the aquitard thickness exceeds 500 m. The shape of the helium profile suggests helium concentrations in the underlying Maules Creek Formation varied over recent geological time.

The future usage of this method depends on the depth and thickness of the aquitard of interest. Deeper aquitards are at higher temperatures, which enhances the diffusion of helium in quartz, resulting in faster equilibrium, and thus more reliable results. Subsurface temperatures should be 40 °C at a minimum. In thicker aquitards (tens to hundreds of metres), internal helium concentrations are slow to adjust when helium concentrations change in adjacent formations. Therefore, equilibrium of helium between quartz and pore water can be assumed for such thick aquitards.

Spatial and temporal scale influences on conceptual model development – examples from CSG water injection studies

Ryan Morris[1]
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Australia Pacific LNG undertook a series of aquifer injection trials targeting three different aquifers across four sites in the Surat Basin, Queensland. Following the trials, two operational schemes commenced operation in early 2015, with over 14GL injected to May 2017. Hydraulic and water quality responses observed during the short-term trials and through the long-term far-field pressure effects from operational injection have provided insight into how the scale of the imposed stress may lead to different hydrogeological interpretations. Examples will be presented of local versus regional hydraulic responses in the context of the system structural regime and how this has been used to advantage for injection scheme design, how hydraulic boundary behaviour may differ dependent on duration, water quality changes during long term pump tests, and intraformational heterogeneity and the associated hydraulic implications.

DAY 2: Wednesday, 12 July 2017

TRACERS / ISOTOPES

Evolution of chemical and isotopic composition of inorganic carbon in the unsaturated and saturated zones of a semi-arid zone environment

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Estimating groundwater age is important for any groundwater resource assessment and radiocarbon (^{14}C) dating can provide this information. However a thorough investigation of the water in the soil-plant-atmosphere continuum leading to the evolution of dissolved inorganic carbon (DIC) in groundwater is required for interpretation in a water-limited environment. In this study we trace the evolution of DIC through the unsaturated and saturated zones after prolonged drought and post-flooding of a major river system, the Darling River. In doing so, we quantified the contribution of carbon from various processes influencing the ^{14}C content of DIC in groundwater. None of the simple ^{14}C adjustment models could be applied for age estimation. Therefore, we used a combination of a graphical method and mass-balance calculations. It was found that the saline groundwaters evolved via carbon exchange between DIC- carbon dioxide gas ($CO_{2(g)}$) in the unsaturated zone and DIC-carbonate minerals in the saturated zone with water-sediment reactions driving ion exchange on clay minerals facilitating carbonate dissolution. This study shows the problems associated with using radiocarbon dating in a semi-arid zone or water-limited environment and the required carbon measurements needed to reduce this uncertainty.

The impact of wildfire on the geochemistry and hydrology the vadose zone

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7. University of Birmingham, Edgbaston, Birmingham, United Kingdom
8. Optimal Karst Management, Sandy Bay, TAS, Australia

Wildfire can dramatically modify the surface environment by removing surface vegetation, killing microbial communities and changing the soil geochemical and physical structure. Wildfires are a widespread phenomenon in Australia with 87,810 ha burnt in 2015-2016 in NSW alone (New South Wales Rural Fire Service, 2016). However, there has been little research on the impact of wildfire on vadose zone hydrology in Australia or elsewhere.

Limestone caves can be used as natural laboratories to study the impact of the surface environment on vadose zone hydrology in real time. We conducted a two year monitoring program to examine the short term (less than one year) post-fire impacts on the geochemistry and hydrology of vadose zone water in Glory Hole Cave, Kosciuszko National Park, NSW. We ignited an experimental wildfire on the surface over the cave after 1 year of monitoring and compared the pre- and post-fire data.

The findings indicate that there is a short term post-fire response in the organic and inorganic geochemistry vadose zone water. There was a post-fire spike in dissolved organic carbon, dominated by the hydrophilic fraction more than one month post-fire which was most likely due to high influx of ash from the fire. There was a multi-month increase in organic-associated metals such as Cu and Zn. The concentration of trace metals such as Fe and Si increased by an order of magnitude less than three months post-fire and was attributed to a flush of small colloidal organic matter. This study enabled us to establish that there is an organic and inorganic cave vadose zone water response to wildfires. The findings of this study can inform fire management strategies in order to protect sensitive karst environments in addition to water resource managers concerned with fluxes of mobilised metals nutrient fluxes to the vadose zone.

Integrated analysis to improve conceptualisation and characterisation of faults for use in regional groundwater models – hydrochemical and hydraulic analysis

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The aim of this project was to integrate analysis of hydrochemical, geophysical, hydraulic and structural geology to develop methodologies to improve characterisation of faults using a case study of the Gloucester Basin, NSW and incorporate the knowledge into a regional groundwater model. This paper presents the hydraulic and groundwater hydrochemical characterisation of the Gloucester Basin, with a focus on an area where CSG exploration occurred.

Hierarchical Cluster Analysis and Principal Components Analysis were performed on water quality data from all bores, as well as subsets of the data including data from grouped layers 1-6, 8, and 8-12 of the geological model, and within the focus area. Hydraulic head contours for layers 1-6, 8, 10 and 11-14 were combined with fault interpretation from seismic data and TDS contours to estimate flow orientations.

No distinct pattern in groundwater chemistry across the basin, or within the area of interest was evident. Water from layer 6 was consistently grouped together in the different analyses, indicating less hydrochemical variation. HCA and PCA also showed that TCMB04 had a relatively distinct hydrochemical composition, mainly driven by pH.

Hydraulic head analysis showed an east-west flow, with discontinuity across certain fault segments. Vertical flow was evident in shallow layers at particular fault segment locations. WK11 showed an up forward flow, opposite to WK12 and WK14, inferring a chimney of permeability enhancement. In the Stratford area, hydraulic head contours and TDS distribution showed a significant discontinuity, suggesting a lack of across fault flow but indicating vertical flow in a damaged zone. In this case, hydraulic analysis was more useful for elucidating flow orientation and fault characteristics than multivariate statistical methods applied to groundwater chemistry data; which is mostly descriptive in nature. However, TDS was a strong indicator of up-welling along fault damage zones.

A new diffusion method for heterogeneous drill cores using radioactive bromide or iodide

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Diffusion is sometimes a dominant process affecting radiotracers commonly used to quantify water resources, such as ^{3}H, ^{14}C and ^{36}Cl. However, measuring diffusion in heterogeneous environments including fractured rock currently requires many samples and assumptions. Typical diffusion coefficients derived from small rock samples are insufficient to determine diffusive losses in such settings. Larger representative lengths of drill cores are often available, but current diffusion methods cannot utilise large samples. Isolating the diffusive fluxes from other tracer losses, such as adsorption or precipitation, within a representative sample over a reasonable period is necessary to gauge and correct for diffusive tracer losses.

A paired radioactive-stable tracer radial diffusion method using lengths of drill core in a close-fitting acrylic tube diffusion cell has been devised and tested in the laboratory. With frequent injections, the radioactive decay of the short-lived radiotracer (^{82}Br or ^{131}I) maintains a steeper activity gradient and therefore diffusive flux into the core than the accumulating stable isotope of the same ion (Br or I). Therefore, the normalised radiotracer lost from the diffusion cell reservoir ($1-A_t/A_0$) remains greater than the diminishing stable tracer losses ($1-C_t/C_0$). The range of possible diffusive loss becomes $[(0.5 + C_t/C_0 – A_t/A_0) \pm (0.5 - C_t/2C_0)]$, which converges logarithmically with repeated injections.

Within two weeks, five drill cores yielded daily diffusive reservoir losses for bromide tracers: coarse sandstone 10±2%, medium sandstone 11±1%, massive limestone 2±1%, basalt 2±1% and basaltic breccia 3±1%. The iodide results were very similar once corrected for relative diffusion coefficients and duration, though higher in one basalt core.

Larger, representative heterogeneous cores can now be assessed. The derived rate of tracer loss can be applied to correct for diffusive losses of commonly used environmental radiotracers. This provides a previously unavailable correction for determining flow paths, rates and ultimately water resources in heterogeneous environments.

The CSIRO noble gas facility: new technology and first applications in QLD, NT and WA

Axel Suckow[1]
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CSIRO has pioneered the application of environmental tracers in groundwater, surface water and aquitard pore water. The latest advancement involved the development of the first and only laboratory on the southern hemisphere to measure all stable noble gases (He, Ne, Ar, Kr, Xe) in (ground)water samples operational since 2017. We also developed the sampling and preparation capacity for radioactive noble gas isotopes (^{85}Kr, ^{39}Ar, ^{81}Kr).

Noble gases are the most versatile environmental tracer in groundwater. They allow estimating flow velocities on time scales from years (^{85}Kr), centuries (^{39}Ar), millennia (^{4}He), up to one million years (^{81}Kr) and beyond (^{4}He, ^{40}Ar, ^{21}Ne, ^{134}Xe, ^{136}Xe). Knowledge of flow velocities is indispensable when managing groundwater as a resource for drinking water, agriculture, industry and mining. Noble gases also allow for the reconstruction of infiltration conditions (i.e., temperature, salinity and altitude). Infiltration processes, such as recharge after flooding a dry riverbed or constant infiltration from a permanently losing stream, can also be identified using noble gases. Noble gases assess groundwater flow systems, surface water – groundwater interactions, groundwater – seawater interactions, aquitard permeability and inter-aquifer connectivity.

We demonstrate the capabilities of the new facility, designed specifically for Australian groundwater conditions, including high concentrations of reactive gases (CH_4) and helium. The first analysed datasets will be presented, including CSIRO projects in the Surat Basin, QLD, aquifers in Northern Australia (NT and WA) and Rottnest Island, WA. We invite cooperation in the use of noble gases as a palaeoclimate tool to derive a record of soil temperatures over the last ice age and in the use of radioactive noble gases, ^{39}Ar delivering the only dating tool for the important time scale of centuries.

Understanding recharge and mixing on floodplains in the Murray Basin

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Floodplains are complex hydrological zones that may receive both discharge from regional groundwater and recharge from river water during high flow events. The floodplains on the Murray River host important ecosystems (particularly the river red gum forests); however, changes to river flows and landuse changes that result in a rise in the regional water table have locally severely affected these regions. This project uses isotope geochemistry (^{3}H and ^{14}C) together with major ions to address the timescales and patterns of floodplain recharge and groundwater mixing on the degraded Pike floodplain (South Australia).

The study sampled groundwater from the shallow low hydraulic conductivity Coonambidgal Formation and the underlying Monoman aquifer. Groundwater ^{3}H activities in the Monoman Formation decrease with depth from ~1 to <0.02 TU while the Coonambidgal groundwater has 3H activities of 0.25 TU. There is no correlation between ^{3}H activities and the proximity to surface water channels on the floodplain. Groundwater ^{14}C activities are between 40 and 95 pMC and are less well correlated with depth. Groundwater Cl concentrations are between 300 and 750 mmol/L and there is a broad inverse correlation with ^{3}H activities.

The combined geochemical data imply that groundwater recharge is dominantly through the floodplain rather than through the channel banks, which in turn requires preferential flow through high hydraulic conductivity zones in the Coonambidgal Formation. The recently recharged waters mix in the aquifers with the regional groundwater on timescales of a few years to decades. Development and preservation of fresh shallow groundwater, which may sustain vegetation, on this floodplain requires that flooding events occur and that regional water table rise is limited.

Ecohydrologic functioning of ephemeral streams

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While arid and semiarid environments encompass 70% of Australia's land mass and one third globally, information on the hydrology and ecologic functioning of dryland regions is limited. Accelerating human demand for water resources as well as changing climate are driving significant changes in surface and subsurface flows of ephemeral streams, which pose enormous challenges to their sustainable management (Safeeq & Fares 2016).

Best practice in the management of rivers and streams requires predictive data on the relationships among flow regimes, surface-ground water interactions, and the key ecological water requirements of the biota. However, disentangling these interactions and the pressures on them can be particularly difficult in arid regions because of extreme natural variability in rainfall and recharge (Dogramaci *et al.* 2015; O'Donnell et al. 2015).

Mining poses one of the main pressures on water resources in dryland regions; many of the world's largest mines operate in arid environments, including the major iron ore operations of Rio Tinto and others in the Pilbara region of northwest Australia. These mines increasingly abstract large volumes of fresh groundwater to access ore below water table. Water that is surplus to mining needs may be re-injected to aquifers, discharged back to the environment, or diverted offsite to develop regional agricultural programs (GHD 2015). Thus, one of the most pressing issues for managers in the mining sector (both in Australia and worldwide) is devising best practices for managing water for the life of the mine through to closure, including minimising impacts on key rivers and streams.

The University of Western Australia (UWA), NCGRT and Flinders University in collaboration with Rio Tinto, are investigating how surface and ground waters interact in ephemeral streams, and how riparian and floodplain vegetation both respond to and influence these interactions on daily, seasonal, and decadal scales. The study will address the worldwide paucity of integrated ecohydrologic studies of arid environments. The approach will utilise a suite of innovative as well as well-tested and robust isotopic and environmental tracer techniques, coupled with measurement of water flux and integrative modelling, in order to resolve the relative importance of shallow alluvial water, deeper groundwater and soil water in sustaining riparian and floodplain ecosystems.

Environmental tracers and hydrogeophysical techniques to characterise SW-GW interactions in a heavily faulted sedimentary basin associated with coal seam gas development

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The objective of this study was to investigate the sources and pathways of methane in a heavily faulted sedimentary basin under coal seam gas exploration. The study site was in the Gloucester Basin, NSW, which at the time of this investigation was in an exploration and pilot testing phase of a major coal seam gas project. A comprehensive hydrogeophysical field-based approach was used. This included hydrochemistry, methane and carbon isotopes, methane concentration, noble gases and apparent age tracer data to characterise the surface water and groundwater aquifer system. Data acquisition was designed to identify locations of preferential groundwater and methane discharge along Waukivory River and the Avon River using a run-of-river survey during a baseflow period. Time domain electromagnetic (TEM) surveys were used to locate structural geological features within 100 m depth of the surface in the study area and to assist with the interpretation of the hydrogeochemical data. The results were used to formulate a conceptual model of groundwater–surface water interactions in the Gloucester Basin and to assess the potential role of faults as conduits for groundwater, methane and solute transport from deeper formations to the alluvium and river network. Large resistivity/conductivity changes in the near-surface along the transect lines were attributed to faulting in the top 100 m of sediments. A number of sub-vertical faults were identified, that extended to below the depth of investigation of the shallow TEM and coincided with later delineated faulting in seismic data. Helium, radon and methane trends in surface water all indicated some preferential zones or 'hotspots' for groundwater discharge, including potentially from deeper sources. The study showed that connectivity between deeper formations and the overlying alluvial aquifer and surface water system was associated with the location certain fault architectures. Whilst a small source of groundwater, the methane flux from deeper formations to the alluvium and surface water was still materially significant because of the extremely high methane concentrations found in coal seam and interburden material.

Physical and chemical controls on apparent groundwater age discrepancies inferred from multiple environmental tracers

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Groundwater age represents the time that has elapsed between water entering an aquifer and data collection. Determining groundwater ages within an aquifer system has the potential to better constrain estimates of groundwater recharge, flow rates and therefore to increase the reliability of groundwater models, including predictions. However, the age of groundwater cannot be directly measured but must be inferred from measured concentrations of selected individual or multiple environmental tracers such as tritium (3H), chlorofluorocarbons (CFCs) and carbon-14 (14C). Water samples analysed for environmental tracer concentrations represent mixtures of waters of different ages due to variations in flow paths, recharge and discharge patterns, and aquifer heterogeneity. In addition, environmental tracer concentrations may be impacted by various (bio)geochemical reactions. This can lead to significant discrepancies between the groundwater ages interpreted from different tracers, referred to as the apparent ages. Recent analysis of groundwaters sampled in WA's Pilbara region show groundwater ages of < 50 years, based on measured CFC concentrations, while suggesting apparent ages of ~9,000 years, based on measured 14C concentrations (~30pmC).

This study uses numerical experiments to systematically study the transport of multiple environmental tracers to better understand which physical and geochemical processes can create these significant discrepancies in apparent ages. In the model simulations transport of environmental tracers in fractured rock is represented through a dual-domain approach, with the simulated mobile zones representing fractures and the model's immobile zones representing the rock matrix. The model simulations suggest that age discrepancies can only be created for a narrow range of dual-domain characteristics. Therefore other potential influences on the observed age patterns such as (i) screen length of observation wells (ii) climate variability and (iii) previously unaccounted geochemical reactions are also investigated.

Stable isotopes as indicators of dissolved methane sources and cycling in the Gippsland Basin, Victoria

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A suite of environmental tracers were analysed from the Gippsland Basin, Victoria, to determine the origins of methane in groundwater and characterise the biogeochemical and physical processes controlling its occurrence and cycling.

Water samples were collected from a range of depths and lithology, and were analysed for stable isotopes of methane plus a suite of other tracers - radiocarbon, noble gases (He-4, Ne, Ar), $\delta^{18}O$, $\delta^{2}H$ and $\delta^{13}C_{DIC}$. The data were analysed within the hydrogeological framework to characterise sources of methane in groundwater and identify possible transport processes.

Methane isotopic compositions ranged widely throughout the system. Two predominant groups of methane were found, both of which were of bacterial origin. One group contained isotopes with typical acetate-fermentation signatures ($\delta^{13}C_{CH4}$ = −45.8 to −66.2‰ and $\delta^{2}H_{CH4}$ = −204 to −311‰), and largely occurred in deep groundwater, near the coast. The other group exhibited unusually depleted $\delta^{13}C_{CH4}$ values by typical global standards (−83.7 to −97.5 ‰) and $\delta^{2}H_{CH4}$ values between −236 and −391‰. This group is associated with relatively shallow groundwater, near areas of extensive lignite. Radiocarbon and He-4 data indicate that groundwater age increases with depth, however inter-aquifer mixing complicates age interpretations. Stable isotopes of water in the deepest parts of the system show relatively depleted $\delta^{18}O$ and $\delta^{2}H$, suggesting isotopic modification during methanogenesis and/or depleted signatures associated with palaeo-recharge conditions.

The study provides the first data on dual-isotopic compositions of methane in the Gippsland Basin, and new insights into sources and cycling of methane in a multi-layered sedimentary basin. The basin is one in which extensive groundwater extraction and mining activity occurs, which may be having ongoing effects on inter-aquifer connectivity for both water and gases.

DAY 2: Wednesday, 12 July 2017

TRACERS / ISOTOPES

Keynote: Continental shelf-scale aquifer-ocean interactions: The impact of geological heterogeneity. *Holly Michael, University of Delware.*

Interdisciplinary research for sustainable groundwater management in conjunction with geodesy, geothermic and coastal oceanography. *Makoto Taniguchi, Research Institute for Humanity and Nature.*

Modelling offshore fresh groundwater in the Perth Basin. *Leanne Morgan, University of Canterbury.*

Estimating groundwater recharge to the lower Tertiary Aquifer near Barwon Downs. *Louise Lennon, Jacobs.*

Quantifying surface water – groundwater exchanges in the Campaspe Catchment (MDB) from geochemical tracers. *Camille Bouchez, Flinders University.*

The value of groundwater age in identifying temporal variability of recharge in the Pilbara region. *James McCallum, Flinders University.*

Estimates of site-scale groundwater recharge variability across a legacy low-level radioactive waste disposal facility in the Sydney Basin. *Doug Anderson, UNSW.*

Spatial and temporal variation in recharge and its influence on scenario modelling Western Cape York Regional Groundwater flow model. *Leon Leach,* Department of Science, Information Technology and Innovation *SA.*

The Lamington and Main Range Volcanics in QLD and NSW: their significance as preferential recharge areas in the Clarence-Moreton Basin. *Matthias Raiber, CSIRO.*

Estimating shallow groundwater take in the Shepparton Irrigation Region: technical approach. *Tara Taylor, Jacobs.*

Continental shelf-scale aquifer-ocean interactions: the impact of geological heterogeneity

Holly Michael[1], Kaileigh Scott[1], Xuan Yu[1], Khan Mahfuzur[1], Koneshloo Mohammad
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Exchange of water between land and sea impacts fresh groundwater resources, nearshore aquatic ecosystems, and the chemistry of the ocean over geologic time. Theoretical salinity distributions in coastal aquifers based on homogeneous aquifer properties consist of a freshwater-saltwater interface that extends landward from the coastline and a distribution of groundwater discharge across the land-sea boundary that decreases rapidly with distance offshore. However, observations indicate that both freshened groundwater and high rates of submarine groundwater discharge can exist far offshore. While it is known that heterogeneity in aquifer properties affects both salinity and submarine groundwater discharge (SGD), few studies incorporate geologic structure explicitly. *Objectives*. We addressed this difference between theory and observation by simulating groundwater-seawater interaction in heterogeneous continental shelf aquifers. *Design and Methodology.* We simulated groundwater flow in heterogeneous coastal aquifers to demonstrate that the independent observations of offshore freshwater and SGD are linked, and can be explained by interactions between geologic structure and variable-density flow and transport. We developed a geostatistical model of coastal heterogeneity using lithologic logs from the Bengal Delta, and extended it to encompass geologic connectivity likely typical along the land-sea margin. *Original Data and Results.* Results show that heterogeneity results in spatially complex salinity distributions that extend tens of km offshore. The density gradients that result drive high rates of circulation of sea water through the continental shelf. These processes are highly variable, but are affected by the land-sea connectivity of high- and low-permeability sediments. Further, homogeneous models with equivalent, upscaled hydraulic conductivity cannot produce patterns in salinity and SGD that are consistent with observations. *Conclusion*. These findings suggest that freshened groundwater resources and large solute fluxes are common characteristics of continental shelves worldwide. These new insights may alter estimates of ocean chemical budgets and improve our ability to manage coastal water resources.

Interdisciplinary research for sustainable groundwater management in conjunction with geodesy, geothermic and coastal oceanography

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In order to manage groundwater resources sustainably, interdisciplinary groundwater research had been made in Asia in conjunction with coastal oceanography, geothermic and geodesy. Long term changes of subsurface environment in Asia due to urbanization and global change, had been analyzed including groundwater storage changes which were detected by geodesy satellite GRACE and others. The second issue is subsurface warming due to global warming and urbanization in conjunction with Geothermic. Third issue on interdisciplinary groundwater problem is the exchange of water and dissolved materials between land and ocean as submarine groundwater discharge into the ocean and saltwater intrusion into the land in conjunction with coastal oceanography. Groundwater-energy-food nexus is another interdisciplinary issue for sustainable groundwater management. All data for these interdisciplinary groundwater research were collected from data observed in situ, satellite data, results from numerical simulation models, and statistic data in Asian countries. Integrated water managements for sustainability are discussed for transformation to sustainable groundwater use in Asia. Groundwater is a key for adaptation to the changing climate and society, and an important entry point for water-energy-food nexus for sustainability. Interdisciplinary groundwater research is necessary for sustainable groundwater management, with adjacent disciplines such as geodesy, geothermic and oceanography.

Modelling offshore fresh groundwater in the Perth Basin

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The objective of this study was to improve the conceptualisation of fresh groundwater occurring in the offshore extension of confined aquifers underlying Perth, Western Australia. These aquifers (the Leederville and Yarragadee) are a critical water resource for the city of Perth. Onshore geological and hydrogeological data were used in conjunction with offshore geological information from petroleum exploration wells to develop a preliminary representation of the offshore stratigraphy and structure. The stratigraphy was used in the development of a two-dimensional variable-density flow and solute transport numerical model. This model extends from 10 km inland to the continental shelf, 90 km offshore.

Simulations provide evidence for long-term sea-level variations (associated with glacial cycles) being a key driver of offshore fresh groundwater emplacement in the Perth basin confined aquifers. Simulations also indicate that the position of the interface between seawater and freshwater may not have reached equilibrium with present day sea levels. As such, the interface may still be moving landward in response to the rise in sea level that has occurred since the last glacial maximum (around 20,000 years ago).

This study offers insights into the key drivers of offshore fresh groundwater distribution in the Perth basin aquifers and highlights the importance of transience in this system.

Estimating groundwater recharge to the Lower Tertiary Aquifer near Barwon Downs

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The key recharge process for Lower Tertiary Aquifer in the vicinity of Barwon Downs is recharge from rainfall. Previous studies have provided some estimates of groundwater recharge to the LTA; however these often incorporate little or no field data and provide a broad range of recharge estimates. The objective of this study was to estimate groundwater recharge to the LTA in the Barwon Downs region using independent techniques to improve the accuracy and confidence in the numerical model.

Given the considerable variability in the spatial and temporal distribution of recharge, it is best practice to apply multiple methods to reduce the uncertainty of recharge estimates. This study used two methods to estimate recharge using chemical tracers – the tritium method and the chloride mass balance method. These methods were selected as they use field data to characterise actual recharge to the aquifer, integrate unsaturated zone processes and are applicable over the time scales of interest.

To support the isotope and chloride based estimates of recharge, a one dimensional unsaturated zone model was also developed. This model was used to simulate recharge in a number of different soil profiles. The main advantage of the model is that it can provide more detailed estimates of the month to month and year to year variability than the temporally averaged figures from chemical tracers.

This assessment concluded that groundwater recharge rates to the outcropping LTA over the last 50 years are most likely equivalent to an average rate of 9% and 11% of annual rainfall. However, recharge in some areas may be as high as 26% of the annual average rainfall. Additionally, it was found that historical recharge rates over the last 100 to 1000s of years may be considerably lower, representing around 5% of the modern annual average rainfall.

Quantifying surface water – groundwater exchanges in the Campaspe Catchment (MDB) from geochemical tracers

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Quantifying the magnitude of SW–GW exchanges is crucial and is the very first step towards a coordinated management of water resources. Focused on the Campaspe catchment, a sub-catchment of the MDB, this works aims at investigating the temporal and spatial variability of SW-GW exchanges from the geochemical signature of the river. Radon-222 activities and water stable isotopic compositions were measured in April 2016 (18 samples), Dec 2016 (20 samples) and May 2017 (22 samples) and used to calibrate groundwater discharge along the stream. An overall similar pattern of groundwater discharges between sampling periods is apparent and shows that the river is losing in the upstream part and gaining downstream. Discrepancies between sampling periods could be related to variable water allocations in the catchment with weirs and irrigation activities impacting local hydraulic gradients. This study also exploits hourly EC and water level data recorded since April-2016 at seven points of the river, in order to provide insights into SW-GW exchanges at a finer time scale. Indeed, while temporal river EC and flow data should reflect temporal patterns in SW–GW interactions, field data have rarely been used as quantitative proxies of SW-GW exchanges. Here, we measure characteristic time of water level and EC signals as a response to perturbations created by flood events. The results are analysed in terms of flood intensity and river characteristics. In the context of allocation-dominated river flows, geochemical tracers should provide relevant insights into water dynamics of the river – aquifer continuum. This approach strongly benefits from complementary groundwater modelling studies within the Campaspe Catchment.

The value of groundwater age in identifying temporal variability of recharge in the Pilbara region

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Groundwater ages represent an interaction between past climate, land surface processes and aquifer properties. A key to understanding the age of groundwater, and how it reflects past processes, is the ability to estimate groundwater ages. To assist in the determination of groundwater ages, we developed a method that interprets the concentration of multiple environmental tracers with a non-parametric model of groundwater ages. The model assumes only that similar aged water is present in the sample in similar age proportions. We applied the method to data collected in the Pilbara region of NW Australia. Environmental tracer data consisting or Carbon-14, Argon-39, Krypton-85, Tritium, CFCs and SF_6, were collected from seven mine de-watering bores between 2014 and 2015. The interpreted age distributions consisted of a number of groups that were consistent between different wells. The water present in samples consisted of a young component of water <10 years old, a component of water approximately 80–300 years old and water approx. 600–1000 years old. Whilst the exact proportions of each component were uncertain, the ages present in the sample were clearly identified. The young water component present in all the sampled bores is consistent with recent changes in the groundwater system due to pumping. The second component, water with ages between 80 and 300 years was present in five of the seven wells. Other studies in the Pilbara region have identified that this period was characterised by extreme flooding events, indicating that a large proportion of the aquifer storage was recharged under a different and more extreme climate. Our results highlight the value of groundwater age studies in understanding the extended history of groundwater resources, as hydraulic measurements only reflect changes of shorter periods.

Estimates of site-scale groundwater recharge variability across a legacy low-level radioactive waste disposal facility in the Sydney Basin

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2. Australian Nuclear Science and Technology Organisation, Lucas Heights, NSW, Australia

The Little Forest Legacy Site (LFLS) is a legacy, low-level radioactive waste disposal facility located at Lucas Heights in eastern NSW, Australia. The site was operated by the Australian Atomic Energy Commission between 1960 and 1968. Landfilling of wastes was to a maximum depth of three (3) metres into clay and shale material of the Hawkesbury Sandstone Formation.

Monitoring of radionuclide containment at LFLS has been ongoing since the emplacement of waste. In recent decades the level of characterisation at LFLS has intensified to develop a more comprehensive understanding of the site geology, hydrogeology and hydro-geochemistry. This additional work is being undertaken to support detailed plans for site management.

Recent site characterisation activity has included coring and geological logging, a range of geophysical surveys, monthly monitoring of groundwater and surface water quality and various laboratory analyses. Groundwater levels have also been recorded every 15 to 30 minutes since mid-2007 at twenty-three (23) locations about the site.

This paper reports the results of our preliminary analysis of the comprehensive groundwater level monitoring data at the LFLS. This includes an analysis of the data with the episodic master recession (EMR) tool recently published by USGS. The EMR program provides a largely automated workflow to estimate groundwater recharge as a function of individual groundwater recharge events. When coupled with historical and/or synthetic rainfall time-series data the output of the tool can also be used to support simple but rapid simulation of past and/or future site groundwater levels.

The data analysis techniques trialled in this study will be of interest to most hydrogeologists routinely involved in site characterisation studies. Our estimates of groundwater recharge rates into the clays and shales of the Hawkesbury Sandstone Formation at the LFLS may also be of interest to many practitioners working in the Sydney Basin.

Spatial and temporal variation in recharge and its influence on scenario modelling Western Cape York Regional Groundwater flow model

Leon Leach[1]

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Between1972 and 2015, about 150 gigalitres of groundwater was extracted from artesian bores tapping the Gilbert River aquifer (located near Weipa Cape York Peninsular, Queensland, Australia). This extraction resulted in a cone of depression extending up to 80 kilometres from the borefield as defined by the one metre drawdown contour. There are proposals to establish addition borefields and an assessment of the likely impacts was required.

The specific objectives of the assessment were to:

- identify the capacity of the groundwater resources to meet existing demands
- establish the likely short-term and long term cumulative impacts of the additional demands of up to 20GL/year over 40 years, on existing users and springs.

The average annual rainfall over the recharge beds increases in a northerly direction from 1140 mm/year (near Coen) to 1950mm/year (near Heathlands).

In previous groundwater studies a constant annual recharge of 35 mm/year was applied over the recharge beds. A feature of this study area is recharge emerges as baseflow to streams. Stream measurements suggest recharge is influenced by antecedent dry conditions and to consecutive rainfall days. In order to replicate this aspect, daily estimates of recharge were derived for 12 rainfall locations using the SplashMulti software. It was found recharge is more episodic and has higher spatial and temporal variation then previously considered.

In order to account for the spatial and temporal variations in projected borefield extraction, recharge, and stream base flow, a transient regional groundwater flow model (Modflow_USG) at the day scale was required and was successfully calibrated to the groundwater level and stream flow data.

Scenario modelling indicates that after 40 years of additional demand, the cone of depression is likely to extend up to 120 kilometres from the proposed borefields that after 100 years from the cessation of pumping, there is near full recover.

The Lamington and Main Range Volcanics in Qld and NSW: their significance as preferential recharge areas in the Clarence-Moreton Basin

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4. Groundwater, Geoscience Australia, Symonston, ACT, Australia

The Lamington and Main Range volcanics form a major regional fractured rock aquifer system (more than 12,000 km^2) within the Clarence-Moreton Basin in south-east Qld and north-east NSW. Although widely recognised as an important hydrological feature, there has been no systematic or comprehensive basin-wide assessment of their significance as a major preferential recharge area.

Within the Clarence-Moreton bioregional assessment, an integrated hydrogeological assessment of basin-scale aquifer systems involved developing a 3D geological model, groundwater recharge and regional stream flow assessments, and characterising aquifer hydrochemistry (within the volcanics and neighbouring aquifer systems). The 3D geological model yielded a median thickness of approximately 130 m for these volcanic aquifers, and a maximum thickness of ~800 m near the crest of the volcanics in elevated areas. However, borehole lithological data confirmed that these volcanic rocks do not consist of a single homogeneous basalt flow nor form a single aquifer, but instead consist of many thinner overlapping basalt flows (up to ~10 m thick). The groundwater recharge assessment (using chloride mass balance) indicated recharge rates that can locally be more than 1000 mm/yr, with recharge rates to the volcanic aquifers at least one order of magnitude greater than recharge rates for most sedimentary bedrock units. However, a large proportion of groundwater recharge to the Lamington Volcanics discharges locally with short transit times (days to months) into the alluvium or streams, whereas only a small proportion percolates to deeper aquifers.

Based on this integrated approach, we have developed conceptual models that describe the relationship of the volcanic aquifers with alluvial aquifers and streams as a primary driver of alluvial groundwater and surface water quality in the Clarence-Moreton Basin. This conceptual understanding provides important knowledge for assessments of any future coal seam gas or agricultural development activities within the Clarence-Moreton Basin.

Estimating shallow groundwater take in the Shepparton Irrigation Region – technical approach

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2. Goulburn-Murray Water, Tatura, VIC, Australia
3. Jacobs, Canberra, ACT, Australia

Shallow groundwater within the Shepparton Irrigation Region (SIR) is accessed from discontinuous shoestring sands and is more commonly constrained by seasonal hydrological loading than competition between users. Under the Basin Plan, the Water Resource Plan must detail how the annual volume of groundwater take will be determined. The Basin Plan requires that the determining method be fit-for-purpose and there are provisions for flexibility in the approach. This flexibility enables consideration to be given to cost effectiveness. The discontinuous nature of the sand aquifers means that the resource cannot be realistically considered as a single 'consumptive pool'. Additionally, there are high operational costs associated with area-wide metering. Within this context, work was undertaken to develop a methodology for estimating and reporting shallow groundwater extraction in the SIR.

Work completed in 2014 assessed costs and suitability of various methods of usage estimation. This work concluded that metering a subset of bores would be a suitable method as a means of substantially reducing cost, whilst maintaining a reasonable level of certainty in regional scale estimates of take. Historical metered usage data was available across the SIR. Subset sites were selected that were compliant with Goulburn-Murray Water safety criteria and largely operational, recognising that this would bias the sample towards higher levels of take. A realistic match between estimated and historical metered usage was achieved by extrapolating subset metered take as a percentage of entitlement moderated by linear relationships between shallow groundwater take, and spring rainfall and Deep Lead extraction. The method produced results that were consistent with historical levels of take albeit a slight over-estimate of the actual volume (a conservative approach to reporting).

This presentation explores the technical approach employed and demonstrates that metering in the SIR can be met with a fit-for-purpose, cost effective method as an alternative to area-wide metering.

DAY 2: Wednesday, 12 July 2017

MODELLING

Keynote: River basin-scale integrated surfacesubsurface hydrologic modelling to support agricultural risk management. *Steven Berg, Aquanty.*
Simulating complex surface water/ groundwater interactions during flood events with a fully-integrated physics based hydrologic model. *Steven Berg, Aquanty.*
MIKE SHE modelling of an ephemeral catchment water balance. *Hossein Daneshmandl, Monash University.*
Groundwater in catchment hydrology: getting the signposts right. *Douglas Graham, DHI.*
Qualitative uncertainty analysis: why we need to slow our thinking about groundwater models. *Luk Peeters, CSIRO.*
The importance of being uncertain (for groundwater modellers). *Kate Holland, CSIRO.*
AlgoCompute: large-scale calibration and uncertainty analysis made easy in the cloud. *Damian Merrick, HydroAlgorithmics.*
Cloud computing for groundwater model calibration and uncertainty analysis. *Kevin Hayley, Groundwater Solutions.*
Bayesian uncertainty quantification in practical groundwater modelling with the aid of Gaussian process emulator. *Tao Cui, CSIRO.*
Using heat and rhodamine as groundwater tracers in a strongly heterogeneous aquifer: flow & transport insights using inversion modelling. *Theo Sarris, Institute of Environmental Science and Research.*

River basin-scale integrated surface-subsurface hydrologic modelling to support agricultural risk management

Steven Frey[1], Michael Callaghan[1], Hyoung-Tae Hwang[1], Young-Jin Park[1], Rick McConnell[2], Steven Berg[1], Edward Sudicky[1]

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2. DYMAC Risk Management Solutions, Lacombe, Alberta, Canada

Providing a scientific basis for water management policy, and assessing the physical characteristics underlying hydrologic risk, typically requires watershed-scale assessments that encompass a few hundred km^2 at a minimum. However, agriculture-focused water resources challenges often encompass much larger areas, and can easily extend to major river basins (>100,000 km^2). Given the recent increase in crop losses attributed to large-scale extreme climate related events (i.e. overland pluvial flooding, excess moisture, and drought), and the concern that the frequency of these events will progressively increase in response to climate change, there is growing demand for large-scale hydrologic risk assessments. Because of complex interactions between climate, surface water, groundwater, and soil moisture across much of the agricultural landscape, robust physically-based 3-D integrated hydrologic models provide a holistic means of performing water related risk assessment for these types of applications.

In this presentation we discuss a large-scale modelling-based agricultural risk assessment project whereby fully-integrated surface/subsurface water models are being developed using the HydroGeoSphere platform for the South Saskatchewan River Basin (SSRB, ~150,000 km^2) located in the predominately arid region of Western Canada. The hydrologic responses within its major sub-basins are nested seamlessly within the full-basin scale model in order to capture additional details at an increased resolution.

Results from this work demonstrate that comprehensive physically-based hydrologic simulation platforms are becoming increasingly relevant and feasible tools for addressing water related challenges facing global agriculture. Visualization of transient model results includes spatially-distributed soil moisture, groundwater levels, recharge and discharge patterns at high resolution in relation to surface topographic controls and water bodies.

Once complete, the SSRB modelling platform will facilitate large-scale spatially-distributed projections of flood, drought, and other water-related risks to crop production at unprecedented detail, over temporal intervals ranging from days to decades.

Simulating complex surface water/groundwater interactions during flood events with a fully-integrated physics based hydrologic model

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The optimal design of reactive covers for treating contaminants seeping from a riverbank to a stream requires a comprehensive understanding of the discharge of water and solute fluxes along the bank profile. This is particularly true following flood events that result in riverbank discharge rates back into the river during the recession period that are significantly higher than baseline conditions. Traditional modelling approaches used to describe surface water/groundwater interactions during flood events typically rely on simplified analytical solutions, or highly abstracted numerical solutions which simplify river geometry, and ignore bank soil heterogeneity.

To overcome these limitations a rigorous physics-based numerical model was developed using HydroGeoSphere. This numerical model incorporates channel geometry, heterogeneous bank soil distribution, and observed river stage data to drive the model. The model was used to simulate the interaction of surface water and groundwater within the riverbank soils during flood events, including in-channel and floodplain events.

The interaction between surface water and groundwater was computed by applying a conservative tracer to the surface water in order to track its migration into the bank soils on the rising limb of the flood hydrograph, and its return to the channel as the flood recedes. The results of this study include increased understanding into: the potential depth of penetration of surface water into the bank and the degree of mixing with groundwater; estimation of infiltration and exfiltration velocities and fluxes; timing of return flows after a flood event and their sensitivities to hydraulic conductivity; and, the identification of key discharge zones. All which are critical factors in reactive cover design.

The numerical simulations conducted as part of this study provided insights into the complex interactions between surface water and groundwater that occur during a flood event that would otherwise have been very difficult to glean from field data alone.

MIKE SHE modelling of an ephemeral catchment water balance

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3. Department of Civil, Environmental and Architectural Engineering, University of Padova, Italy

In arid and semi-arid environments, streamflow could be seasonal with highly nonlinear responses to rainfall and antecedent soil moisture. Physically-based modelling of such catchments is challenging due to the sensitivity to initial conditions, and the need to model all the components of the water balance appropriately. This paper investigates complexities around modelling the entire water cycle applying an integrated modelling framework, MIKE SHE, to a southwestern Victorian ephemeral catchment used as a pasture for grazing.

The three-dimensional Darcy equation and the one-dimensional Richards equation are used to couple the saturated and unsaturated zones. Surface flow is represented by the two-dimensional diffusion wave approximation. Root water uptake is described by the Kristensen & Jensen (K&J) dynamical reduction model, whose parameters were ascertained through model calibration and sensitivity analysis. Catchment discharge and climatic data were obtained from onsite gauges and a nearby weather station.

Good calibration and validation fit was achieved for discharge hydrograph and groundwater heads at the catchment outlet. Due to unmeasured heterogeneities in soil properties, upper slope bores showed some discrepancies from the observed levels; however, differentials conform to observations in one of these bores, indicating that the model provides realistic head fluctuations. Recursive simulation results showed that transition from an arbitrary initial condition to a steady-state solution depends heavily on the natural rainfall regime variations. A sensitivity analysis of probable combinations of K&J parameters revealed that the entire parameter space produced negligible variations in water table dynamics but corresponded to a more pronounced diversification in distributed evapotranspiration.

Despite simplifying assumptions, MIKE SHE proved capable in capturing ephemeral catchment flow dynamics. Recursive model run could be helpful in investigating attenuation rate in sensitivity to initial conditions as for this study it depended largely on the amount of precipitation suggesting the irrelevance of the steady state approach for ephemeral catchments.

Groundwater in catchment hydrology – getting the signposts right

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A sketch map is a simple conceptual model, where complexity is reduced to the essential details. There is no need to label all the streets. However, the map is useless if a key signpost is wrong. Groundwater modelling is analogous. We simplify the complexity to the essential details for reliable decision making. Yet, what if the signposts are wrong? Groundwater is driven by rainfall on the land surface, which also drives hydrology. Runoff, streamflow, ET and recharge are the signposts. In groundwater models, these processes are simplified to satisfy boundary constraints. However, recharge is spatially and temporally complex, streamflow is highly dynamic and non-linear, and feedback is substantial. The alternative is to simulate groundwater as part of the hydrology using dynamic, distributed, physics based methods. Such models include overland flow, river hydraulics, unsaturated infiltration, ET and groundwater flow. An integrated model internally partitions rainfall into runoff, infiltration and evapotranspiration – avoiding the double accounting common with separate models. Groundwater-surface water interaction changes dynamically with changing stream levels and flooded areas. Riparian vegetation competes for groundwater discharge to streams. A primary outcome is a full, distributed, dynamic water balance – not just a “groundwater water balance” of the 5 % of rainfall left over after ET. Integrated models are useful when surface processes affect sub-surface conditions – and vice versa. The most common objections to integrated models relate to high data requirements and excess model complexity. Typically, these objections are a strawman for a lack of knowledge and expertise. In reality, most modellers are specialized in either groundwater or surface water - rarely with expertise in both. The real issues affecting model reliability (e.g. a poorly defined recharge boundary) are ignored and effort is spent increasing the fidelity of the model domain. The streets are labelled, but the signposts are wrong.

Qualitative uncertainty analysis: why we need to slow our thinking about groundwater models

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Daniel Kahneman's 2011 book '*Thinking Fast and Slow*' popularised the notion that humans, including groundwater modellers, do not always think rationally, but often instead use a variety of mental shortcuts. Rational and systematic reasoning requires deliberate effort, which Kahneman associates with 'slow' thinking.

Applying a systematic, rational and critical mindset is essential when developing or evaluating numerical groundwater flow models, as each is inevitably based on a number of subjective choices. One way to identify and avoid mental biases and shortcuts, such as expert over-confidence or confirmation bias, is to carry out a qualitative uncertainty analysis.

A qualitative uncertainty analysis involves systematically listing and discussing model choices and assumptions. It formally evaluates the rationale of an assumption in terms of data and resources available, as well as technical challenges and available alternatives. Perhaps most importantly, a qualitative uncertainty analysis discusses how assumptions affect predictions.

Qualitative uncertainty analyses were routinely applied as an integral part of uncertainty analyses undertaken for the Bioregional Assessments Programme. The open and transparent listing and discussing of assumptions was found to be a daunting task. The evaluation of the potential effects of model assumptions on predictions was particularly challenging, as many groundwater models were found to feature non-linear interactions and feedback mechanisms.

While qualitative approaches to uncertainty analysis do not resolve subjective model choices, a plain English discussion of assumptions proved to be an invaluable tool when communicating the importance of various assumptions to clients and stakeholders. It also provided a useful starting point for interactions with reviewers. In addition, qualitative uncertainty analyses are a great platform to identifying and prioritising opportunities to reduce the uncertainty of modelled predictions.

The importance of being uncertain (for groundwater modellers)

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Numerical models make an important contribution to the assessment of potential environmental Impacts, such as the potential cumulative impacts of coal resource development on water resources and water-dependent assets, including rivers, wetlands and groundwater systems. Uncertainty analysis, where potential sources of uncertainty in model predictions are analysed using quantitative or qualitative techniques, are used to build confidence in model predictions. While techniques to quantify the uncertainty in model predictions are well documented, effective communication of predictive uncertainty that instils confidence in the model and its predictions remains a challenge.

This paper describes the challenges and solutions used to communicate the uncertainty analysis developed for the Bioregional Assessment Programme in Australia. To do this, numerical models are run hundreds or thousands of times to quantify the sensitivity of model predictions to input parameters using a credible range of possible input parameters. The resulting range of possible model predictions is a high-dimensional dataset, which is challenging to visualise and summarise.

Bioregional Assessments have simplified the communication of these often very skewed distributions of model predictions by reporting the probability of exceeding a specified threshold or percentile estimates of a model output. Model predictions are reported in three ways: 1. A conservative zone to rule-in and rule-out impacts; 2. Maps, tables and plots that show the range of estimates; and 3. Median, 5th and 95th percentile estimates of model outputs described in the text of the report.

The open and transparent communication of the uncertainty associated with the numerical models used in the assessment of potential environmental impacts ultimately improves confidence in the model and its predictions.

AlgoCompute: large-scale calibration and uncertainty analysis made easy in the cloud

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AlgoCompute is a new web-based platform that makes it easy to perform simulation runs in the cloud. It allows scaling out to any desired number of compute nodes, which is particularly valuable when undertaking complex uncertainty analysis, calibration or optimisation tasks. AlgoCompute is accessed through a web browser: you log in, provide it with your model files, initiate new runs, and monitor ongoing runs.

The system is designed to integrate well with PEST, and the platform automates the setup and pull-down of appropriate processing resources, distribution of model data and results, and coordination of PEST slaves. For model runs, various versions of MODFLOW are provided, from MODFLOW-96 through -2005, -NWT and -USG, in addition to HydroGeoSphere for integrated modelling.

The web interface allows monitoring of console outputs from each simulation instance to check on progress, and email notifications may be sent whenever a run is completed, or each time a new optimisation iteration is reached in a PEST optimisation. Runs may be terminated manually at any time. On completion of a run, model result files are made available in AlgoCompute's cloud storage system, allowing them to be downloaded directly from the web interface or transferred to a Dropbox folder to be automatically synchronised with desktop or laptop computers, ready for inspection and post-processing with other tools.

AlgoCompute's access to cloud resources is entirely self-contained: users do not need to maintain their own accounts with a public cloud provider, nor to provision their own virtual machines for running models or write scripts to start, stop and monitor progress. Additionally, being completely web-based means that no custom software installations are required, allowing modellers to access the system with minimal support from IT personnel.

Cloud computing for groundwater model calibration, and uncertainty analysis

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Highly parameterized inversion methods of groundwater model calibration, and associated sub-space methods of predictive uncertainty analysis, have become prevalent in groundwater modeling research and practice. To make these methods computationally tractable it is essential to employ parallel computing. Currently, there is a major shift in information technology towards centralized cloud computing resources. This presentation discusses the use of cloud computing for groundwater model calibration, shares insights gained from several highly-parameterized calibration projects conducted using cloud computing, and presents two different software packages for conducting parallelized PEST based groundwater model calibration, and uncertainty analysis using cloud computing.

Over the past six years several highly parameterized calibration projects have been completed using the Amazon EC2 Cloud Service. A custom HTTP protocol based Python program, was used to transfer file and initiate beoPEST processes on large distributed networks for calibration and uncertainty analysis.

To make highly parallelized, cloud computing based, calibration accessible to a wider base of groundwater modeling practitioners, a new version of PEST tailored to highly parallelized environments has been developed, PEST-HP, and integrated into a Microsoft Azure based cloud computing service named “PEST.cloud”.

Calibration of a regional-scale model of groundwater flow is provided to illustrate the methodology. Aquifer properties were calibrated to more than 1,500 static hydraulic head measurements, and a ten year monitoring period during industrial groundwater use with to 450 adjustable parameters. The PEST based model calibration was parallelized on up to 250 computing nodes located on Amazon’s EC2 servers.

Highly parameterized calibration and uncertainty analysis has been successfully conducted using cloud computing services for several years. The new developments in PEST Software will allow this type of analysis to be more widely adopted, allowing null space monte carlo uncertainty analysis to become a standard practice.

Bayesian uncertainty quantification in practical groundwater modelling with the aid of Gaussian process emulator

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Bayesian inference provides a mathematically elegant and robust approach to utilize observations to constrain numerical models. However, a formal Bayesian analysis is rarely conducted in practical groundwater modelling, particularly for regional groundwater models. Technical challenges to its implementation include long model runtimes, and the difficulty to define a suitable likelihood function.

To overcome the challenges, we propose a framework to combine model emulating techniques and approximate Bayesian computation (ABC). Highly efficient Gaussian process emulators are trained using thousands of snapshots from the MODFLOW model to replace the computationally demanding process-based groundwater model. ABC relaxes the need to explicitly define a likelihood function, and also allows a powerful and flexible strategy to define multiple objective functions during model constraining. The proposed framework was applied to a newly developed regional groundwater model in the Clarence-Moreton Basin to assess the potential impact of coal seam gas (CSG) development on relevant groundwater systems.

Results: 1. The trained emulators based on 3700 model runs can reproduce the MODFLOW model outputs accurately, which is verified by scatter plots, model mean absolute error (MAE), coefficient of determination (r^2), and the root mean square error (RMSE). 2. Although context and prediction specific multiple objective functions were used, the observations did not constrain most parameters significantly. 3. The overall potential impact of the simulated CSG development scheme in the Casino area is minor with extreme drawdown at the water-table of about 1 m within the central area of the development.

Statistical emulators are an efficient tool to replace process-based models when computer efficiency is a critical issue for groundwater model application, such as uncertainty analysis, real-time prediction, and model coupling. The surrogate-based ABC overcomes barriers for applying Bayesian analysis on complex non-linear groundwater models with long runtimes.

Using heat and Rhodamine as groundwater tracers in a strongly heterogeneous aquifer: flow and transport insights using inversion modelling

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Using heat as an active tracer for aquifer characterization is a topic of increasing interest for providing complementary insights on groundwater flow and transport pathways. Groundwater temperature profiles are being extensively used in fractured and karst aquifers to provide a better understanding of the main flow and transport structures that dominate a system. Alluvial gravel aquifers are inherently heterogeneous as a consequence of their complex sedimentary architecture, with significant implications for reliable predictive contaminant transport modelling required in water resource management decision making. This heterogeneity is further accentuated by the existence of open framework gravel (OFG) facies, set within a sandy gravel matrix, that exhibit hydraulic conductivity up to three orders of magnitude higher than that of the matrix.

An extended heat and solute tracing experiment was undertaken at ESR's experimental site at Burnham, 25 km southwest of Christchurch, NZ. During the experiment warm (37 degrees) Rhodamine WT solution was injected for 16 days and temperatures and RWT concentrations were periodically monitored in an array of 22 observation wells over an 80 days period. A three dimensional, dual species, transient, contaminant transport model has been developed to provide an understanding of how the two tracers moved through this highly heterogeneous aquifer. The concept of a dual domain system has been tested numerically against field observations, while inversion modelling of the underlying hydraulic conductivity field provides interesting results regarding the delineation of preferential flow paths and the characterization of the aquifer heterogeneity.

DAY 2: Wednesday, 12 July 2017

MODELLING

Keynote: Per- and poly- fluoroalkyl substances (PFAS) investigation. *Vicki Pearce, Department of Defence.*
Understanding emerging pollutants in a connected system. *William Glamore, UNSW.*
Simulation of PFAS transport in coastal sands aquifers at Williamtown, NSW. *Cassie Turvey, Hydro Simulations.*
Assessing health risks for groundwater contaminated with Per and Polyfluoroalkyl Substances (PFAS): lessons learned. *Therese Manning, EnRiskS.*
Impact of PFAS chemicals on insitu microbial communities. *Denis O'Carroll, UNSW.*
Predicting the potential recovery of petroleum fuels from impacted aquifers. *Robert Lenhard, CSIRO.*
Microbial technologies for bioremediation and biogas production in subsurface environments. *Mike Manefield, UNSW.*
LNAPL dynamics in the subsurface: linking multi-phase and multicomponent processes. *Kaveh Sookhak Lari, CSIRO.*
A numerical model incorporating nonlinear decay and sorption isotherms for simulating transport of contaminants emanating from instantaneous spill. *Amarsinh Landage, Institute of Technology, India.*

Per- and Poly- Fluoroalkyl Substances (PFAS) Investigation, Department of Defence

Author names withheld

Defence is undertaking investigations associated with legacy Aqueous Film Forming Foam (AFFF) containing per- and poly-fluoroalkyl substances (PFAS); including perfluorinated sulfonate (PFOS), perfluorohexane sulfonate (PFHxS) and perfluorooctanoic acid (PFOA). AFFF has been used extensively worldwide, including in Australia, since the 1970s by both civilian and military authorities to extinguish liquid fuel fires. AFFF acts quickly by smothering fuel when a thin film of foam forms on the fuel, stopping contact with oxygen. Immediate life and safety concerns need to be met in cases of emergency as liquid fuel fires are dangerous. AFFF has been and still is, considered to be the most effective way to reduce this danger. Historically, AFFF contained PFAS including PFOS and PFOA however as information emerged that PFOS and PFOA could have environmental impacts, Defence switched to using a more environmentally safer product. The historical use of AFFF across the Defence estate has resulted in PFAS contamination, with preliminary investigations at certain Defence sites showing that surrounding off-site areas have also been impacted. Defence has undertaken a range of actions to better understand the potential impacts of historical AFFF use. This has included: conducting an internal review to establish the practices during which AFFF had been used on the Defence estate; commissioning trials of alternative AFFF products; the acquisition of a more environmentally safer product; changes to management and use of AFFF; and finally, incorporating PFOS/PFOA into routine environmental monitoring following implementation of effective laboratory capability to analyse these chemicals.

As well as firefighting foams, PFAS have had many uses in common household and industrial applications. These include stain resistant applications for furniture and carpets, fast food or packaged food containers, make up, personal care products and cleaning products. Most people in developed countries are likely to have levels of PFOS, PFHxS and PFOA in their blood due to widespread use. There is currently no consistent evidence that exposure to PFAS causes adverse human health effects. Defence became aware that PFAS was an emerging persistent organic pollutant in 2003 and released policy in 2004 to cease the use of AFFF containing PFAS for training purposes, and implemented a number of activities, such as: commencing the phase out of legacy AFFF product, changing the operational AFFF product used by Defence to a more environmentally safe product that does not contain PFOS/PFOA as active ingredients; and changing the way that Defence uses AFFF to ensure that the risk of releasing AFFF into the environment is minimized.

In 2010 Defence commenced detailed investigations into contamination associated with PFAS. In 2016 the Australian Government committed $55 million from the existing Defence budget to manage, contain and remediate PFAS on, and in the vicinity of, Defence properties. This saw the establishment of a Branch dedicated to the National Investigation and Management of PFAS. The PFAS Investigation and Management program is part of a broader Whole-of-Government approach. The policy environment relating to PFAS is complex and dynamic. At times, issues need to be coordinated across a number of jurisdictions and Defence continues to work with other Commonwealth and/or State/Territory Governments, along with local authorities. In order to oversee the Whole-of-Government response to address PFAS contamination at Commonwealth-owned sites and the impact on affected communities, the Australian Government has established a PFAS Taskforce within the Department of Prime Minister and Cabinet. Defence will continue to monitor the Australian and international industry to ensure it remains up to date on PFAS management and remediation technologies. Defence has undertaken a number of trials over the past 12 months and continues to progress those which have demonstrated potential for full scale implementation.

Understanding emerging pollutants in a connected system

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This research was initiated in response to the establishment of an Independent Expert Panel at the Williamtown RAAF base following the acknowledgement that PFAS chemicals were recorded across the air force base as well as at off-base locations. The research focused on developing a Conceptual Site Model with limited understanding of the pollutants distribution but with the aim of ensuring that the investigation area would encompass all of the potentially impacted community and associated risks. The establishment of the Conceptual Site Model was hampered by complex surface and groundwater interactions across the region.

A detailed knowledge review was undertaken to examine the migration potential of PFAS contaminants across the Williamtown and Salt Ash region. This was supported by local understanding of the aquifer properties and selected field investigations to highlight the role of surface and groundwater interactions. This method resulted in the establishment of detailed investigation area risk maps.

A range of historic data was available to integrate with international reports on PFAS chemical properties to estimate transport rates and risk factors. The resultant risk maps are currently in the process of being validated by extensive field work campaigns.

The development of an independent expert group with a broad understanding of various hydro-geochemical processes has led to the establishment of an investigation area risk map and Conceptual Site Model for the Williamtown and Salt Ash area. This has guided extensive on-ground investigations and appears well supported by preliminary field data. The unique influence of gaining and losing flood mitigation drains has been critical in understanding risk across the large area. Future locations with emergent pollutants may benefit from the established approach undertaken at this site.

Simulation of PFAS transport in coastal sands aquifers at Williamtown, NSW

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Aqueous Film Forming Foams (AFFF) containing per- and poly-fluorinated alkyl substances (PFAS) have been used historically for fire suppression and training at the Williamtown RAAF Base. PFAS chemicals are highly soluble and do not degrade, remaining in the environment for long periods.

RAAF Williamtown is situated on the highly permeable Tomago Sand Beds aquifer which adjoins the Stockton Sand Beds aquifer. Both aquifers are tapped by municipal and private bores and groundwater discharges to waterways used for recreational and commercial fishing.

As part of AECOM's Environmental Site Investigation, HydroSimulations built a regional-scale MODFLOW-SURFACT groundwater flow and transport model to verify conceptualisation of the aquifer system and predict the fate of PFAS originating from the base. The model was calibrated to replicate groundwater levels and match the conceptual distribution of PFAS based on recent groundwater samples, identifying key sources and uncertainties in PFAS distribution. MODPATH was used to identify the ultimate groundwater discharge locations and estimate the PFAS travel time in groundwater.

A key finding was that the simulation of PFAS transport through groundwater alone was not able to replicate the current PFAS concentration distribution observed downgradient of the Base. Subsequent simulations including PFAS movement through surface water drainage networks improved the modelled distribution against laboratory reported concentrations, indicating that overland flow plays a role in PFAS transport from the base. There has been concern for the potential contamination of the adjacent Stockton Sands aquifer, however model results indicate a hydraulic barrier exists at Tilligerry Creek, caused by convergent groundwater flow from north and south of the creek upwelling against estuarine clays and discharging at the creek. The upwelling effect will continue as long as groundwater levels in the Stockton Sands are maintained, and tidal gates at surface water drains allow discharge of surface water during low tides.

Assessing health risks for groundwater contaminated with per and polyfluoroalkyl substances (PFAS) - lessons learned

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In October 2015, the NSW Government formed an expert panel to provide ongoing advice on contamination from the use of fire-fighting foams at the RAAF Williamtown Base. Preliminary investigations had identified that perfluoroalkyl substances from these foams were moving off the Base into the local community. A detailed site investigation and human health risk assessment (HHRA) were commissioned to inform management of the contamination in the areas around the Base. The role of the expert panel was to review the Site Investigation and HHRA to provide independent advice to the NSW government and the local community. The expert panel focused on developing an understanding the issues related to these unusual chemicals which are extremely persistent, bioaccumulative and water soluble.

These fire-fighting foams were historically made of per and poly fluorinated alkyl substances (PFAS) including chemicals like perfluorooctane sulfonate (PFOS). The unusual characteristics of these chemicals has required detailed consideration of significantly more exposure pathways than is common for contaminated land and groundwater investigations. The chemicals have moving widely in the environment. The rural fringe nature of this region has required a range of exposure pathways be evaluated including uptake into a variety of edible foods (e.g. fish, cattle meat, milk, honey, fruit and vegetables etc.). Issues such as large temporal and spatial variability, limits of reporting, interactions between surface water and groundwater (daylighting), biaoccumulation and availability of toxicological information have made development of a robust human health risk assessment a larger exercise than is common for contaminated sites.

The panel and its working groups have been discussing the best ways to address such issues. Discussion of the issues related to understanding fate and transport of these chemicals and how people and the environment might be exposed will be presented.

Impact of PFAS chemicals on insitu microbial communities

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PFAS compounds have exceptional interfacial properties and, as such, they have been widely used since the 1960s for a range of applications, including in aqueous film forming foam (AFFF). These foams are designed to spread rapidly over hydrocarbon liquid surfaces – a desirable property for rapidly extinguishing fuel fires. However, this ability to spread rapidly and to be naturally resistant to degradation means that they have a very high environmental persistence and can be rapidly transported away from the original source. Their unique properties mean that each individual PFAS compound may impact insitu microbial communities to differing extents or may be degraded by insitu microbial communities to differing extents, if at all. Furthermore, PFAS may have unexpected impacts on specific microbial functional groups (aerobic heterotrophic bacteria, nitrate reducing bacteria, sulphate reducing bacteria, iron reducing bacteria, organohalide respiring bacteria, methanogenic archaea) and that these effects may prove diagnostic for PFAS impacted areas. Given their unique chemical structures PFAS are highly surface active further complicating an assessment of their environmental fate and impact to insitu microbial communities.

In this study we collected over 80 water samples from a PFAS impacted site in Canada. Using these samples we conducted an in depth assessment of the impact of PFAS to insitu microbial communities. Specifically, insitu microbial communities were characterized using next generation sequencing to obtain the entire microbiological profile of microbes in sampled aquifers. Data is analysed in conjunction with available site data (e.g., subsurface stratigraphy), monitoring well data (e.g., pH, ORP, inorganic species) and soil data (e.g., soil type, organic carbon). This data provides important insights into these interactions potentially opening up new avenues for the development of insitu bioremediation technologies.

Predicting the potential recovery of petroleum fuels from impacted aquifers

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Contamination of groundwater by petroleum fuels can harm human health and the environment. To help reduce the potential harmful impacts, the petroleum fuels are pumped from wells to the surface for disposal or reuse. This is commonly referred to as petroleum fuel recovery. The design of cost-effective petroleum fuel recovery activities depends on assessing the subsurface volume of the petroleum fuels and the rate at which they may migrate toward recovery wells. Besides assessing the total petroleum fuel volume in the subsurface, it is important to determine the distribution of petroleum fuel that is mobile and can migrate to wells in reasonable time periods. Additionally, assessing the immobile petroleum fuel volume entrapped by water and the petroleum fuel volume that is relatively immobile above the water table (i.e., residual) also is important for longevity and risk assessment. To help bring science to practice for petroleum fuel remediation, a model was developed to predict the free, residual, and entrapped petroleum fuel volumes in a vertical slice of the subsurface based on current petroleum fuel levels in wells and historic water table fluctuations. The model predicts elevation-dependent free, residual, and entrapped petroleum fuel saturations from the aqueous and petroleum fuel liquid pressures as reflected by the liquid levels in wells at hydrostatic conditions. Further, the model predicts elevation-dependent petroleum fuel relative permeabilities for the free petroleum fuel from the free, residual, and entrapped petroleum fuel saturations. Integration of the saturations and relative permeabilities over a vertical slice of the subsurface yields petroleum fuel volumes and transmissivity. Presented results show model predictions for several hypothetical scenarios. The model is potentially valuable for designing cost-effective petroleum fuel operations and understanding limitations of petroleum fuel recovery from the subsurface.

Microbial technologies for bioremediation and biogas production in subsurface environments

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Objectives: To characterise and harness the microbial ecology of subsurface environments and develop microbial technologies to enhance pollutant biodegradation and biogas production.

Extensive laboratory and field programs using contemporary anaerobic culturing and molecular microbial ecology techniques have been deployed. These include low flow sampling techniques, biostimulation, bioaugmentation, DNA extraction and sequencing, quantitative PCR, crystallography, genomics, microscopy, proteomics and analytical chemistry.

Extensive data sets describe key microorganisms in groundwater ecosystems for bioremediation and biogas production and community shifts in response to field manipulations. Field data sets spanning five years describes successes and failures of manipulating microbial communities to enhance pollutant (organochlorine) biodegradation at contaminated sites in NSW and Victoria and biogas production from coal seams at the Lithgow State Coal Mine, NSW.

We have discovered and described bacteria of commercial relevance to biotechnology application in groundwater environments. We have demonstrated effective bioremediation strategies for sustainable clean-up of organochlorine contaminated groundwater including biostimulation and bioaugmentation approaches. These microbial technologies have been commercialised through establishment of biotech start-up Novorem Pty Ltd. We have also demonstrated at field scale a commercially relevant enhancement of biogas production from coal seams with implications for the global coal bed methane industry.

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LNAPL dynamics in the subsurface: linking multi-phase and multi-component processes

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We aim here to highlight recent advances in linking multi-phase and multi-component processes in a modelling framework to track natural behaviours and remediation strategies for light non-aqueous phase liquid (LNAPL) groundwater contamination problems. LNAPLs, such as petroleum fuels, travel as a separate phase relative to water, air and soil, but also consist of thousands of compounds that partition and pose risks to each of these phases and domains. Our intention is to elucidate how multi-phase and multi-component modelling helps better understand the short and long term fate and risks of LNAPL contamination in subsurface media.

We determined and updated a modelling platform to incorporate key attributes and conceptual understanding. Short and long term simulations were undertaken of spill releases, along with comparison of model outputs against field data from active gasoline recovery options. A hysteretic feature was embedded.

The simulations show the criticality of linking multiphase and multicomponent features for LNAPLs. The platform also indicated the importance of hysteretic behaviour in determining LNAPL component partitioning. Release scenarios allow assessment of likely medium to long term distributions and compositional changes as LNAPL product migrates through the vadose zone to groundwater. The framework was able to mimic product recovery data from a field trial, validating its main features.

A multi-phase and multi-component modelling framework has been validated for assessment of LNAPL groundwater contamination risks. Short and longer term simulations have elucidated key understandings and the code has been validated for LNAPL product recovery scenarios. This is key to improved estimation of endpoints associated with different remediation techniques. It can also provide information about changing LNAPL composition and risks over time.

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2. *Sookhak Lari, K. and Johnston, C. D. and Davis, G. B. 2016. Gasoline Multiphase and Multicomponent Partitioning in the Vadose Zone: Dynamics and Risk Longevity. Vadose Zone Journal. Vol. 15. Issue 3. pp.-15.*

A numerical model incorporating nonlinear decay and sorption isotherms for simulating transport of contaminants emanating from instantaneous spill

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Groundwater plays a significant role worldwide in meeting water demand for domestic, agricultural and industrial uses. However, the availability of groundwater depends upon controlling exploitation and recharge of groundwater, climatic characteristics, aquifer system and the vulnerability of groundwater systems to polluting sources. In recent years, public attention has tremendously increased on groundwater contamination by hazardous industrial wastes, leachate from landfills, spills of oil and other toxic liquids, and agricultural chemicals. This necessitates improved contaminant transport models to understand the migration of contaminants characterized with nonlinear chemical kinetics. The main objective of this paper is to present a finite difference numerical model incorporating nonlinear constitutive elationships for the kinetics of decay and sorption isotherms for modeling transport of contaminants emanating from instantaneous spills in groundwater systems. The governing partial differential equation with specified initial and boundary conditions is solved using an implicit finite difference method and a computer code is developed for predicting contaminant transport behavior in groundwater system. The implicit method used here is unconditionally stable. In addition to the nonlinear decay, two nonlinear sorption isotherms described as Freundlich and Langmuir isotherms are considered in the study. Results obtained from numerical model are compared with that obtained from analytical models for the instantaneous spill. Results reveal that the predictions obtained from numerical model are found to be in excellent agreement with analytical solutions for a wide range of field conditions with regard to dispersion and source definition. Sensitivity analysis is also carried out for the quantitative description of the effect of nonlinearity in the sorption parameters and in turn on the time-space distribution of the contaminant. Such model would be helpful to water resources planners to compare alternative actions for the appropriate management of groundwater in terms of both quality and quantity.

DAY 2: Wednesday, 12 July 2017

INVESTIGATIONS

Using atmospheric and Earth tides as a natural tracer to hydraulically characterise groundwater systems

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Determining groundwater state of confinement and calculating aquifer compressible storage properties through geological sequences at high vertical resolution is difficult and time-consuming. We demonstrate that atmospheric and Earth tides can be used as a natural stressor to hydraulically characterise the subsurface over depth instead of aquifer testing and subsequent inversion of heads. Atmospheric and Earth tides induce oscillations in hydraulic heads that can be identified in the frequency domain. We analyse hydraulic heads measured in 9 piezometers screened at different vertical depths in a sequence of unconsolidated clays between 5-55 m in conjunction with atmospheric pressure and synthetic Earth tide records. The amplitude and phase response to atmospheric tides at 2 cpd frequency is accurately quantified by removing the influence of the Earth tide. This permits precise calculation of barometric efficiency (BE) values over depth. In conjunction with porosity estimates, this leads to vertically resolved values of specific storage and compressibility. We verify our results by using the hydraulic head response to rainfall loading at the surface. Further, when the system is confined there is a phase difference of 180° between atmospheric pressure and hydraulic head at 2 cpd, as is stipulated by the stress balance. We illustrate that this phase difference can be used to determine state of confinement over depth, and that this confinement changes over time depending on moisture storage within the overlying soil. Our new approach only requires a continuous record of water level and atmospheric pressure that is longer than ~16 days. The method simplifies hydraulic characterisation of multilayered groundwater systems and can therefore significantly improve conceptual models with less effort compared to traditional approaches.

Accumulative evidence highlighting that the Narrabri and Gunnedah formations are mythical

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The Narrabri and Gunnedah Formations, used to describe the valley-filling sedimentary sequences in portions of the Murray-Darling Basin, have never been formally defined. The hydrogeological evidence for naming these formations is reviewed in the context of modern sedimentary models. Are we using the right architectural model?

Hundreds of lithological logs from the Murrumbidgee, Namoi, and Gwydir catchments are used to examine the evolution of each alluvial aquifer. For each depth interval, the catchment-wide proportions of coarse (gravel, sand) and fine (silt, clay) sediments is determined. Sediment size distributions are then examined in the context of past climates and the conceptual inland fluvial model for distributive fluvial systems. Vertical hydraulic connectivity is examined using new hydrogeochemical data and nested groundwater hydrograph sets.

All systems show the core features of aggradational distributive fluvial systems. The valley-filling sequences for all catchments examined transitioned from high energy wet environments at depth, dominated by sand and gravel deposits, through to the modern-day low-energy silt and clay dominated depositional environments. Gravel and sand deposits dominate in the proximal portion of the catchment, and low energy silt and clay deposits dominate in the distal portions. The apparent existence of the Narrabri and Gunnedah Formations is due to changing sediment grain size proportion and channel fill sand connectivity. Both the facies and hydrograph analyses show that semi-confining layers are only local. Extensive hydrogeochemical data from the Namoi catchment show continuity of mixing between basement and surface inflows.

All catchments have many sedimentary architectural features consistent with the distributive fluvial system model, and reflect changing climate throughout the Neogene and Quaternary. Use of the Narrabri and Gunnedah Formation nomenclature, which has been incorporated into the National Aquifer Framework, is not supported by either the sedimentological, hydrograph or hydrogeochemical record.

GAB aquifer attribution process

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A methodology was required as part of the 2016 GAB Hydrogeology Study to determine water source for all bores screened in GAB aquifers across the Qld portion of the basin.

The development of a master data suite (MDS) which provides an 'aquifer attribute' for all active bores in the GAB was critical to the completion of the main study. There are ~96,000 bores (RNs) registered in the DNRM Groundwater Database within the GAB WRP area, and inside a 100km buffer outside the defined limits of the GAB. Aquifer attributes are available from a number of data sources for about half of these RNs: leaving a very large number of records without assignment.

A methodology was developed to populate these missing records.

Original data and results: A three stage approach was developed:

- Firstly, hierarchal assessment of existing datasets with highest confidence datasets taking priority.
- Secondly, for sites with no aquifer information, a spatial approach to assignment of aquifer was developed using a regional geological model and applying nearby water source information.
- Thirdly, a process was developed to assess and verify results.

The process determined the 'interval of groundwater intake' for each bore, and considered multi-aquifer verification, and unique data sets with potential to skew the interpretation (eg, Condamine alluvium). Application of a geological model for aquifer assignment for RNs for no information available was completed, and consideration of external data sources such as QPED was applied.

The process resulted in successful assignment of an aquifer attribute for close to 100,000 bores, using a hierarchical approach with increasing reliance on data with highest confidence. Spatial representation for 'data-light' RNs was then applied, and data verified prior to implementation to broader study requirements.

Borehole magnetic resonance logging tools and hydrogeological study in the Illawarra coal measures and Hawkesbury Sandstone of the Sydney Basin

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Borehole Magnetic Resonance (BMR) logging tools have been used routinely in the oil and gas industry for decades. Their ability to give lithological independent porosity and fluid property information makes them invaluable in assessing a reservoir's properties. BMR tools utilise a magnetic resonance technique to measure signals from hydrogen nuclei in water. This signal measures the total porosity as well as a distribution or relaxation rates (T2) of the nuclei within the pore spaces. From the measured T2 decay, a T2 distribution curve can be obtained that is related to pore size. This pore size can be separated into specific retention (bound fluid) and specific yield (free fluid). Empirical formulas can then be used to determine the hydraulic conductivity of the formation. Until recently BMR tools have been large and expensive, inhibiting their use in mineral mining and hydrological sectors. However, with the introduction of a slim hole BMR tool this data is now available to the wider market. This paper describes the principles of BMR and how to interpret the measured data. A basic hydrogeological characterisation model of some coal measures and overburden strata using BMR data is also presented with examples including aquifer/aquitard definition, hydraulic properties analysis (T, k, Sy). The hydraulic properties are compared with other testing techniques (packer testing and cores). Issues with functions of scale of measurements are addressed as are relevance to hydrogeological characterisation. Finally it is shown how the data can be used in conceptual and numerical modelling applications and how the inclusion of BMR data can improve data models and decrease the reliance on traditional aquifer testing methods.

Analysis of aquifer parameters in the Triassic Sydney Basin during the WestConnex hydrogeological investigations

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Recent hydrogeological investigations for the WestConnex motorway tunnelling programs beneath Sydney have improved our knowledge of the Triassic sediments of the southern Sydney Basin. Previously during resource investigations in western Sydney, triggered by the Millennium Drought, pump tests were conducted to assess the capacity of the Hawkesbury Sandstone and calculate aquifer parameters. During the WestConnex investigations the hydraulic conductivity of the Hawkesbury Sandstone and Ashfield Shale was measured *in-situ* by packer testing and in the laboratory using a permeameter. Porosity was also measured in the laboratory from core samples collected during the drilling programs. These hydraulic parameters have been used to assist in developing three-dimensional flow models to assess potential impacts of the drained WestConnex tunnels on the environment.

The Hawkesbury Sandstone and Ashfield Shale are dual porosity aquifers where groundwater is transmitted primarily though secondary structural features, rather than the primary porosity or interconnected void space between grains of the rock matrix. Packer test data analysis confirmed the hydraulic conductivity tends to decrease with depth due to increasing over burden pressures causing a decrease in sub-horizontal defect apertures with depth.

Sydney Basin sediments exhibit hydraulic conductivity anisotropy where the horizontal (K_h) hydraulic conductivity is typically greater than the vertical (K_v) due to well-developed horizontal bedding planes and laminations and less well developed vertical defects. In this investigation the K_h:K_v ratio has been estimated using real data, rather than relying on model calibration. Hydraulic conductivity measurements by *in-situ* (packer) and *ex-situ* (permeameter) tests has allowed the measurement of K_h and K_v respectively. Average packer test results (harmonic mean) for the Hawkesbury Sandstone (K_h = 0.011 m/day) and laboratory (K_v = 0.00028) confirms K_h is greater than K_v by approximately two orders of magnitude. Porosity results within the Hawkesbury Sandstone range from 11.3 to 19.2% and 5.6% for the Ashfield Shale.

Detecting groundwater flow using time series ground temperature measurements

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Groundwater movement in the shallow subsurface is an important variable in understanding the mass balance of water cycles in and around surface drainage areas. Moving water carries heat, which offers the possibility of detecting groundwater motion through time series measurements of ground temperature. Heat Needles are instruments for recording temperature in the top 1.1 m of the ground. Each Heat Needle contains highly sensitive (sub-millikelvin) and accurate (±3 mK) sensors at the ground surface and at 20 cm spacings from 0.1 m to 1.1 m depth. They passively record ground temperature at 15 minute intervals for up to 12 months on a single deployment.

Hot Dry Rocks and the Mexican Center for Geothermal Energy Innovation collaborated on a six-month trial deployment of six Heat Needles over the Simirao geothermal area in Central Mexico. While the ground temperature at five of the sites mimicked the changes in surface temperature over time, the temperature of the ground at the sixth site varied in a way that could not be explained by changes in surface temperature. The inferred cause of the observed temperature changes was groundwater movement in a shallow aquifer, which in turn was probably connected to a deeper and hotter reservoir.

Heat Needles are capable of detecting temperature changes far more subtle than those detected at Simirao. They represent an emerging tool for passive monitoring of groundwater movement.

Optimising of Greater Wellington Regional Council's groundwater monitoring networks using multi-correlational and Kriging based methods

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Groundwater resources of the Wellington region have a high environmental and cultural value in sustaining freshwater ecosystems and an important social and economic value in meeting water demands for domestic, municipal, agricultural and industrial purposes. Greater Wellington Regional Council (The Regional Council) is in the process of rationalising its groundwater level and quality networks in line with the above mentioned objective values.

This paper presents methods used by the Council aimed at optimising of groundwater level observation networks and the improvement in representativeness of the network. A multi-correlation analysis was undertaken to determine which wells to exclude (or commit lesser monitoring resources) from the current network because they add little or no beneficial information (redundant). A set of key (index) wells were identified and used to generate multi-regression equations to produce data in place of the redundant wells. Kriging based spatially balanced and density sampling algorithms were used to optimise the monitoring network and also identify where new well locations are required. The algorithms were used to find the set of wells whose removal leads to the smallest increases in the weighted sum of the:

- Mean standard error at all nodes in the Kriging grid where the piezometric surface is estimated (the Kriging grid was modified to include index wells identified from the multi-correlation method)
- Root-mean-squared error between the measured and estimated water level elevation at the removed sites
- Mean standard deviation of measurements across time at the removed sites.
- Mean measurement error of wells in the reduced network

A total of 24 monitoring wells were regarded as redundant and removed or downgraded in terms of monitoring frequency and equipment. However an additional 30 new wells were identified for installation. The final number of additional wells will be dictated by budget constraints and acceptable levels of uncertainties in the data.

Effects of intraborehole flow on purging and sampling long-screened or open wells

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Wells with long screens or open intervals are common and in some cases they are all that is available to investigate a groundwater system. However, such wells create a shortcut for vertical flow of water, driven by hydraulic head gradients. In a recharge area, water moves vertically down through the borehole and, over time, a plume of 'contaminating' water develops in zones with lower head. When the well is pumped, yield from zones with lower head will actually be water originating from zones with higher head. This process requires special consideration if groundwater samples are to be accurately interpreted.

This modelling study investigates mixtures of groundwater sampled from a long-screened well and the time needed to purge a plume of intraborehole flow as a function of preceding un-pumped duration. An unconfined regional groundwater system (dimensions of 3000 x 77 x 75 m) was simulated using MODFLOW, with recharge applied across the surface and discharge via a constant head boundary on one side. A long-screened well was represented using the Multi-Node Well Package (MNW2) and water was traced by simulating groundwater age in MT3DMS. Un-pumped and pumped stress periods were applied in uniform, layered and heterogeneous systems.

Results show that the volume of intraborehole flow can exceed the common practice of purging three casing volumes, even under small vertical head gradients and short times. Pumping a well draws water from all permeable zones in the screened interval so, unless packers are used to target specific intraborehole flow receiving zones, total pumped volume must greatly exceed the volume of intraborehole flow if it is to be fully removed. Complete purging may not be feasible, so identifying which depths a sample actually represents avoids misleading interpretations and provides representative data for at least some depths in a wells screened interval.

CT imaging and centrifugation to characterise dual porosity fluid flow and solute transport

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Advanced techniques including CT imaging and centrifugation can be combined to characterise flow and solute transport through dual porosity and low permeability media. Observing and quantifying physio-chemical influences on the migration and attenuation of contaminants through geological media with both matrix and preferential flow paths is difficult. We present examples of combining advanced techniques to characterise these processes within semi-consolidated soil samples and rock cores, including centrifugation (steady-state and interrupted flow methods) and CT imaging (static fluids and dynamic flow). For example, a new centrifugation method was developed to measure the effective porosity of a clayey-silt soil with preferential flow paths using a non-reactive flow tracer. Experimental and numerical modelling results (Crane et al. 2015) were consistent with field tests showing relatively high vertical permeability (Timms et al. 2016). 3D CT imaging of these soil samples at a resolution of 49 micron is providing statistics on pore throat networks and the associated topology (connectivity) between large pores. Other examples of advanced core characterisation include comparisons of sandstone permeability with variable solute chemistry, using either de-ionized or formation fluids. CT imaging of these rock cores reveals the micro-scale relationship between pore spaces, swelling and mobilisation of clay particles, and the mineral matrix. Differences in permeability between centrifugation tests and other core permeability methods highlight the importance of testing under in-situ conditions.

Future research could combine field investigations with these experimental techniques to improve estimates of effective porosity and long term physio-chemical interactions. Advanced centrifugation and CT techniques could apply to many porous media challenges including long term corrosion of concrete, in-situ leach extraction of commodities, long term integrity of porous water treatment membranes and the performance of barriers for carbon sequestration, mine tailings and nuclear waste disposal.

Groundwater dynamics in upland catchments of NSW

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The Key Sites research analyses how natural landscape processes, including land and water salinisation, are impacted by changes in landuse and climate.

Eight long term monitoring sites were established across NSW in a north-south transect from Quirindi in the north to Wagga Wagga in the south in 2002-2003. The sites are located in first and second order upland sub-catchments, with some undergoing landuse change from annual crop and pasture to perennial pastures and trees. A range of components of the hydrological cycle including climate and groundwater were measured.

Analysis of monthly groundwater data from 2003 on 71 boreholes across all sites using the auto-regressive model HARTT (Hydrograph Analysis: Rainfall and Time Trend) was conducted. There was a relationship between changes in groundwater level and rainfall that varied on a continuum from high (R^2 0.80 – 0.97; n=31) through to low (R^2 <0.50; n=6) across the sites.

The calculated lag time between rainfall and groundwater response varied from less than 1 month to 46 months, with most highly responsive (1 month or less (n= 62)). The underlying trend is for the groundwater to fall from 14 to 360 mm/year in 51 boreholes ($P<0.05$) and rise from 16 to 189 mm/year in 10 boreholes ($P<0.05$). The underlying trend in the other 10 boreholes was small ($P>0.05$).

Rainfall was the major driver in the rise and fall of groundwater across all sites. This challenges the paradigm that the removal of deep rooted vegetation is the primary driver responsible for the rise in groundwater and the consequential mobilisation of salts stored deep in the profile in upland catchments.

DAY 2: Wednesday, 12 July 2017

INVESTIGATIONS

Speeding the transition to conjunctive water management in Australia

Andrew Ross[1]

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Publish consent withheld

Understanding aquifer type transition in the Dumaresq River Alluvium, Queensland/NSW Border Rivers

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During the conceptualisation and calibration stages of a new groundwater model currently under development, issues related to transition from confined to unconfined state were identified in specific reaches of the study area. This gradual transition from confined to unconfined state has implications for the water balance, integrity of aquifers and groundwater quality.

Groundwater development in the Dumaresq River Alluvium commenced in 1950s; the current groundwater monitoring network consists of 102 bores on both sides of the border, of which, about 57 pipes are currently read. There are nine monitoring bores in QLD that are equipped with loggers and telemetered (https://water-monitoring.information.qld.gov.au/host.htm). This subset of the monitoring network provided vital information on groundwater dynamics for the study reaches.

Based on the available hydrogeological information, the study area was conceptualised into three layers: an upper aquifer directly underlying the ground surface, a semi-confining layer that becomes confining further downstream, and a lower aquifer, comprising the most productive zone. The Texas Beds and the sediments of the Great Artesian Basin represent the bedrock in the study area.

Between Mingoola and Roseneath, the groundwater system exhibits predominantly unconfined to semi-confined characteristics. From Roseneath to Texas, the system transitions to semi-confined/ confined characteristics, as the thickness and extent of the confining layer increases. However, downstream of Texas, the groundwater system becomes predominantly confined and there is a clear distinction in the hydraulic response between the upper and lower aquifer.

Groundwater extractions increased substantially during the millennium drought (2002-2010), when groundwater level falls below the confining unit in some reaches. After the millennium drought, groundwater levels have partially recovered. However, conversion from confined to unconfined state may have led to physico-chemical changes such as a change in groundwater quality.

Smart water science? Using the internet-of-things to collect hydrological data

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Like you, we wondered whether the new technology and infrastructure^ for the internet-of-things (IoT) represents an enormous opportunity to collect huge amounts of environmental data at low cost. Unsurprisingly, other people agreed and granted us funding to implement one of the first applied IoT hydrology projects in Australia. Eschewing talk of the technology #HypeCycle, our gen-y scientists were terribly enthusiastic. Our baby-boomer scientists to this day remain sceptical. One thing we all share is a curiosity about the uncertainties and limitations of the new network. We'd like to share our findings. We will present:

- an overview of the new Low Power Wide Area Network (LPWAN)^;
- a frank discussion of the accuracy, precision and reliability of IoT sensors;
- how the network communicates with our existing data management platforms; and
- the return on investment for our organisation.

Our proof-of-concept research project focusses on two applications: 1) real-time tracking of flood height and extent, and 2) transmission of daily water usage data from metered dams and bores to the regulating agency. Could this be a promising frontier for hydrological data collection? We'd like to build a conversation on the potential applications (and implications) of this technology.

The raw data sets and full report will soon be available on our website: https://www.waterconnect.sa.gov.au/Science-and-Research/Science.

^ By end-2017, the Low Power Wide Area Network (LPWAN) will cover 95% of Australia and NZ's population. In Europe, the network is mature and is being used to track/monitor/manage all sorts of things. Low-cost sensors (< $50) use radio signals to send/receive small payloads of data (8-12 bytes, < 140 msgs/day/device) to the cloud over distances up to 20 km. Subscription is around $2/year/device. The sensor tech in Australia is immature, however is moving quickly.

Characterising groundwater development opportunities and constraints in northern Australia as part of the Northern Australia Water Resource Assessment

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While at least 16 million hectares across northern Australia is potentially suitable for irrigated agriculture, access to water remains a key constraint on economic development in a region comprising 40 percent of Australia's land mass. In recognition of the challenges and opportunities facing many stakeholders, the Australian Government initiated the Northern Australia Water Resource Assessment. The Assessment comprises ten research disciplines (activities) to provide a comprehensive overview and integrated evaluation of the feasibility, economic viability and sustainability of water and agricultural development in key parts of the north. CSIRO researchers in the groundwater hydrology activity are partnering with communities, consultants and three State and Territory jurisdictions. We will provide comprehensive assessments of both opportunities for, and risks associated with, groundwater resource development in three priority regions: the Fitzroy River catchment (WA), the Mitchell River catchment (Qld) and four river catchments located around Darwin (NT).

Many aquifers in northern Australia underlay vast geographical areas where water resources are unallocated and existing groundwater infrastructure is sparse. The lack of infrastructure and hydrogeological information has limited past assessments of groundwater in northern Australia and hindered assessments of development potential. The groundwater hydrology activity is collecting a range of data through a combination of targeted field investigations and desktop analyses. New data collected from field investigations will include groundwater and surface water sampling, water level monitoring, drilling and geophysics. New and historical data will be used to refine conceptual models of key aquifer systems in each region. Analytical and numerical modelling will be used to estimate the scale of groundwater development opportunities in each region. Overall, the activity will provide all levels of government and stakeholders with appropriate understanding of the groundwater resource development opportunities and constraints in each region, whilst also providing tools and information to assist with future water planning.

Groundwater tinder – a guide for water dating techniques

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Understanding surface water-groundwater interaction, groundwater flow, recharge and discharge areas, and hydraulic connectivity can be greatly enhanced by the use of dating water. With so many options, how do you find your perfect isotope match? Sick and tired of trying different techniques and getting nowhere? You used to date young groundwater but now you realise it is old groundwater you are more interested in and don't know where to start? This desktop study presents a brief guide of groundwater dating techniques, so you can find the one (or ones) you've been looking for.

A literature review summarising the advantages and disadvantages of several groundwater dating isotope techniques are discussed. Sampling design considerations are discussed and presented with reference to eastern Australian groundwater assessments and conceptual model design.

Designing a dating isotope sampling program needs special consideration where your goals need to align with the ability and applicability of the technique. A compilation of up-to-date and emerging groundwater dating methodologies are summarised and merits compared, providing a one-stop guide for designing your next groundwater dating program. Commonly used isotopic dating techniques are assessed.

Isotopic dating of groundwater is a powerful tool used globally to enhance hydrogeological conceptual models, including identifying groundwater provenance and hydraulic connectivity. However, careful consideration is required when choosing the isotopic technique to provide appropriate results suited to meet the project objectives. This study summarises the salient factors for consideration when designing your isotope sampling program.

Groundwater investigations to support irrigated agriculture at La Grange, Western Australia

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The La Grange project was initiated by the WA government to stimulate the expansion of irrigated agriculture in the West Kimberley. The La Grange groundwater area, south of Broome was targeted because of the potential for rapid expansion of the area irrigated. The Broome Sandstone is the dominant fresh groundwater resource in the 36,000 km^2 area, with an allocation limit of 50 GL/a. The objective of this study was to improve the understanding of the soils and groundwater at La Grange so that irrigated agriculture can profitably expand without impacting existing water users and wetlands or inducing seawater intrusion.

Field investigations included a soil survey, bore census, airborne electromagnetic (AEM) survey, drilling, test pumping and groundwater geochemical sampling. Groundwater head data was analysed to produce a contemporary watertable surface, which indicated that most coastal wetlands and larger inland wetlands are reliant on the Broome Sandstone. About 500 km^2 of productive soils overlie areas where groundwater is shallow enough to be pumped economically.

The AEM survey provided spatial data on the base of the aquifer and an estimation of the location of the saltwater interface. The AEM was also used to strategically locate bores to provide a regional monitoring network for changes in groundwater level and early warning of movement of the SWI, as well as spatially distributed hydrochemistry sampling points.

Isotope analyses indicate that recharge (11.6 to <16.5 mm/yr) only occurs after intense rainfall events in the wet season. Three hydrochemical methods produced similar estimates. Groundwater in the Broome Sandstone ranges from ‘modern’ at the watertable to older than 20,000 years at its base in coastal areas. Predictions made by a regional groundwater model indicate that using a preferred area map produced during this project to guide abstraction will be significant in minimising impacts on sensitive wetlands and the SWI.

Seasonal groundwater storage fluctuation in Sukhuma District of Southern Laos by field assessment and remote sensing

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Groundwater is the main source of domestic water supply in many developing regions. In Sukhuma District of Southern Laos, for example, groundwater pumping has been increasing in recent years due to population growth and increased climate variability. Within the context of limited data on groundwater resources and the essential need of such information for their sustainable management, this research aims at quantifying the seasonal changes in groundwater storage in Sukhuma District by combining sparse in-situ measurements with remote sensing data. Groundwater levels, rainfall and streamflow were measured in the field. Total water storage (TWS) data from the Gravity Recovery and Climate Experiment (GRACE) satellites, soil moisture, canopy water storage and other hydrological data derived from the Global Land Data Assimilation System (GLDAS) and rainfall data derived from the Tropical Rainfall Measurement Mission (TRMM) were downloaded for statistical analysis. The period of this study was from Jan 2015 to March 2016. The methodology was based mainly on the water balance equation and the regression method. The groundwater storage fluctuations were estimated from the changes in TWS by calculating the other components of the water balance equation from GLDAS and TRMM. The results were then used to validate the water balance from in-situ observation data in Sukhuma District using a regression method. This research provides a feasible and cost-effective approach to estimating seasonal groundwater storage fluctuations and assessing the data needed for planning sustainable groundwater resources development in regions with sparse field observation.

Managing groundwater for ecological response

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The River Murray is a major resource that provides water for industry, agriculture and domestic use. The River also supports environments that are culturally, socially and ecologically important. It is a managed river where constant negotiation and innovation is required to meet the needs of industry and environment. This management is complicated by the impact of the highly saline regional groundwater, which discharges to the River and floodplains.

Surface water has been managed to provide additional flows that support the floodplains and along the River. Historically, management of groundwater has focused on reducing saline groundwater inflow to the river. The South Australian Riverland Floodplains Integrated Infrastructure Program (SARFIIP) aims to take the next step and manage groundwater to support the environment. SARFIIP is a $155 million program funded through the Murray-Darling Basin Authority (MDBA) which aims to improve the watering and management of key River Murray floodplains in South Australia's Riverland.

This challenging project needs to not only understand how groundwater and ecology are linked, but also how useful information could be provided to managers and decision makers. A collaborative approach has been taken involving ecologists, hydrogeologists, groundwater modellers, hydrologists, GIS analysts and managers involved in the broader program. A methodology has been designed where separate components of the floodplain system, groundwater, surface water and ecology, are analysed individually to extract information important to the ecology of the floodplain. These separate parts are then merged in such a way that the combined influence is able to be examined.

By bringing together the separate components that impact ecological response, the relationships between them have become better understood. This improved understanding has led to the development of a practical methodology capable of assessing proposed management actions for their potential to have beneficial or harmful consequences for floodplain ecology.

Solute transport model of the Pike Floodplain, South Australia

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The Pike Floodplain groundwater model has been developed as part of the South Australian Riverland Floodplains Integrated Infrastructure Program (SARFIIP). SARFIIP is a $155 million program funded through the Murray-Darling Basin Authority (MDBA) which aims to improve the watering and management of key River Murray floodplains in South Australia's Riverland. By implementing managed inundation and groundwater manipulation of the Pike and Katarapko floodplains, the aim is to increase soil moisture availability to support native floodplain vegetation.

Historically, salinity investigations of the River Murray region have focused on the salt flux to the river, while neglecting the impact to the floodplain. The role of the Pike Floodplain model is to assess the salinity impact of works and measures on the floodplain. Building on the previously developed flow model of the Pike Floodplain, a solute transport model has been developed. The solute transport model is intended to be used to assess the ecological and environmental impacts and benefits of SARFIIP management options. Due to the scarcity of salinity data in the region, a quantitative calibration of the model was not practical and so a qualitative check of the model performance has been undertaken. Assessment of the model performance was undertaken using a number of criteria, including comparison to AEM data and ecological health data from the site.

Criteria have been developed which categorise conditions that are likely to be beneficial to, and similarly negatively impact, the health and recruitment of two tree types found on the Pike Floodplain. Python scripting has been used to determine the percentage of time the modelled water level and salinity meet the specified criteria over the benchmark period of 1975-2015. Comparison of these modelled results with on ground tree health surveys suggests that the shallow, low salinity areas in the model correspond to healthy vegetation on ground.

How conductivity structure controls fluid mixing in heterogeneous Darcy Flow

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4. Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, California, USA

Fluid flow in heterogeneous porous media is unique in that the physical structure of the host medium completely dictates the attendant flow properties, including fluid mixing. Whilst many models of solute transport and reaction assume well-mixed conditions within a solute plume, in reality these plumes typically exhibit incomplete mixing due to the strong fluid stretching dynamics within such heterogeneous flows. These heterogeneities have been observed to generate several fluid stretching regimes (sublinear, linear, superlinear) which directly impact the mixing and dispersion dynamics. Such incomplete mixing has a very significant impact on reactive transport, where the observed effective reaction rate is often much slower than that corresponding to well-mixed conditions. Hence models of incomplete mixing are required which capture the impacts of the heterogeneous medium.

We present an overview of recent developments on this topic, and show how fluid mixing can be predicted directly from the medium conductivity structure (e.g. conductivity variance, correlation structure) via the use of a continuous time random walk (CTRW) approach to solving the governing stochastic models. This approach provides *ab initio* predictions [1,2] of the different stretching regimes observed in Darcy flow from the conductivity structure [3] and provides significant insights into the mechanisms which control fluid stretching and mixing. In turn, these stretching rates provide the inputs to lamellar models of fluid mixing [4,5] which provide predictions of the evolving concentration PDF within a evolving plume.

These advances not only provide the ability to predict fluid mixing and dilution directly from the Darcy-scale medium properties, but generate deep insights into the physical mechanisms which govern fluid mixing and dilution in these systems. By using a first-principles approach to quantitatively link conductivity structure and fluid mixing it is possible to directly identify the medium properties which govern fluid mixing and dilution, and also develop uncertainty analysis for cases where these properties are not well-quantified.

1. *[1] Dentz M, Lester DR, Le Borgne T, de Barros FPJ. Coupled Continuous Time Random Walks for Fluid Stretching in Two-Dimensional Heterogeneous Media. Physical Review E 94, 061102 (2016)*
2. *[2] Dentz M, Le Borgne T, Lester D, de Barros FPJ. Scaling Forms of Particle Densities for Le´vy Walks and Strong Anomalous Diffusion, Physical Review E 92, 032128, (2015)*
3. *[3] Tyukhova A, Dentz M, Kinzelbach W, Willmann M. Mechanisms of Anomalous Dispersion in Flow Through Heterogeneous Porous Media, Physical Review Fluids 1, 074002 (2016).*
4. *[4] Le Borgne T, Dentz M, Villermaux E. Stretching, coalescence and mixing in porous media, Physical Review Letters 110, 204501 (2013)*
5. *[5] LeBorgne T, Dentz M, Villermaux E. The Lamellar Description of Mixing in Porous Media, Journal of Fluid Mechanics 770, 458–498 (2015)*

DAY 3: Thursday, 13 July 2017

PLENARY

Plenary Groundwater and the Law. *Mr Saul Holt QC, 8 Petrie Terrace Chambers*

Hydrogeology and the law

Saul Holt QC[1]

1. '8 Petrie Terrace' Chambers, Brisbane, QLD, Australia

Hydrogeological issues have sat at the heart of series of legal cases in Queensland deciding whether to approve coal mines. Many involved mining in the Galilee Basin with the most significant determining the impact of the Adani Coal Mine (one of the largest proposed coal mines in the world) on the protected Doongmabula Springs. More recently, a long running case about the proposed New Acland Coal Mine in the Darling Downs has focused on impacts to local groundwater users. Both of these cases have involved extensive evidence from hydrogeologists about the conceptualisation and numerical modeling used.

Saul Holt QC was the lead Barrister for the objectors in both cases. He will discuss the intersection between hydrogeology and the legal process focusing on how well (or not) the legal system copes with the complexity of the science and offer some tentative views on the questions and challenges for hydrogeologists that the two cases raise.

DAY 3: Thursday, 13 July 2017

INVESTIGATIONS

Keynote: Bioregional Assessments: using groundwater, surface water and ecological models to determine the impacts of coal resource development on water resources. *David Post, CSIRO.*

Lessons learned from modelling the changes in groundwater due to large coal mines and CSG in the Bioregional Assessments Programme. *Russell Crosbie, CSIRO.*

New methods for modelling the impacts of CSG development activities in the Surat Cumulative Management Area. *Daan Herckenrath, OGIA QLD.*

Permeability modelling in the Surat Basin using artificial neural networks. Gerhard Schoning, DNRM QLD.

Use of geophysical log signatures to define regionally consistent lithostratigraphic boundaries for the Surat and southern Bowen basins. Keith Phillipson, DNRM QLD.

Comparison of predictive uncertainty methods to quantify iron ore dewatering impacts. Vahid Shapoori, AGE.

Using analytical models as the platform for managing large scale mine dewatering operations. *Keith Brown, Rio Tinto.*

A water balance model for the prediction of groundwater levels adjacent to Fortescue Marsh. J*inquan Wu. FMGL.*

Does specific storage change in time and how? *Katarina David, UNSW.*

Modelling inter-aquifer leakage associated with compromised well integrity. *Rebecca Doble, CSIRO.*

Bioregional Assessments: using groundwater, surface water and ecological models to determine the impacts of coal resource development on water resources

David Post[1]
1. CSIRO, Canberra, ACT, Australia

The Australian Government Department of the Environment and Energy has commissioned an ambitious, multi-disciplinary programme of bioregional assessments to improve understanding of the potential impacts of coal seam gas and large coal mining activities on water resources and water-dependent assets across six bioregions in eastern and central Australia. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and large coal mining development on water resources.

The analysis of these potential impacts relies heavily on the outputs of quantitative numerical models of groundwater, surface water and ecological impacts. Exchange of information (and associated uncertainties) between these models is obviously necessary, but facilitating this exchange between models that run at different time steps and may have differing input/output stuctures is not a trivial task. Complicating this further is the task of coordinating groundwater modellers, surface water hydrologists and ecologists, all of which have disparate backgrounds and may use the same term to mean very different things.

This presentation will describe the overall methodology underpinning bioregional assessments as well as provide an overview of the modelling workflow, describe the issues that arose during its implementation, as well as how these issues were resolved. Results of the programme to date will be presented.

Further details of the programme as well as the reports published thus far can be found at http://www.bioregionalassessments.gov.au.

Lessons learned from modelling the changes in groundwater due to large coal mines and CSG in the Bioregional Assessments Programme

Russell Crosbie[1], Luk Peeters[1], Sreekanth Janardhanan[2], Tao Cui[2], Trevor Pickett[2], Andy Wilkins[3], Warrick Dawes[4], David Post[5]

1. CSIRO Land and Water, Glen Osmond, SA, Australia
2. CSIRO Land and Water, Dutton Park, QLD, Australia
3. CSIRO Energy, Pullenvale, QLD, Australia
4. CSIRO Land and Water, Floreat, WA, Australia
5. CSIRO Land and Water, Canberra, ACT, Australia

The Australian Government's Bioregional Assessment Programme provides transparent scientific information to better understand the potential impacts of coal seam gas and coal mining developments on water resources and water-dependent assets. This presentation is an overview of the groundwater modelling that was conducted in six subregions: Gloucester, Hunter, Namoi, Galilee, Clarence-Morton and Maranoa-Balonne-Condamine.

Although each model was developed using different code, they addressed the same research question in a similar way. Each model provides a probabilistic prediction of the changes in drawdown and surface water – groundwater interactions for two alternate futures, a baseline and additional coal resource development. All of these models have been designed to be numerically robust to enable a comprehensive sensitivity analysis to be conducted resulting in a comprehensive uncertainty analysis of the model predictions.

The sensitivity analysis revealed that the model parameters that the predictions are sensitive to are not always the same model parameters that the observations are sensitive to. This has major implications for our confidence in model predictions – a well calibrated model may not be constraining the predictive uncertainty. This has resulted in drawdown predictions where the 95th percentile can be several orders of magnitude greater than the 5th percentile.

Overall, the drawdown at the water table was greatest for open cut coal mines but they had the smallest extent, conversely coal seam gas developments had the least drawdown at the water table but over a greater area. The potential for cumulative impacts on drawdown of the water table exist where developments are close together. This suite of models is developed independent of the proponents and regulators of coal resource developments and so can provide unbiased information to all stakeholders. To demonstrate transparency of the modelling, all inputs, outputs and executables will be available from http://www.bioregionalassessments.gov.au.

New methods for modelling the impacts of CSG development activities in the Surat Cumulative Management Area

Daan Herckenrath[1], John Doherty[2], Mark Gallagher[1], Luca Traverso[1], Keith Phillipson[1]
1. Office of Groundwater Impact Assessment, Brisbane, QLD, Australia
2. Watermark Numerical Computing, Corinda, QLD, Australia

The Office of Groundwater Impact Assessment (OGIA) is responsible for preparing an Underground Water Impact Report (UWIR) for 'cumulative management areas' (CMA) i.e. areas where the impacts of water extraction for multiple resource development activities overlap. In 2011, the Surat CMA was declared and the first UWIR was published in 2012. As part of this UWIR a regional groundwater flow model was developed to predict the cumulative impacts of groundwater extraction by Coal Seam Gas (CSG) activities within the Surat CMA. Since this time OGIA has undertaken several studies to address a number of unique modelling challenges that apply to assessing the impact of coal seam gas extraction on regional groundwater systems. These studies culminated in a revised groundwater model that was used to re-predict impacts for the purposes of the 2016 Surat CMA UWIR. This presentation will highlight some of the adopted methodologies with potential for wider application to other CSG development areas, including: 1) the development of a revised version of the MODFLOW-USG groundwater flow modelling code to approximate dual-phase flow in coal seams; 2) simulation of CSG extraction using a "descending drain" methodology that recognizes the gas filled nature of CSG wells; and 3) initial parameterization of the regional model using stochastic lithology permeability models and "numerical permeameters". The presentation will conclude with the model predictions that are most relevant to OGIA's stakeholders and identify areas for further research.

Permeability modelling in the Surat Basin using artificial neural networks

Gerhard Schoning[1], Daan Herckenrath[1]
1. Department of Natural Resources and Mines, Brisbane, QLD, Australia

The Office of Groundwater Impact Assessment (OGIA) is responsible for assessing the cumulative impacts of groundwater extraction by large-scale Coal Seam Gas (CSG) activities in Surat Cumulative Management Area (CMA). For this area a regional groundwater flow model has been developed and is being periodically updated and revised to predict the cumulative impacts of groundwater extraction for CSG production purposes. Initial parameterisation of this model is undertaken using stochastic lithology permeability models and numerical permeameters which translate the available small-scale permeability and wireline log derived lithology data into stochastic distributions of regional-scale permeability. In order to refine and improve the existing probabilistic lithology permeability models, OGIA has developed a number of Artificial Neural Networks (ANN's), an increasingly popular technique for extracting information from large datasets.

Using wireline logs and permeability data for over 4,000 CSG wells OGIA has developed several ANN's to extract complex data structures and predict permeability for coal and non-coal lithologies for various stratigraphic units in the Surat Basin. OGIA has further evaluated both the neural network architecture and different regularisation settings to optimise the ANN's performance.

The optimised ANN's yielded better results than permeability estimates obtained with conventional petrophysical methods such as the K-Timur-method and porosity-permeability relationships and outperformed multivariate linear and polynomial regression. By using gamma ray, density, depth-of-burial and location as input features, the models could on average explain 70% of the variance in core and DST permeability datasets not used to train the model. The current ANN's have subsequently been used to generate high resolution permeability profiles at each well which will be used to parameterise OGIA's next generation local and regional groundwater flow models. These results suggest that ANN's are a powerful tool to predict permeability where large data sets of borehole permeability measurements and geophysical logs are available.

Use of geophysical log signatures to define regionally consistent lithostratigraphic boundaries for the Surat and southern Bowen basins

Linda Foster[1], Renate Sliwa[2], Keith Phillipson[1]
1. Department of Natural Resources and Mines, Brisbane, QLD, Australia
2. Integrated Geoscience Pty Ltd, Brisbane, QLD, Australia

As part of the reconceptualisation and redevelopment of a regional groundwater model for the assessment of cumulative impacts in the Surat Basin, a new regional geological model (the Geomodel) was constructed. The Geomodel was developed dominantly through primary stratigraphic interpretation of wireline logging of petroleum and gas wells and water bores.

At the core of the Geomodel are lithostratigraphic packages correlated from consistent and recognisable wireline log characteristics. The model includes the major stratigraphic units, from the basement underlying the Bowen and Surat basins through to the surface Cenozoic sediments. There has been a progressive evolution of the understanding of the formation and geology of the Surat and Bowen basins. Past stratigraphic interpretations have been undertaken over a long period of time by many entities, using multiple and often outdated stratigraphic schemas. While there is still debate about the exact location and extent of various units, the interpretation for the Geomodel focused on providing consistent lithostratigraphic packages for modelling and used (Green et al. 1997) as its main guide, with some deviation to ensure regional consistency in the lithostratigraphic units. Over 38,000 individual lithostratigraphic picks from wireline data from more than 4,800 P&G wells and water bores was correlated for 25 Surat Basin surfaces and six Bowen Basin surfaces.

In addition to providing a regionally consistent set of surfaces the method adopted is considered to be both objective and repeatable since it relies primarily on analyses of wireline log data. The final Geomodel and underlying stratigraphic picks have been used by OGIA to support a range of other activities including: i) maximising the value of groundwater level and quality data stored in the Queensland groundwater database, by attributing each bore to one or more stratigraphic database; and ii) independently assessing whether or not CSG production wells extend into other aquifers.

Comparison of predictive uncertainty methods to quantify iron ore dewatering impacts

Vahid Shapoori[1], Neil Manewell[1]
1. AGE (Australasian Groundwater and Environmental Consultants), Brisbane, QLD, Australia

Groundwater models are often overly simplistic representations of complex systems. Predictive parameter uncertainty of simple groundwater flow models can be quantified using an array of non-linear techniques. A comparison of formal Bayesian approaches including GLUE (Generalised Likelihood Uncertainty Estimation), Markov Chain Monte Carlo using DREAM (DiffeRential Evolution Adaptive Metropolis), and Null-Space Monte Carlo is made. A large scale numerical model was developed to simulate groundwater impacts from iron ore mining in Western Australia and was assessed using three predictive uncertainty techniques. Our results demonstrate that GLUE and DREAM produce broader groundwater impacts when compared to Null-Space Monte Carlo results. GLUE and DREAM analysis reveals multi-normal and non-normal parameter distributions using information from the observation dataset. The key is to improve the understanding of the methodology, and to analyse posterior parameter distributions to ensure worse case impacts are fully explored. This study provides a framework to quantify uncertainty using regional models when highly parameterised inversion is not possible.

Using analytical models as the platform for managing large scale mine dewatering operations

Keith Brown[1], Kate Bailue[1], Garth Cooper[1]
1. Rio Tinto Iron Ore, Perth, WA, Australia

A large proportion of Rio Tinto's Pilbara iron ore resources occur below the groundwater table. Mathematical groundwater modelling is, therefore, an important tool to support decision making and inform dewatering strategies. The orebody geometry of the Pilbara is such that management of mine dewatering can be undertaken on a pit by pit basis. Until now, however, models used to advise dewatering operations are deposit, or regional scale, multi-pit numerical models. These models invariably fail to meet the needs of the business in the operational space due to issues with the scale of conceptualisation, and in the complexity of the model design that results in lengthy run times. As a consequence, these types of models are unable to readily contribute to 'on the run' decision making processes.

A different approach to managing operational mine dewatering has been successfully rolled out across Rio Tinto's Pilbara iron ore operations. Large scale models have been replaced with small scale, simple analytical superposition model solutions that focus on individual pits. The approach recognises a 'fit for purpose' modelling strategy (Brown & Trott, 2014). Analytical superposition models provide an ideal platform to quickly address queries such as operational borefield management. Calibration standards are maintained and predictions have also proven to be just as reliable as more 'sophisticated' models. The new approach meets business imperatives, making groundwater more relevant to decision making in the mine dewatering space. Furthermore, critical conceptual assumptions of the hydrogeological system, such as aquifer properties or boundary conditions can be tested quickly and easily, to provide further insights into the uncertainties associated with a particular prediction.

A water balance model for the prediction of groundwater levels adjacent to Fortescue Marsh

Jinquan Wu[1], Tim Wilkinson[1], Jordin Barclay[1], Fuli Wang[1], Andrew Brooker[1], Paul Ricketts[1], Chris Oppenheim[1]

1. Fortescue Metals Group Limited (FMGL), East Perth, WA, Australia

Effective management of water resources is fundamental to the sustainability of Fortescue's operations, the environment and, most importantly, the communities within which the business operates. Adjacent to Fortescue's Chichester Hub operations, the Fortescue Marsh is a wetland of national significance and is considered to be a unique wetland form in Western Australia.

A water balance model has been developed for estimation of baseline groundwater levels (GWL) at monitoring bores on the northern fringe of the Fortescue Marsh. The water balance model uses historical weather data and temporal marsh surface water level (SWL). Marsh SWLs were either derived from satellite images or reconstructed from a flood area model using climate data (Rouillard, et al., 2014). The near marsh monitoring bores were installed to provide early warnings for water level changes near the marsh. Baseline GWLs at the monitoring bores are required for establishing trigger levels, which take account of climatic variability.

The model consists of four major modules:

1. A nonlinear depth-dependent module for estimating evapotranspiration loss
2. A linear module for estimating throughflow loss from the GWL in the monitoring bore
3. A static potential profile module for estimating the depth-dependent specific yields from soil texture class
4. A surface water module to estimate rises in GWL after regional recharge events from historical marsh SWLs.

There are a total of six parameters in the model: canopy type, soil texture class, critical GWL and coefficient for throughflow loss, offset above marsh SWL, and effective ground elevation. A brute-force optimisation program is developed to calibrate the first five parameters. The effective ground elevation is estimated from local topography. Predictions of groundwater levels at the 12 near marsh monitoring bores using the calibrated parameters correlate well with observed data.

1. *Rouillard, A., G. Skrzypek, S. Dogramaci, C. Turney, and P. F. Grierson, 2014. Impacts of a changing climate on a century of extreme flood regime of northwest Australia. Hydrol. Eart Syst. sci. Disscuss. 11: 11905-11943.*

Does specific storage S_s change in time and how?

Katarina David[1], Wendy Timms[1], Lee Barbour[2]
1. UNSW, Sydney, NSW, Australia
2. University of Saskatchevan, Saskatoon, Canada

Realistic values of specific storage (S_s) for groundwater systems are important to determine the spatial extent and timing of changes in groundwater heads when the groundwater system is mechanically stressed. However, numerical groundwater models of underground excavations typically assume a constant literature value of S_s. Our research used both in situ and laboratory obtained data. High frequency pore pressure data was evaluated to understand the variability and changes in S_s within sedimentary strata overlying a longwall coal mine. Pore pressure data from a vertical series of 6 vibrating wire piezometers (50 to ~278 m depth) recording at hourly intervals used barometric pressure loading for the period before and during mining. The site was located near the centre of a longwall panel that extracted coal at a depth of 300-400 m. The data was processed to calculate loading efficiency and S_s values by multi-method analyses of barometric and earth tide responses. In situ S_s results varied over one to two orders of magnitude and indicated that S_s was changing before and after extraction of underlying coal seams. Laboratory geomechanical tests were undertaken to compare with in situ findings. The vertical leakage of groundwater within the constrained zone (~10 to ~150 m depth) was found to be limited before mining, although some degree of vertical hydraulic connectivity was observed. Depressurization was evident in the fractured zone directly overlying the coal seam, and S_s changes at ~250 m depth indicated this confined aquifer may have became unconfined, while other zones remained confined. Our results demonstrate that high frequency pore pressure data can provide realistic time series S_s values. We have shown, for the first time, that variability of S_s can be significant, and that these changes can provide important insights into how shallow and deep groundwater systems respond to underground mining.

Modelling inter-aquifer leakage associated with compromised well integrity

Rebecca Doble[1], Chris Turnadge[1], Luk Peeters[1], Bailin Wu[2], Dirk Mallants[1]
1. CSIRO, Glen Osmond, SA, Australia
2. Energy, CSIRO, Clayton, VIC, Australia

Inter-aquifer leakage may be enhanced where coal exploration bores are inappropriately decommissioned or where the integrity of water bores and coal seam gas (CSG) wells has been compromised. Such features may provide leakage pathways for groundwater from a CSG production zone to overlying water bearing aquifers. This project was designed as a rapid assessment of the potential impacts of leaky CSG wells using conservative, single phase groundwater models and analytical solutions. Two leakage pathways were considered: a leaky well with flow through the partially degraded cement annulus between the well casing and the rock matrix and a fully open, inappropriately decommissioned exploration well or abandoned production well.

Analytical solutions were developed first to represent passive flow through a vertical conduit between two aquifers separated by an aquitard. Closed-form equations were used to explore the theoretical conditions that may lead to noticeable impacts on the groundwater balance. These conditions included conductivity of the well seepage pathway and the hydrogeological properties of the adjoining aquifers and aquitard.

A complementary numerical analysis was undertaken to confirm whether or not the theoretical hydraulic conditions resulting in inter-aquifer leakage are physically plausible. For this the MODFLOW Unstructured Grid model (MODFLOW-USG) with the Continuous Linear Network package was used with parameters representing conditions similar to the Gunnedah Basin, New South Wales. Groundwater quality impacts were also assessed using the advection-dispersion equation.

Single well numerical analyses that assumed a relatively large effective well conductivity suggest that it is unlikely that there would be a significant impact from partially degraded wells on the groundwater balance of a hydrogeological system similar to the Gunnedah Basin. It is plausible, however, that inappropriately decommissioned exploration or production bores will enhance inter-aquifer leakage. Future analysis will consider the potential cumulative effects of multiple leakage pathways on the groundwater system.

DAY 3: Thursday, 13 July 2017

MANAGEMENT

Keynote: GRIPP: promoting policies and practices for sustainable groundwater management. *Karen Villholth, IWMI (South Africa).*

Reimagining River Murray SIS groundwater pumping to achieve ecological outcomes in SARFIIP. *Craig Flavel, Australian Water Environments.*

Dynamics of lowersalinity lenses along the South Australian River Murray. *Juliette Woods, Flinders University.*

Drought decision support tool. *Louise Lennon, Jacobs.*

Can we manage groundwater? Statistical evaluation of the effectiveness of groundwater management for resource management and environmental protection during drought. *Emma White, University of Melbourne.*

Water resource effects of varying land use in southeastern Australia. *P. Evan Dresel, Department of Economic Development, Jobs, Transport and Resources VIC.*

Challenges in considering cumulative impacts: a Survey of Australian Groundwater Practitioners. *Rebecca Nelson, University Melbourne.*

Cape York Peninsula stratigraphic and monitoring bore drilling: new insights into the hydrogeology of the GAB in the Carpentaria Basin. *James Hansen Department of Science, Information Technology and Innovation, QLD.*

Monitoring of river/ estuary/aquifer system shows need for integrated management. *Rebecca Morris, Otago Regional Council.*

A comparison of over-pumping control methods in Heihe river basin and North China Plain. *Haijing Wang, Hydrosolutions.*

GRIPP: promoting policies and practices for sustainable groundwater management

Andrew Ross[1], Karen Villholth[2]
1. Australian National University, Canberra, ACT, Australia
2. International Water Management Institute, Pretoria, South Africa

Our planet's main source of freshwater is held underground in aquifers. Since 1950, the global use of groundwater has increased by 300%. This has brought huge social and economic benefits but has also led to serious concerns about groundwater resources' sustainability, water quality and ecosystems and habitats that depend on or supply these resources. Following a series of regional consultations, the Global Groundwater Governance Project, through a partnership of major global agencies, developed a shared vision and Global Framework for Action for groundwater to 2030. As a subscriber to the vision, the Groundwater Solutions Initiative for Policy and Practice (GRIPP) is a recent global initiative, which aims to bring multi-disciplinary expert knowledge and multilevel collaboration to achieve sustainable groundwater management for livelihoods, food security, climate resilience and economic growth. GRIPP aims to achieve its goal by supporting effective institutional partnerships, capacity development and proven practices working with country agencies at various scales. Local success stories in groundwater management are a source of inspiration, but major investment and commitment to action is required to achieve national and regional impact. GRIPP is an independent consortium of partners, from UN and CGIAR organizations, academia, NGOs, private sector, donors and professional associations that advocates the importance of investment in groundwater to high-level decision-makers. Further, GRIPP is developing, implementing, outscaling and sharing collaborative solutions and tools to promote sustainable groundwater management. GRIPP is coordinated by the International Water Management Institute and has eight core members as well as a growing number of associated partners. The National Centre for Groundwater Research and Training is a core member of GRIPP and, together with the Australian Water Partnership, is collaborating with GRIPP partners to develop and implement regionally and globally relevant solutions and projects. This presentation will introduce GRIPP, its ongoing activities and emergent achievements.

Reimagining River Murray SIS groundwater pumping to achieve ecological outcomes in SARFIIP

Andrew Telfer[1], Whendee Young[2], Rob Burnell[1], Alison Charles[1], Damian Newham[1], Craig Flavel[1]
1. Australian Water Environments, Eastwood, SA, Adelaide, Australia
2. Major Projects, Department of Environment, Water and Natural resources, Adelaide, SA, Australia

Salt Interception Schemes have been an integral part of the Murray Basin salinity management program since the 1980's, and have been so effective that during the Millenium Drought it is estimated that the operation of the Salt Interception Schemes avoided exceedances of the 800EC salinity target at Morgan that would have occurred for over 40% of the decade.

In addition to salinity benefits, it has also become clear that the operation of the Salt Interception Schemes has provided an substantial ecological benefit, particularly to large floodplain flora.

The SARFIIP program is being implemented as an integrated surface water and groundwater management strategy to improve the ecological condition of the Pike and Katarapko floodplains in South Australia. In this program, Australian Water Environments and the Department of Water and Natural Resources (Major Projects) are collaborating to deliver pragmatic and empirically based design options to manage the salinity impacts and the ecological risks associated with surface inundation of floodplains, and further the designs will enhance the ecological benefits of surface inundation. Groundwater pumping alone, without surface inundation, is anticipated to provide significant ecological benefits to existing vegetation.

The paper will provide an insight into the next generation of groundwater management infrastructure in the River Murray floodplains.

Dynamics of lower-salinity lenses along the South Australian River Murray

Tariq Laattoe[1], Adrian Werner[1], Juliette Woods[2]
1. School of the Environment, Flinders University, Bedford Park, SA, Australia
2. Flinders University and Department of Environment, Water and Natural Resources*, Bedford Park, SA, Australia*

Rivers in arid and semiarid regions may traverse saline aquifers, creating buoyant freshwater lenses in the adjoining riparian and floodplain zones. The River Murray in South Australia is an example, as the groundwater within the floodplain is naturally highly saline, but lenses of lower salinity exist adjacent to the river and creeks. These lenses provide an additional water source to vegetation such as river red gum and black box. Changes to the management of the River Murray and its floodplain can alter the extent and stability of the lenses, potentially impacting the health of the floodplain ecosystem. A study is investigating lens dynamics through hydrogeochemistry, laboratory studies, and modelling; this presentation discusses the modelling results so far.

A series of analytical solutions were developed to describe the interface between fresh and saline waters within the floodplain, under static conditions with and without dispersion. The analysis was compared with laboratory results from sand tanks. A numerical model simulating variable-density groundwater flow and transport was developed to explore a wider range of conditions than is possible with analytical methods.

The analytical solutions and sand tank experiments demonstrate that it is possibly for a low-salinity lens to form even when the river is under gaining conditions. Deeper aquifers, more transmissive riverbeds, and larger freshwater-saltwater density differences produce more extensive lenses. The numerical model illustrates the importance of transient effects such as changing river levels, floodplain inundation, and evapotranspiration. The analytical solutions provide a screening method for the occurrence and long-term stability of low-salinity lenses while the numerical modelling is being used to assess the potential impacts of floodplain management in South Australia.

Drought decision support tool

Louise Lennon[1], Vincent Pueche[1], Simon Treadwell[1], Sarah Gaskill[2]
1. Jacobs, Melbourne, VIC, Australia
2. Melbourne Water, Melbourne, VIC, Australia

Melbourne Water, as waterway manager, has identified important drought refuges and Groundwater Water Dependent Ecosystems (GDEs) that require active management during dry periods to maintain important values like native fish and platypus populations. To facilitate management of individual drought refuges and implementation of actions outlined in Environmental Water Action Plans (EWAPs) for each refuge, Melbourne Water commissioned the development of a Decision Support Tool (DST). The DST has been designed to assist environmental flow planners and decision makers to quickly review the current status of priority drought refuges and GDEs. The tool places relevant information at manager's fingertips to facilitate timely decisions around implementation of actions required to enhance or protect each drought refuge.

The tool makes use of available data (e.g. groundwater and stream level data, water quality data, and climate data and forecasts) to provide up-to-date information on the status of drought refuges, trends in condition and forecasting of trends. It incorporates a focus on trigger levels identified in EWAPs so that decisions can be made on management actions at local and regional scales.

The tool incorporates a simple regional traffic light assessment of seasonal trends in rainfall, stream flow and groundwater levels across Melbourne's catchments. It provides up-to-date information on the status of priority drought refuges based on local monitoring data and compares the current status to trigger levels for stream flow and groundwater levels. The tool also provides statistical analysis of rainfall, stream flow and groundwater and predicts trends in stream flow and groundwater levels assuming a "no rainfall" scenario.

This presentation will provide an overview of the tool, demonstrate the key features and discuss how the tool can be updated to incorporate additional data.

Can we manage groundwater? Statistical evaluation of the effectiveness of groundwater management for resource management and environmental protection during drought

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Regulation of groundwater through the use of management plans is becoming increasingly prevalent as global groundwater levels decline. But seldom are plans systematically and quantitatively assessed for effectiveness. Instead, the state of an aquifer is commonly considered a proxy for plan effectiveness despite being a combination of many drivers.

Groundwater management under uncertainty is challenging, often provisional and experimental, and for this research, was structured as a systems control problem. This enabled development of an assessment rubric to determine whether groundwater management plans have the required features that allow plan effectiveness to be quantitatively tested.

The rubric was applied to 15 Australian groundwater management plans and only 47% were found to be testable [*White et al.*, 2016]. However, testability does not indicate plan effectiveness and testable plans do not necessarily achieve planned objectives. To numerically quantify the effectiveness of groundwater management, the impact of extraction restrictions was probabilistically assessed by simulating management of a simple unconfined groundwater system using MODFLOW [*McDonald*, 1984] and Flopy[*Bakker et al.*, 2016]. Water managers were privy only to head levels in a varying number of grid cells assigned as monitoring wells, and used that limited information to make allocation decisions at each time step. Extraction rates for each simulated management period were determined based upon the observed heads from the previous management period and adjusted depending upon triggers outlined in the management plan. The effectiveness of water restrictions as a management technique for the purpose of maintaining supply reliability under various decision making frequencies, aquifer response times and climate scenarios was explored.

It is crucial that groundwater management plans be effective, and in order to determine their effectiveness, we need to start testing them.

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Water resource effects of varying land use in south-eastern Australia

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Changes in vegetation cover have the potential to impact groundwater and surface water resources through changes to evapotranspiration. Information on this relationship is required to develop policies for controlling land use change to mitigate possible reductions in water resource availability due to water balance change.

We monitored precipitation, flow, and groundwater over 6 years in seven small upland catchments of south-west Victoria dominated by pasture or blue gum plantations. Rainfall was highly variable (394-978 mm/yr) and annual streamflow made up < 1% to 21% of the rainfall.

Plantation flow approaches or exceeds pasture flow during wetter years in two geologic settings investigated. Low flow in one of the plantations is believed to be due to effects of underlying limestone karst.

There is a strong correlation between winter flow in both plantation and pasture catchments for similar geologic setting. Rain events in other seasons typically produce a greater response in plantations than would be predicted from the winter relationships between land uses. This suggests that summer flows are dominated by overland flow. Thus, the plantations do not have a major streamflow effect in summer.

Groundwater levels declined in the plantations but remained stable in the pasture catchments, although still below the 1990s Millennium Drought levels. Unplanted areas along plantation stream drainages increased recharge, offsetting recharge decline under the trees.

Evapotranspiration ranged between 90-97% of rain in pasture catchments and 100-110% of rain in plantation catchments, indicating trees are transpiring groundwater. Groundwater depths in the plantations are deeper than levels previously considered accessible by tree roots.

The minimal effect on streamflow within the catchments suggests that tree plantations in this setting do not have as significant an effect on water resources as previously suggested. However, the reduced recharge is an important consideration in the recharge areas of significant aquifers.

Challenges in considering cumulative impacts: a survey of Australian groundwater practitioners

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Considering and managing the cumulative impacts of groundwater withdrawals can help avoid unanticipated adverse impacts related to assessing and managing individual activities in isolation. Yet Australian laws and policies dealing with considering and managing cumulative impacts provide little guidance on implementation, and little research exists documenting how implementation occurs in practice, and the challenges experienced. Understanding these challenges will ultimately help improve the effectiveness of these laws. An exploratory survey of groundwater practitioners in all Australian States and Territories—the first of its kind—was undertaken to understand the challenges experienced by practitioners in considering cumulative impacts. Survey respondents were drawn from attendees and registrants for the 2016 Distinguished Lecture series of the National Centre for Groundwater Research and Training and the International Association of Hydrogeologists (Australia). The survey included a combination of pre-coded response options and open questions. Respondents were asked to identify the importance of cumulative impacts, challenges in considering them, the importance of these challenges, and potential solutions. Results were collected electronically and on paper forms. The study uses content analysis to code key themes relating to challenges and solutions, and contrasts these themes with those identified in similar surveys undertaken overseas, and with challenges identified in the relevant scientific literature (typically case studies relating to specific geographic locations or projects, rather than individual laws or policies). Emergent themes relate to information availability (particularly in relation to baseline conditions) and modelling challenges, perceived constraints relating to regulation and regulatory institutions, allocation of responsibility between proponents, and social/political factors. The survey results can help guide regulators (eg groundwater licensing agencies and environmental and resources planning agencies), development proponents, and communities (including groundwater users and others) in relation to areas that would benefit from further policy development or clarification, resourcing, and attention during regulatory processes.

Cape York Peninsula stratigraphic and monitoring bore drilling: new insights into the hydrogeology of the GAB in the Carpentaria Basin

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The Queensland Coordinator-General in considering the environmental impact assessment reports for expanding bauxite mining on Cape York Peninsula concluded that expansion could proceed subject to a number of conditions and recommendations. This included recommendation 6 that directed the Department of Natural Resources and Mines (DNRM) undertake work to determine and report on the sustainable capacity of the Great Artesian Basin (GAB) in the Cape York region to inform on any future development in the region.

To deliver this report DNRM requested that the Department of Science, Information Technology and Innovation (DSITI) undertake an assessment of the availability of groundwater resources and the potential impacts of proposed increased groundwater extraction from the GAB.

Following an assessment of all available hydrogeological data across Cape York Peninsula, several key knowledge gaps were identified. To address these knowledge gaps a drilling program was designed to better define the stratigraphy and hydrogeology of the GAB, and to expand the monitoring bore network across Cape York Peninsula.

During the Cape York Peninsula drilling program, four test holes were drilled at three sites. Three monitoring bores were constructed and one test hole was decommissioned. Data collected included rock chip and groundwater samples, field water quality and yield data, and wireline logs. Interpretation of this data to better define the stratigraphy of the region allowed for the development of more refined hydrogeological conceptual and groundwater flow models.

The Cape York Peninsula drilling program produced the key project outcomes of improving the monitoring bore network across Cape York Peninsula and also meeting set objectives and targets. The drilling program closed knowledge gaps and provided data for improved assessment and modelling of groundwater systems in the region.

Monitoring of river/estuary/aquifer system shows need for integrated management

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The Kakanui River and estuary in the Northern Otago Province in southern New Zealand has long been a popular recreational area for both residents and tourists. However, long-term surface water quality monitoring has shown an increase in nutrients in both the river and estuary which has caused growth of macro-algae and reduced recreational use. Otago Regional Council has set a nitrogen target for the Kakanui River of 0.075 mg/L. It has also set a nitrogen leaching rate of 20 kgN/ha/yr over the adjacent Kakanui-Kauru Alluvium aquifer, which is a thin gravel aquifer highly connected to the Kakanui River. In a bid to understand the groundwater-surface water interaction with respect to nitrate losses and effects on the Kakanui River, a monitoring program is being carried out. Fifteen monitoring bores and 14 surface water quality and/or flow sites have been monitored on a fortnightly / monthly basis from March 2014 to March 2017. An Estuary Hydrodynamic Model was completed to determine an appropriate instream nitrogen target. The program is on-going, but results to date verified the 0.075 mg/L nitrogen concentration was appropriate to stop prolific algae growth. Groundwater modelling will be carried out in 2017/18 to verify if the nitrogen leaching rate (20 kgN/ha/y) is appropriate to deliver nitrogen target of 0.075 mg/L in the Kakanui River. Preliminary results show that in a dynamic system it is not possible to manage different water sources on their own (estuary, river or aquifer). An integrated approach is required to solve the water quality issues. Depending upon the modelling results there may be implications for land use management to meet community values. Strategic planning between science and policy will be required to provide the best outcome for both the community and the environment.

A comparison of over-pumping control methods in Heihe river basin and North China Plain

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The aim of an ongoing Swiss Development and Cooperation project in China is to develop strategies how to monitor and control over-pumping in arid Heihe river basin and semi-arid North China Plain.

A real-time monitoring and control system has been designed to control groundwater overpumping in two pilot regions. The real-time data collection includes groundwater pumping rates, groundwater level observations, cropping areas from remote sensing and volumes of surface water imported. All data are collected monthly in real-time and fed to a groundwater model to provide decision support for where and how to enforce water right.

The two regions represent different features: the wells in Heihe cover much larger irrigation areas (over 200 mu per well) with an annual water right of 800 m^3/mu, while a typical well in in NCP covers only 30-50 mu with an annual water right of 150 m^3/mu. The real-time pumping monitoring and control through smart meters works well in Heihe. Water rights are loaded on IC cards through which pumps are operated. The system is installed and maintained through a private-public-partnership model in Luotuocheng irrigation district. It is in the service company's direct interest to maintain the system for water fee collection.

Pumping monitoring in North China Plain showed a challenge due to the huge number of irrigation wells which are not suitable for installing smart meters. Metering pumping of every single well in in Hebei province (3.9 million wells) is not feasible. Yet, electricity consumption of every single well is monitored for electricity fee collection. On this basis, pumping volume can be monitored through electricity consumption metering, provided the conversion ratio is determined by pumping tests.

High capacity wells can be monitored and controlled through smart meters. The large amount of small wells on the other hand can be monitored and controlled through electricity consumption.

DAY 3: Thursday, 13 July 2017

SOCIAL MANAGEMENT & POLICY

Keynote: Design, integration and implementation of a regional groundwater monitoring network in the Surat Basin: key challenges and opportunities. *Ben Cairns, OGIA.*

Making groundwater impacts from the CSG industry more transparent in Queensland. *Ross Carruthers, Department of Natural Resources and Mines QLD.*

Addressing local concerns using regional context. *Sean Cassidy, EMM Consulting.*

Global food-water nexus requires regional humanitarian groundwater innovations. *Okke Batelaan, Flinders University.*

A cultural and hydrogeological assessment of Hookina Springs. *Lauren Houthuysen, Department of Environment, Water and Natural Resources SA.*

The benefit of early planning and stakeholder engagement in groundwater monitoring. *Carly Waterhouse, Klohn Crippen Berger.*

Mekong Delta's groundwater resources: perception, practices and coping strategies of smallholder farmers in Khmer village. *Van Kien Nguyen, American Geophysical Union / Australian National University.*

Managing artesian concerns near managed aquifer recharge operations in Adelaide, South Australia. *Craig Flavel, Australian Water Environments.*

Fusing modelling and engagement practices to support assessment of conjunctive water use opportunities. *Baihua Fu, Australian National University.*

Modelling the impacts of plantation forestry on groundwater: science and policy. *Cameron Wood, Department of Environment, Water and Natural Resources SA.*

Design, integration and implementation of a regional groundwater monitoring network in the Surat Basin – key challenges and opportunities

Steve Flook[1], Ben Cairns[1], Keith Phillipson[1], Sanjeev Pandey[1]
1. Office of Groundwater Impact Assessment, City East, Brisbane, QLD, Australia

The Surat and southern Bowen basins are complex multilayered aquifer systems extensively developed for private water use since the 1800's and more recently for petroleum and gas (P&G). The Office of Groundwater Impact Assessment (OGIA) is responsible for the design of a regional monitoring network to support research, system conceptualisation and regional groundwater modelling.

OGIA is an independent entity established under the Water Act 2000. Since 2011, OGIA has been responsible for the assessment of cumulative groundwater impacts from P&G activities in the Surat Cumulative Management Area (CMA) – an area of overlapping impacts. Every three years, OGIA prepares an Underground Water Impact Report (UWIR) which establishes a groundwater monitoring network and identifies responsible tenure holders for the implementation. There are currently more than 500 monitoring points in the network which has required significant financial investment and support from tenure holders.

The objectives governing the design of the monitoring network are to improve understanding of system response within production areas; identify pressure changes near specific areas of interest; understanding of background trends in pressure; and to provide sufficient data for model calibration.

There are a range of challenges in the design and implementation of a network extending over an area of 100,000 km^2 encompassing more than 20 hydrostratigraphic units, varying hydrochemical conditions, multiple fluid phases and with monitoring depths up to 1,500 m below ground. As a result, construction and instrumentation differ significantly and necessitate careful data treatment and density correction requirements. There is also a need to balance the opportunity of existing infrastructure and maintaining adequacy of the regional network.

This paper presents the unique challenges, opportunities and learnings in establishing such an extensive and complex network. The presentation will focus on the approach to network design and how key challenges have been collaboratively overcome by industry and OGIA.

Making groundwater impacts from the CSG industry more transparent in Queensland

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The Coal Seam Gas Compliance Unit was established within Queensland's Department of Natural Resources and Mines in 2012. The unit includes a dedicated Groundwater Investigation and Assessment Team (GIAT) consisting of 11 staff with groundwater hydrogeology, drilling, geochemical, GIS and community engagement skills.

Major activities undertaken by GIAT over the past 5 years include: -

- Undertaking over 100 investigations into potentially impaired bores with 5 bores found likely to be impaired by CSG development.
- Implementation of an independent groundwater monitoring network including the CSG Net community based groundwater monitoring and CSG Online continuous monitoring programs across the CSG development footprint of the Surat Basin.
- Contracting research into gassy bores and microbial issues ultimately leading to amendments to policy settings around gassy bores and make good.
- Holding quarterly CSG Groundwater Issues Forums with CSG company lead hydrogeologists to share knowledge and experiences.

Benefits from GIAT activities include: -

- Landholder complaints in relation to potentially impaired bores have reduced markedly.
- Landholders are empowered to monitor their water bores, accepting that they have a shared responsibility for groundwater monitoring to protect their own interests.
- Government has a transparent, effective and efficient monitoring network.
- Monitoring results are used to independently cross-reference and verify groundwater monitoring results from CSG companies, providing enhanced community confidence in the industry.
- Effectively involving stakeholders helps build public confidence and provides a forum for engaging in robust discussions about complex groundwater issues.

GIAT has contributed significantly to landholders having an improved knowledge and understanding of groundwater systems and CSG impacts. This has been achieved by involving landholders in monitoring activities and promoting transparency of data availability by both government and industry. Similar programs are being actively considered for use in other sectors in Queensland where industries may impact on landholder access to groundwater resources.

Addressing local concerns using regional context

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Application of regional, basin-wide, information can be beneficial when investigating local areas with limited data. Construction and operation of an underground salt mine and waste storage facility at a depth of 850 m is proposed in the Northern Territory. A water assessment was completed to assess potential impacts to water resources and users from the construction and operation of the proposed project.

The existing local and regional hydrological and hydrogeological environment is assessed using a risk-based approach. The potential risks on water resources and on water users are identified and quantified on a local and regional scale, and mitigation and management measures are proposed.

Water investigations, spanning two years, have included the collection and analysis of extensive local and regional data. A conceptual model based has been derived based on the site specific local data incorporating regional understanding of the hydrogeology of the Amadeus Basin and surface water systems.

Overall there are few potential water related impacts due to:

- depth to groundwater and localised magnitude and extent of groundwater-related impacts;
- limited number of landholder bores in proximity of the project; and
- absence of GDE's.

In remote areas with spatially limited baseline data, application of a regional, basin-scale conceptual understanding can be valuable for identifying potential localised impacts.

Global food-water nexus requires regional humanitarian groundwater innovations

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1. National Centre for Groundwater Research and Training, Flinders University, Adelaide, SA, Australia

The global community agreed on the 2030 Agenda for Sustainable Development in a UN meeting in September 2015. As of 1 January 2016 and for the coming 15 years the focus is on 17 Sustainable Development Goals (SDGs), with which we aim to eradicate poverty, inequalities and address climate change. Goal 6 is specifically about water; 'Ensure access to water and sanitation for all'. Pressing global concerns with respect to water exist for the 1.8 billion people whose drinking water is contaminated: everyday 1,000 children die due to diarrhoeal diseases. Water scarcity affects 40% of global population, with 1.7 billion people dependent on groundwater basins where the water extraction is higher than the recharge, and 70% of all water extractions are used for irrigation, while 795 million people are deprived of sufficient food. In this contribution, we review pressures on the global water-food nexus and will argue that in order to make progress on the SDGs we need to focus on innovations in regional water management, especially in remote and under-developed areas. We advocate for and follow the SDG, which involves using a targeted research approach on implementing integrated water resources management at all levels of government, non-government and community organisations. These goals support and strengthen the participation of local communities in improving water management, and extend the call to expand international cooperation and capacity-building of developing countries in water-related issues. We will exemplify this by experiences from two research case studies, 'Cross-cultural management of freshwater on the resource-constrained island of Milingimbi, NT' and 'Integrated water, soil and nutrient management for sustainable farming systems in South Central Coastal Vietnam'. These case studies show that research has an important role to play in science-based innovation of water resources management and has been well supported and taken up by the local communities.

A cultural and hydrogeological assessment of Hookina Springs

Lauren Houthuysen[1], Steve Barnett[1]
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Hookina Creek has been identified as an important cultural, archaeological, biological and hydrological site, and is the only registered storyline in South Australia under the *Aboriginal Heritage Act 1988*. Hookina Spring (Pungka Pudanha) is an important healing spring for the Adnyamathanha people and there is strong interest from the local community to maintain the spring against threats such as erosion, livestock grazing, water extraction, tourism, weeds and feral animals which could damage the ecological and cultural value of the site. Engagement with the Adnyamathanha people was undertaken at the outset of the project to learn of their experiences and understanding of the spring.

The objective was to provide an understanding of the nature of the spring and creek system by identifying the source of water flowing from the spring using groundwater age dating and hydrochemical analyses. The aims were to identify whether the spring is vulnerable to changes in land use at a local or regional scale and whether water management might effective in mitigating potential impacts.

Spring water and groundwater samples were collected. The age of the water suggests an older regional source for the spring rather than a recent local source, which suggests that local changes in land use would not have a great impact on spring flow.

The results of our study have helped the Adnyamathanha community gain a better understanding of the groundwater processes that likely govern Pungka Pudanha Spring hydrology and factors that need to be considered to effectively manage potential impacts. Furthermore, this project has helped DEWNR's scientists, policy officers and water planners better understand the relationship between Traditional Owners and culturally important sites, and is an example of how Aboriginal knowledge can enhance and improve our approach to natural resources management.

The benefit of early planning and stakeholder engagement in groundwater monitoring

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1. Eco Logical Australia, Brisbane, QLD, Australia

Groundwater monitoring programs are undertaken for a variety of reasons: in advance of a project to inform a baseline; throughout approval processes; and, ultimately, to demonstrate compliance. Investment in data collection can be challenging in the early stages of the project, where the viability of a project is uncertain. However, projects can quickly move forward in seeking formal approval in advance of the preferred level of data being available. Commonly, water data may be collected with scant understanding of the real purpose of the data gathering and with a focus on water quality, with minimal consideration of the importance of measuring and understanding the processes (hydraulic head and gradients) yielding the existing, and driving potential changes to, water quality. Whilst this approach can provide a large dataset, it will typically also provide a poor return on investment.

This paper explores a number of significant issues that may arise when appropriate planning of monitoring schemes is not undertaken. We discuss how significant cost savings may be achieved over the long term while collecting an appropriate level of data to characterise baselines, effectively measure impact on the water environment and satisfy stakeholder needs for reassurance and transparency.

Flexibility including some redundancy in monitoring schemes is critical. Groundwater monitoring plans should be flexible to change, whether driven by changes in project assemblage, location of infrastructure, or regulatory changes. Investment in planning of monitoring goals and requirements at the earliest stages of a project provides a better understanding of the nature of monitoring required, allowing the program to balance appropriately the complexity of the monitoring program against the data required. As such, the monitoring program achieves its ultimate aim of delivering data which allows the project to progress in an environmentally acceptable manner while also ensuring long-term cost savings in its implementation.

Mekong Delta's groundwater resources: perception, practices and coping strategies of smallholder farmers in Khmer village

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Urban and rural water supply development programs have been implemented recently for domestic and agro-industry water supply to serve 19 million of people. Domestic wells have been dug to exploit shallow lenses of freshwater beneath the dunes and beach ridges for over a hundred years. Many deep drilled wells were dug by farmers in coastal provinces for irrigation and shrimp farming. At the same time, reduced river discharge to the delta resulting from dam construction upstream, dikes and polder development in upper parts of the Mekong Delta have the potential to reduce affect ground water recharge substantially. External impacts from climate change and sea level rise will impact both groundwater quality and quantity.

This paper presented the research findings on perception, practices and coping strategies of smallholder farmers in Vinh Chau town of Soc Trang province. Some 30 farmers were interviewed using open ended questionnaires in 2015. The results indicated that perception of groundwater resources become more scared by most participants including women. However, they believed there are no other alternative water sources. Rainwater is enormous, but they perceived that quality is not good for drinking, so they shifted to use portable water which is withdrawal from groundwater. This puts a high pressure on groundwater resources. Almost every household have at least one well up to 160 meter depth. Some have up to three wells for domestic use, irrigation for red onions, and shrimp and fish farming.

The key coping behavior is by increasing depth of wells to withdraw more groundwater. Consequently, the ground water level has dropped over 10 meters in the last 20 years. This study suggests that governments and communities should approach to use rainwater for domestic use and irrigation, and approach alternative methods to reduce groundwater use in the long run.

Managing artesian concerns near managed aquifer recharge operations in Adelaide, South Australia

Craig Flavel[1]
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A lack of water security in Adelaide's drought prone western suburbs led to the creation of managed aquifer recharge (MAR) schemes in parks and sporting clubs. These have been increasingly successful in storing winter stormwater for use in the dryer months. During the wetter months, monitoring of groundwater levels optimises MAR Scheme operation.

The winter of 2016 was the wettest for fifteen years. This caused an increase in water available for groundwater recharge and a decrease in groundwater withdrawal, culminating in an increase in the pressure of the confined T1 aquifer. AGT monitored the groundwater levels as they became artesian. This was done using government monitoring well data combined with site data managed under MAR Risk Management and Monitoring Programs.

Groundwater levels in the T1 aquifer have not been this high for 25 years, and wells started to flow uncontrollably. As a result, aquifer recharge was forced to cease yet it took several months for water levels to drop. Wells were inspected to determine their condition and whether well integrity was the cause of uncontrollable flow.

To prepare for artesian conditions, wells near MAR schemes must be identified and appropriately licensed. To do this, MAR scheme models must consider cumulative impacts due to water use changes and climate changes to increase the success of responsible groundwater management practices in urban environments. Government policy aligning to assign responsibilities according to good groundwater management practices.

Fusing modelling and engagement practices to support assessment of conjunctive water use opportunities

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Effective water resource management requires the consideration of issues at stake within an appropriate coupled human-water systems context. In the case of the Murray-Darling Basin, societal sensitivities mean any approach to progress the management of the system must be defensible and socially acceptable under scrutiny from multiple perspectives (i.e. environmental, social, economic, and scientific). Integrated approaches allow us to elicit, connect and assimilate often-fragmented knowledge and information across sectors and disciplines, and with modelling processes to evaluate the consequences of management options.

We have applied an integrated approach to elicit and explore various conjunctive use options (i.e. managing surface water and groundwater collectively) in the Campaspe catchment. Through disciplinary research – including groundwater and surface water modelling, recharge studies, ecological and social research – and through integrated modelling processes, we have identified and explored the feasibility of conjunctive use options. The approach comprises six key components: 1) identifying issues and conjunctive use options through stakeholder workshops, 2) development of a feasibility assessment methodology for these options, 3) conceptual design of the integrated model, 4) design and development of component models, 5) software implementation of the integrated model and 6) evaluation of the options paying particular attention to uncertainties. The integrated modelling was designed for generating system understanding and management and decision support. It allows us to investigate the consequences of various possible futures, considering climate, water policy and irrigation opportunities on groundwater sustainability, farm profit, river ecology and recreational values.

In the presentation we describe the approach, and discuss the benefits:

- Engaging irrigators in constructive dialogue about ways to improve water management
- Identifying innovative opportunities that have not been considered or tested by policy managers
- Integrating local knowledge and advanced science to aid decision making
- Highlighting knowledge gaps and uncertainties that need to be addressed to support water management

Modelling the impacts of plantation forestry on groundwater: science and policy

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Groundwater management in the South East of South Australia incorporates plantation forestry as a licensed water user. Forest water accounting methods incorporate rates of groundwater recharge interception by forestry, and rates of groundwater extraction where the watertable is shallow (<6 m below ground). However, the method adopted in policy has not been tested against long term observations. Furthermore, hardwood (Tasmanian blue gum) plantations have not been managed as originally intended, as plantations which extract groundwater have remained in place for much longer than policy accounted for. Hence there is a need to revisit plantation forest water accounting methods, and their potential impact on groundwater resources.

An existing numerical groundwater model was revised and re-calibrated to assess whether current policy assumptions on recharge and forestry impacts are consistent with groundwater observations. The model assumes policy adopted rates of groundwater recharge, recharge interception by plantation forestry, and groundwater extraction by plantation forestry. The model was calibrated by varying hydraulic parameters with PEST. Model parameter uncertainty was then investigated using an alternative model calibrated allowing both hydraulic conductivity and adopted recharge rates to vary in parameter estimation.

The model calibrated well to existing policy adopted rates of recharge and forestry impacts, and the hydraulic parameters match our conceptual understanding. The forest water accounting methods can be considered broadly accurate, with a few exceptions. The modelling work will help guide future iterations of water allocation plans in the region, particularly in relation to managing forestry impacts on groundwater. The additional calibration work also helps water planners understand uncertainty in groundwater management numbers.

DAY 3: Thursday, 13 July 2017

CONTAMINATION

Keynote: Waituna Lagoon nutrient loads: a surface water or groundwater issue? *Alexandra Badenhop, University of Canterbury/ Lincoln University.*
Groundwater quality assessment due to geomorphological impacts along north coastal districts of Bay of Bengal of AP, India. *Krishna Kotra. The University of South Pacific.*
Field experiences with nanoiron for contaminated land remediation. *Denis O'Carroll, UNSW.*
How bacteria will help the New Zealand dairy industry. *Richard Cresswell, Eco Logical.*
Strain DCMF: a novel bacterium for remediation of dichloromethanecontaminated groundwater. *Sophie Holland, UNSW.*
FVPDM: a practical approach to assess groundwater and contaminant mass flux under variable hydraulic conditions. *Alex Savaglia, Golder.*
Microbial chloroform respiration – breathing life into toxic environments. *Matthew Lee, UNSW.*
Analysing temporal variability in shallow groundwater quality in southwest Sydney: a multivariate statistical analysis approach. *Sarah Taylor, Department of Energy and Environment (DOEE).*
Genesis and occurrence of high fluoride groundwater in the Thar Desert, Pakistan. *Tahir Rafique, PCSIR Laboratories Complex.*
Use of electrokinetics for enhanced contaminant site remediation. *Denis O'Carroll, UNSW.*

Waituna Lagoon nutrient loads – a surface water or groundwater issue?

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Waituna Lagoon is situated within the Awarua-Waituna wetland complex in Southland, New Zealand, recognised under the Ramsar Convention as a wetland of international importance. While the lagoon currently has significant biodiversity values; the majority of the catchment is intensively farmed, and natural and artificial drainage pathways rapidly route nutrient and sediment to the lagoon. The flipping of the lagoon to a hyper-eutrophic state is considered highly probable without effective intervention. However, it was recognised early on that a high degree of spatial variation in the nature of water quality outcomes despite very similar landuse pressures reflects steep gradients in physical hydrological and biogeochemical attributes. Therefore, the aim of this body of work is to identify how and why water quality outcomes and risk vary across the Waituna Catchment using a high-resolution physiographic approach. The physiographic approach uses the compositional signatures of waters to identify, map and classify the relevant attributes of the landscape that govern the processes controlling water quality outcomes. A temporal element has been added to the physiographic platform already developed for the Southland region, and attempts to answer such questions as “what contribution does baseflow make in terms of P flux relative to lateral soil drainage or overland flow?” and “do relative contributions from each flow path vary with time?”. Answering these questions is vital for sustainable primary production and enables the cost/benefits of water quality improvement controls to be optimised. Benefits of this approach include the use of pre-existing spatial information (e.g., national scale soil, hydrological and geological layers), which enables rapid and cost-effective application and provision of a visual-spatial depiction of the landform based controls over water quality outcomes that can be easily communicated to a range of stakeholders. By using pre-existing data this work integrates layers of information already available to obtain new insights.

Groundwater quality assessment due to geomorphological impacts along north coastal districts of Bay of Bengal of AP, India

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The present study was aimed in finding geomorphological impacts on the groundwater quality along the Bay of Bengal of north coastal districts of Andhra Pradesh, India. Groundwater samples were collected and assessed to identity various geomorphological impacts on the quality of groundwater along the coast. Groundwater samples along the coast of north coastal districts of Bay of Bengal of Andhra Pradesh were collected for two seasons in April and Nov of 2015. 66 groundwater samples of bore and open wells along the coast for two seasons (pre and post Monsoon) were systematically analyzed for their physio-chemical parameters. The results were interpreted for various geochemical assessments with correlative approach for finding the impacts on the groundwater quality.

The correlated statistical analysis showed that there are deviations in some parameters from the prescribed WHO and ISI standards of potable water. Some parameters were found relatively high in the Post Monsoon season than in the Pre Monsoon. The mechanisms controlling the groundwater chemistry can be attributed to the rock weathering. The geochemical evolution of the zones indicates that there was much movement in the groundwater under the influence of the local topography and thus at times favoring the development of intrusion zones along the coast. The hydro-geochemical facies with respect to the flow pattern indicate that the groundwater's due suffer the impacts of the elevated as the study area is topographically a low lying area.

It can be concluded that the groundwater along the Bay of Bengal coast in the north coastal districts of AP, India has been under sever geological and chemical impacts from the local and elevated lands. The recent geomorphological changes that took place along the coast has impacted its quality and the development of intrusion zones is evident.

Field experiences with nanoiron for contaminated land remediation

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Pilot scale injections of nanoiron stabilized with carboxymethyl cellulose (CMC) were performed at an active field site contaminated with a range of chlorinated volatile organic compounds (cVOC). The cVOC concentrations and microbial populations were monitored at the site before and after nZVI injection. The remedial injection successfully reduced parent compound concentrations on site. A period of abiotic degradation was followed by a period of enhanced biotic degradation. Results suggest that the nanoiron/CMC injection created conditions that stimulated the native populations of organohalide-respiring microorganisms. The abundance of *Dehalococcoides spp.* immediately following the nanoiron/CMC injection increased by an order of magnitude throughout the nanoiron/CMC affected area relative to pre-injection abundance. Distinctly higher cVOC degradation occurred as a result of the nanoiron/CMC injection over a three week evaluation period when compared to control wells. This suggests that both abiotic and biotic degradation occurred following injection.

How bacteria will help the New Zealand dairy industry

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New Zealand has adopted the Healthy Rivers approach to environmental restoration and control landuse change with an intent to steer waterways towards pristine conditions that provide social, economic and environmental returns. Nutrients, in particular, have been increasing at all monitoring sites for many decades, reflecting on-going land-use change, specifically the varying fortunes of the dairy industry. Highly transmissive volcanic soils result in seasonal surges in nitrogen and phosphorous loads in baseflow to creeks and rivers, with dairy farms leaching more than 50 kg/ha/a nitrate, compared to 2-5 kg/ha/a from forests and plantations. This nitrate derives from excessive fertiliser use (>250 kg/ha/a) and high returns from animal excreta.

Whilst management practices have significantly improved over the last few decades, reducing leaching by half through efficient fertiliser use and judicial stock management, significant nitrates still permeate the soils and drain to rivers and creeks, resulting in algal blooms, pollution of water supplies and disruption of ecosystems.

The potential exists, however, to further attenuate nitrogen levels through microbial metabolism of facultative anaerobes (primarily *Pseudomonas denitrificans*) in oxygen-poor groundwaters. These bacteria use nitrate as an electron receptor during denitrification and can rapidly reduce nitrate to negligible levels in baseflow to creeks. Rates of denitrification, however, are highly variable, dependent on the oxygen levels in groundwaters and rates of transport through the aquifer. Multiple lines of evidence are required to evaluate the efficacy of denitrification impacts at any given site.

We have use a combination of agricultural (APSIM) and groundwater (MODFLOW_MT3DMS) modelling and local monitoring to elucidate the nitrate story across the Upper Waikato catchments of New Zealand and we use this to help dairy farmers spatially and temporally manage land use change and develop stock management strategies that incorporate denitrification as a principle component of nutrient discharge mitigation.

Strain DCMF: a novel bacterium for remediation of dichloromethane-contaminated groundwater

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Dichloromethane (DCM) is a toxic, persistent groundwater contaminant that is most commonly of anthropogenic origin. It is present at numerous contaminated sites worldwide, as demonstrated by its occurrence at 19% of National Priority List sites throughout the United States, and also typically produced as a breakdown product of trichloromethane, another common groundwater pollutant. As DCM is denser than water, it tends to sink to the bottom of the water table, forming dense non-aqueous phase liquid (DNAPL) pools, from which a steady stream of contaminant can slowly leach into the groundwater over long time periods.

Strain DCMF is a recently discovered bacterium enriched from a contaminated aquifer near Botany Bay, Australia, that transforms DCM to acetate under fermentative conditions. Not only does this novel member of the Peptococcaceae family have great potential in the Australian bioremediation scene, it also represents a unique branch on the phylogenetic tree of life. The genome of strain DCMF was recently sequenced and assembled into a single, 6.4 Mb circular contig. It revealed a host of interesting predicted metabolic features including a highly redundant set of methylamine methyltransferases, suggesting they have a key role in dechlorination. This work characterizes a robust bacterial culture for the bioremediation of DCM-contaminated groundwater and paves the way to identifying a novel dehalogenase capable of anaerobic DCM degradation.

FVPDM: a practical approach to assess groundwater and contaminant mass flux under variable hydraulic conditions

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Assessing contaminated groundwater discharge to a marine environment can be difficult given the complex nature of groundwater – surface water interaction. The objective of the study was to undertake single-well fluorescent dye tracer tests along a transect of wells with decreasing distance from the inferred connection with surface water to characterise the groundwater and contaminant mass flux towards the environment.

The methodology consisted in applying the Finite Point Volume Dilution Method (FVPDM), (Brouyere et al, 2008). The FVPDM involves injecting a tracer in a well at a low and continuous rate. The rate of tracer dilution resulting from groundwater flow through the well is an in-situ measurement of the Darcy flux. In-well contaminant sampling is then used to derive the contaminant mass flux. The measurement does not depend upon estimate of hydraulic conductivity and hydraulic gradient.

The ten FVPDM tests undertaken at the study location enabled an accurate quantification of groundwater and contaminant mass fluxes along the investigated transect. The main benefit of FVDPM was to measure how the Darcy flux responded to variable hydraulic conditions and to show that these fluxes can differ in magnitude according to each specific tidal event (i.e. neap and spring tide).

Direct measurement of groundwater and contaminant fluxes enabled the planning and development of more effective risk mitigation measures to protect the marine environment.

Brouyere et al, 2008. A new tracer technique for monitoring groundwater fluxes: Finite Volume Point Dilution Method. Journal of Contaminant Hydrology 95(121-140).

Microbial chloroform respiration – breathing life into toxic environments

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Chloroform is common groundwater priority pollutant ranked 11th on the US-EPA's list of hazardous chemicals. Chloroform is a naturally occurring compound however; human activity has introduced chloroform en masse into subsurface environments. For example in the USA around 25% of the priority polluted sites are chloroform impacted. Additionally, chloroform is problematic in that it is a powerful inhibitor of most subsurface microbial processes including organohalide respiration. Therefore, where chloroform exists as a co-pollutant with other organohalides, such as chlorinated ethanes and ethenes, bioremediation typically is not possible.

Given the problematic nature of chloroform in anoxic environments, one of our research objectives has been to discover and understand chloroform-degrading bacteria. Using sub-surface sediment (5 m) derived from an organohalide impacted site near Botany Bay Sydney, a novel chloroform respiring bacterium from the genus Dehalobacter was discovered, isolated, biochemically characterized and named Dehalobacter sp strain UNSWDHB. Strain UNSWDHB can tolerate up to 500 mg l-1 of chloroform and dechlorinate it to dichloromethane at a maximal rate of 12 mg l -1 day-1. The reductive dehalogenase (TmrA) was functionally characterized and shown to dechlorinate a range of chlorinated ethanes in addition to chloroform. Additionally isotope ratio mass spectrometry was used to characterize the isotope ratio fingerprint associated with chloroform respiration by strain UNSWDHB. This is a powerful technique for determining in situ activity of microorganisms.

The discovery of this organism has the potential to alleviate the inhibitory effect of chloroform where it exists as a co-pollutant. This can therefore open up many organohalide polluted sites for cleanup by bioremediation.

Analysing temporal variability in shallow groundwater quality in southwest Sydney: a multivariate statistical analysis approach

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Analysis of temporal variability in groundwater quality provides useful information on processes occurring within a groundwater system. In this study, a high resolution (26 sites sampled 20 times over 24 months) geochemical dataset was analysed to inform conceptual model development and to understand what processes were driving observed variations in groundwater quality.

Multivariate statistical analysis (MVA), comprising of hierarchical cluster analysis (HCA) and principal components analysis (PCA) was utilised to compare monthly water quality subsets to the median observed groundwater quality (selected as the baseline, representing average rainfall/recharge conditions during the study). Variability in identified groundwater-types at the site scale, and temporal changes in the composition of groundwater-types, were analysed to determine what processes were causing changes in water quality at the different scales. At the site scale, the results of the conventional approach using the entire available dataset, were compared to those derived from analysing each monthly subset individually. Analysis of individual monthly subsets provided greater sensitivity in that more subtle variations which were not identified by the conventional approach were detected.

The analysis identified seven groundwater-types within the studied system. Salinity, weathering products and evapotranspiration (ET) effects were determined to be the main factors affecting groundwater-type classification. The distribution of the identified groundwater-types could be correlated with landscape features. Temporal changes in groundwater quality were driven by factors including upward leakage, the proportion of fresh recharge, mixing with surface water-derived recharge, and the degree of ET. Variability in groundwater-type composition was limited and short-lived, indicating relative stability in groundwater composition during the study period.

A classification scheme was developed based on the results of the MVA analysis with the aim of allowing preliminary analysis of groundwater quality based on a reduced number of parameters. This may assist managers in identifying potentially important local processes affecting groundwater quality.

Genesis and occurrence of high fluoride groundwater in the Thar desert, Pakistan

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Publish consent withheld

Use of electrokinetics for enhanced contaminant site remediation

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A range of innovative contaminated site remediation technologies have been developed and implemented, including reduction and oxidation based processes. However, achievement of remediation goals at many contaminated sites is still difficult achieve due to challenges associated with delivering amendments uniformly throughout contaminated zones, including low permeability media. The goal of this study was to evaluate the extent to which electrokinetics of amendments could uniformly distribute amendments in clay at a contaminated site. Electrokinetics is uniquely suited to uniformly distribute amendments in impermeable media, such as clay. The study included five distinct transects:

- Electrokinetics + an oxidant (i.e., persulfate)
- Electrokinetics + nanometals
- Electrokinetics + lactate
- Electrokinetics with no amendment
- Control

This design enabled an assessment of the ability of electrokinetics to enhance the transport of amendments. Electrokinetics can induce amendment transport due to electromigration of dissolved constituents (e.g., oxidant and lactate), electrophoresis of charged particles (e.g., nanometals) or electroosmosis (i.e., transport of the bulk water phase). The extent to which these mechanisms transport amendments in the field will be discussed. This study provides crucial information needed for the design of uniform amendment delivery at contaminated sites for subsequent contaminant degradation.

DAY 3: Thursday, 13 July 2017

MODELLING / DATA

Monitoring and modelling groundwater extractions over a data-sparse region of Australia

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Quantifying the rate of extraction from groundwater bores can be essential for regional scale groundwater management and impact assessment. However, regions that are large and remote with many poorly accessible groundwater bores pose great challenges for metering. In the Surat and Bowen Basins in Queensland, Australia, more than 30000 groundwater bores exist; however almost none are metered. Our research uses a case study of the Surat and Bowen Basins to develop new stochastic estimation methods that provide estimates of long term annual average groundwater extractions and their uncertainty. The method involves the collation of multiple sources of extraction estimates ranging from metering to qualitative information; and a set of spatial and temporal data that are potential predictors of extraction. These data are used to construct a generalised linear model to estimate property scale extraction. These estimates are downscaled to bore scale extraction with an occurrence probability model, followed by magnitude distribution for those bores with non-zero extractions. Stochastic simulation allows a comprehensive infilling of long-term annual average extraction rates at all properties, aquifers and all known bores. However, significant limitations remain both in the data-base used and in the generalised linear model, particularly related to attribution of property-scale water demand and temporal variability.

3D modelling of aquifers in South Australia

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3D modelling of aquifers provides a visual representation of well data typically stored in a database. A 3D interactive model containing one or many aquifers can be produced that is excellent tool for demonstrating and explaining hydrogeological features to both technical and non-technical people.

The 3D groundwater features are constructed using existing drillhole information stored in the SA drillhole database. In particular the elevations of hydrogeological features are used to interpolate elevation surfaces, such as the top and bottom of various hydrostratigraphic formations.

Known hydrogeological features for resource regions in South Australia have been constructed in ArcGIS in conjunction with the ANU DEM algorithm and the Arc Hydro Groundwater Toolkit. The resulting 3D model features are hosted in the readily accessible Adobe PDF Reader, in an interactive environment where users can rotate, zoom, apply vertical exaggeration, and make cross sections.

Not only is the 3D aquifer modelling a powerful visualisation and demonstration tool, but we have been able to demonstrate several spin-off benefits from the end product, and from the process involved in the 3D modelling itself which can also add further value to existing data thereby enabling more comprehensive aquifer assessments.

Examples include:

- The capability to assign aquifers to wells that have depth or production zone information but no geological log.
- Collating water level and salinity data from wells, from which 3D water level features for aquifers can be created and used to determine areas of confinement and leakage potential.
- Improving interpretation of aquifer extents and the discovery of new hydrostratigraphic features and structures.
- Development of tools for managing groundwater resources (salinity management, recharge estimates, waterlogging assessment, storage volume calculations).

How groundwater models can evolve over decades: SA models of groundwater salinity and the River Murray

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Salinity is a natural part of the Murray-Darling Basin (MDB) in South Australia, where the groundwater can be saltier than seawater. Natural flows of groundwater salt to the river can be impacted by changes in land use, river regulation, and engineering works. Numerical groundwater models provide quantitative estimates of groundwater salt entering the River Murray due to various management actions. This supports SA's policy development and planning.

South Australia has developed, and is progressively refining, a suite of numerical groundwater MODFLOW models, for the River Murray in South Australia. The models represent decades of work by numerous groundwater modellers since the 1990s. The current models are typically updated and reviewed on a five-year rolling basis, ensuring that the models incorporate new data and knowledge. Improved modelling methodology, approaches and techniques have been applied over time. The models are developed collaboratively between policy officers and groundwater modellers to ensure assumptions and simplifications are appropriate, both scientifically and for policy purposes. A rigorous model review process is an important part of the model development where expert independent reviewers are involved at several stages.

Early generation groundwater models are usually limited by data availability and software capability. More advanced modelling techniques and software improvement enable current groundwater models to simulate closer to reality. A prototype model aims to allow real-time estimates of river salinity and to gauge the impact on floodplain ecology.

SA groundwater models successfully estimate salt load impact to the river from natural and anthropogenic processes. They also identify knowledge gaps in scientific understanding, and help to plan future research.

A technique for estimating optimal constant extraction rates for water levels to remain above pre-specified minimums in the model domain

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The Resource Operation Plan (ROP) process in Queensland seeks to convert water licences into volumetric allocations. The announced entitlement reflects the volume of water available based on measured groundwater levels. When groundwater levels are low, the announced entitlement would also be low.

The main objective of this paper is to show the use of a technique to estimate the optimal conservative entitlement such that pre-selected minimum water levels are maintained during the simulation period. By using different minimum water levels, the storage behaviour of the system can be established for the ROP.

The calibrated Central Lockyer Groundwater model was used to test this method. The model covers the simulation period from 01/07/1987 until 30/06/2014. It has a single convertible layer with variable transmissivity and simulates groundwater levels using extractions and recharge as the major inputs with the time-variant specified fixed head as the boundary in the upper and lower reaches.

This model was used to set up the scenario model for which the optimal constant extractions from 24 management zones were to be determined. The penalty function method was used to determine the conservative optimal extraction rates such that water levels never went below the specified minimums. The historical minimum water levels of September 1995 were used as the target water levels.

The technique for estimating optimal extractions using the penalty function method was successfully implemented. The results of storage behaviour for the scenarios with different minimum water levels were compared to the storage behaviour of the calibrated model. The analyses of these storage behaviours and conservative extraction rates are helpful in understanding the simulated behaviour of the system. From this, rules for announced entitlements can be developed.

Towards data democracy in groundwater science

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The present era provides unprecedented volumes of data that could be available to decision models and tools that can be used to improve understanding and management of Australia's groundwater systems. The challenge is in providing equitable access to all the available data - public and private - in a seamless manner, regardless of its disparate custodianship and collective heterogeneity. Hence the aim of the research is to develop a comprehensive, informative, intuitive-to-use knowledge base of groundwater information that is freely available to the entire community.

Implementing data democracy requires both the technology to interoperably federate data as well as the motivations for custodians to provision their data for all to benefit. A research project being undertaken in Victoria is successfully implementing a system in which numerous groundwater data sets owned and managed by a variety of custodians are brought together in a single web-portal. To the extents possible, the technology adopts *GroundWaterML2* a specification proposed by the Hydrology Domain Working Group of the Open Geospatial Consortium (OGC) in 2016 as a international standard for the transfer of groundwater data, including water wells, aquifers, flow, physical and chemical parameters and management. A number of use-cases were collaboratively developed with the end-users to direct the portal functions.

Around 80 datasets from 8 disparate custodians are interoperably federated in the Visualising Victoria's Groundwater portal, ranging from government data to community contributed data. The greatest use of the data portal is by the private sector (43%) ahead of government, community, water authorities and researchers.

This data democracy system provides timely and equitable access to all the data required to answer the frequently asked use-case questions for both the private sector and public sector decision makers and aids community debates around the groundwater impacts of energy resource developments, urbanisation and changing climates.

Statistical analysis and interpolation of water level data at the Bureau of Meteorology

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Under the Commonwealth Water Act 2007 the Bureau of Meteorology is tasked with collecting groundwater level time series data from states and territories on a regular basis. Currently groundwater level data has several shortcomings, including inconsistent information on quality of data as well as the intermittent and non-continuous readings for most bores across Australia.

To alleviate these shortcomings *HydroSight (http://peterson-tim-j.github.io/HydroSight/)* was created through an ARC linkage grant supported by the Bureau. Now the Bureau is operationalising several of the modules from this tool including:

- *Statistical analysis for data quality assessment* – for automating the numerical identification of water level data monitoring errors and outliers.
- *Create monthly times series* – for automating the time series infilling of groundwater level data using rainfall and a simplified soil moisture transfer function noise model.

The goal for this project is to identify observations that are statistically anomalous and/or erroneous. To achieve this goal, the Bureau needs to run the tool for over 100,000 bores that have water level observations. HydroSight's code has been extracted and modified to read and write directly to the Bureau's databases and fit with the automated processes for ingesting state data.

The analysis uses a set of hydrogeologically relevant heuristics to identify physically questionable observation (e.g. long periods of constant head). Observations are then checked for outliers by iteratively applying a globally calibrated double exponential smoothing time-series model. The remaining data is then interpolated to a regular month observation frequency using a calibrated nonlinear transfer function noise model. The outcome is groundwater hydrographs interpolated to a regular timestep that accounts for between observation forcing dynamics.

The outputs will be made available within the Bureau's suite of groundwater products and will be used to inform the groundwater processes in the Water Resources Assessment Landscape (AWRA-L) model.

Accurate groundwater flow modelling closely linked to constrained 3D geology: a case study from Tunisia

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5. General Directorate of Water Resources, Tunis, Tunisia

In north African nations such as Tunisia, geological exploration under cover remains the most difficult challenge to success in finding continuing water resources, geothermal energy, oil and gas, and minerals. Securing these resources means long term commercial self-sufficiency. Achieving such goals requires understanding the 3D geometries of subsurface geology and structures.

Creation of a realistic 3D geological and structural model of the Kasserine Aquifer System (KAS) in central Tunisia and north-east Algeria, was the main workflow of this project. This was achieved using an implicit 3D method, which honours prior geological data for both formation boundaries and faults. The model built in GeoModeller software provides defendable predictions for the spatial distribution of geology and water resources in aquifers throughout the regional-scale model-domain.

Aquifer connectivity and the hydraulic significance of the major faults was assessed using the 3D model. This was carried out by evaluating the influence of faults on known groundwater flow directions, and the locations of springs, within and between four compartments of the multilayered, KAS hydrogeological system. Possible dual nature of faults in the KAS was identified because some faults appear to be acting both as barriers to horizontal groundwater flow, and simultaneously as conduits for vertical flow. Also explored, was the possibility that two flow directions occur within the KAS, in the region of a small syncline near Feriana.

Beginning as a conceptual study on regional scale, the model was next used to estimate volumetric groundwater resources, and then to perform numerical flow modelling on a finite element mesh coupled with geological information derived from the model, using FEFLOW software. This integrated 3D approach, linked to a model of realistic geology and faults has world-wide applicability for critical understanding of groundwater systems as resources.

Transient seepage in anisotropic plane by multiple conjugate boundary element method

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The transient seepage in anisotropic media can be moddled by an elliptical partial differential equation with kinematic boundary conditions. Introducing an eigen-relation, the general solution and the boundary conditions of the plane problem can be expressed by terms of complex analytical function vector as $f_k(z_k)$ with complex eigenvalues $z_k=x+p_k y$. A new conjugate boundary element method for holomorphic function (CBEM) has been proposed by author recently (see DOI:10.21656/1000-0887.370001[in Chinese]). Employing CBEM and transforming the original plane defined in into several isotropic planes defined in with , a number of weighted residual equations are established as the equivalent weak form to the original governing equations. Following the way similar to the conventional BEM of potential problem, a series of linear equation system with constraned equations can be obtained, in which multiple BEM equations of potential problems are employed and Cauchy-Riemann realtions are used as constrained linear equations in discrete space. Overcoming the mathematical difficulty arising from domain decomposition, domain transformationt and solution of large linear system with weak ill-conditioned matrices, a complete MCBEM for seepage in anisotropic media will be finally established. Three transient free-surface seepage in phreatic surface studied by Rafiezadeh and Ataie-Ashtiani (ref. to EABE 46(2014):51-66) are used as numerical examples, and the results show the reliability and flexibility of the proposed method. Comparing with the other numerical methods to seepage analysis, the most remarkable advantage of the proposed method is suitable for parallel computing, which is discussed at the end of this paper.

1. *Li Guoqing, A Conjugate Boundary Element Method for Complex Analysis of Holomorphic Function, Applied Mathematics and Mechanics - Chinese Edition, 2016 10.21656/1000-0887.370001*
2. *K. Rafiezadeh, B. Ataie-Ashtiani, Transient free-surface seepage in three-dimensional general anisotropic media by BEM, Engineering Analysis with Boundary Elements, 46 (2014) 51-66*

Peering into groundwater models - a transparency wish-list

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The modern numerical model has become a paradox; the omnipotent hydrogeological future-teller for large in-ground developments such as mining is also the single biggest impediment to those wishing to know to what degree impact predictions can be trusted.

The most important shortcomings in the current system of reporting model outcomes to stakeholders are:

- Specific questions that stakeholders want answered are rarely sought or addressed.
- Key conceptualisations, assumptions and the detailed rationale for assigning parameters are rarely revealed.
- The real uncertainties associated with the predictions are rarely assessed by the modellers, far less transparently presented to the stakeholders.

Even where the models provide good approximations of groundwater behaviour in historical and predicted future states, these shortcomings lead to a highly unsatisfactory lack of confidence on the part of agencies (and the community behind them) and an alternately baffled and strident call to "trust me, I've got a model" on the company and consultant's part. The following important steps are suggested to move us on from this situation, to justify the miners' development applications and to provide confidence to the community:

1. Start the assessment by defining, in consultation with key stakeholders, prediction failure and clarify how a Type II error will be avoided to an acceptable (e.g. 95%) degree of certainty.
2. Make modelling only as complex as is necessary, iteratively and only proceeding to greater complexity if it reduces uncertainty. In some cases this will mean using multiple simpler, possibly uncalibrated sub-models or other analysis to check or inform critical components of the larger models.
3. Present key layers and parameters to reveal model conceptualisation for all models (list of suggested layers to be presented).
4. Present uncertainties objectively and transparently, including conceptualisation and assumptions.
5. Use the model(s) to inform future investigations and monitoring, identifying data with maximum "worth" that will plug gaps most effectively.

DAY 3: Thursday, 13 July 2017

INVESTIGATIONS

Keynote: Groundwater salinity hotspot in the Mt Lofty Ranges (SA): connection to an intermittent stream and origin from land-clearing. *Thomas Anderson, Flinders University.*

Salinity forecast via groundwater age simulations. *Giovanni Firmani, DHI.*

Estimating groundwater salinity (EC and Cl-) from direct-push EC logs: soil science vs oil and gas. *Sarah Bourke, University of Western Australia.*

Anisotropy in hydraulic conductivity of jointed rocks: analytical and numerical interpretation of field measurements. *Mahdi Zoorabadi, SCT Operations.*

Determining the effective hydraulic conductivity of a rock mass for modelling purposes. *Stephen Parsons, Jacobs.*

Reliability of spatial patterns of groundwater recharge. *Yueqing Xie, Flinders University / NCGRT.*

Hydrogeological investigation and conceptual model development of the Esperance groundwater area, Western Australia. *Aine Patterson, PSM.*

Groundwater abstraction, heat exchange and reinjection at the University of Auckland Newmarket Campus Innovation Centre. *James Botting, BECA.*

Integrated hydrogeological characterization of a groundwater-fed lake and wetland. *Manitoba, Canada. David Toop, Manitoba Sustainable Development.*

Groundwater salinity hotspot in the Mt Lofty Ranges (South Australia): connection to an intermittent stream and origin from land-clearing

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Clearing of native vegetation for agricultural crops and grazing has been the definitive anthropogenic cause for dryland salinity in Australia and has had a devastating effect on catchment hydrology. In a high rainfall area of the Mt Lofty Ranges, land-clearing has caused a groundwater salinity 'hotspot' to form on a hill-slope producing transient groundwater salinity disequilibrium. The perched saline groundwater is over ten times more saline than the ambient groundwater. This phenomenon is largely unknown in the hydrologic literature. Furthermore, this saline groundwater was observed to discharge into a nearby intermittent stream thereby greatly increasing its salinity.

This surface water-groundwater interaction was investigated by weekly sampling and analysis of the physical parameters of the stream and the saline groundwater hotspot. Samples were analyzed for major and trace elements, stable isotopes of water and stable isotopes of strontium. These indicate that the probable mechanism for the salinity increase in the stream is a water-table rise during wet season recharge, which causes the saline groundwater to drain into the creek. Major and trace elements and strontium isotopes indicate the stream water is a mix of runoff and saline groundwater that has discharged into the creek. Strontium isotopes also identified that the source of salinity in the saline groundwater is largely caused by salts concentrated during evapotranspiration in the clayey unsaturated zone. Stable water isotopes have no relationship to salinity. CFC data indicates that the saline groundwater hotspot has been recently recharged which supports historic land-clearing as the cause of the high salinity.

The preferred model for the origin of the groundwater hotspot involves flushing of accumulated salts from the thick clayey unsaturated zone due to increase recharge following land-clearing. Depending on the veracity of this model, this process of groundwater salinization could be much more widespread than presently appreciated.

Salinity forecast via groundwater age simulations

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Soil and dryland salinity are two problems degrading the environment of Australia. Saline intrusion occurs on the coast and at evapo-concentrated waterbodies. Mine dewatering may enhance the propagation of salinity in the groundwater environment. The environmental impacts and the future water quality from the abstraction bores are often simulated by numerical models.

Water quality predictions are extremely sensitive to the initial salinity distribution. Statistical analysis relying on the simulations of traditional advective-dispersive transport models is often not practical due to long processing times.

A simplified approach to forecast the water quality of a well field is presented with one steady-state groundwater age simulation. The method relies on mapping an initial concentration to the travel times using a post-processing algorithm. The method was repeated for as many times as the number of generated initial concentration fields necessary to build a statistically significant population of realisations without the burden of additional simulations. This reduced the required computation by two orders of magnitude in our example.

The method equivalent to an advective water quality transport model that ignores dispersion. This can be both an advantage or drawback, depending on the situation. Where dispersion effects are dominating, the calculation above mentioned will fail by overestimating peak concentrations. In the case of large-scale models or low-dispersive situations, however, this method can effectively reduce unwanted numerical dispersion and therefore improve the modelling results.

In this work, we present a simple model set up using a 2D vertical cross section with abstraction on the right and a constant head on the left. The model was implemented using traditional transient transport modelling and the steady-state groundwater age simulation. Model results from the transport model and the groundwater age approach are compared for different values of dispersivity and initial salinity.

Estimating groundwater salinity (EC and Cl-) from direct-push EC logs: Soil science vs oil and gas

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Elevated groundwater salinity associated with produced water, leaching from landfills or secondary salinity can degrade arable soils and potable water resources. Direct-push electrical conductivity (EC) profiling enables rapid, relatively inexpensive, high-resolution in-situ measurements of subsurface salinity, without requiring core collection or installation of groundwater wells. However, because the direct-push tool measures the bulk EC of both solid and liquid phases (EC_a), incorporation of EC_a data into regional or historical groundwater data sets requires the prediction of pore water EC (EC_w) or chloride (Cl^-) concentrations from measured EC_a. Statistical linear regression and physically-based models (PBMs) for predicting EC_w and Cl^- from EC_a profiles were tested on a brine plume in central Saskatchewan, Canada. The PBMs tested included two distinct mathematical approaches for estimating EC_w from EC_a; a linear model developed in soil sciences, and a power-law model developed in the oil and gas industry (Archie's Law). A linear relationship between EC_a/EC_w and porosity was more accurate for predicting EC_w and Cl^- concentrations than a power-law relationship. Despite clay contents of up to 96 %, the addition of terms to account for electrical conductance in the solid phase did not improve model predictions. In the absence of porosity data, statistical linear regression models adequately predicted EC_w and Cl^- concentrations from direct-push EC_a profiles. These statistical models can be used to predict EC_w in the absence of lithologic data and will be particularly useful for initial site assessments. The more accurate linear physically-based model can be used to predict EC_w and Cl^- as porosity data become available and the site-specific EC_w–Cl^- relationship is determined.

Anisotropy in hydraulic conductivity of jointed rocks – analytical and numerical interpretation of field measurements

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Hydraulic conductivity of jointed rocks is controlled by conductivity of intact rock blocks and existing discontinuities. Rock discontinuities act as channels for water flow and their conductivity is relatively much higher than hydraulic conductivity of the intact rock. The geometry and inter-connectivity of discontinuity network induce variable hydraulic conductivity across various direction which called anisotropy in hydraulic conductivity. The common filed measurements which are done inside a single hole are not able to measure this behaviour properly. Interference tests which includes an injection or pumping out hole and several surrounding observation holes are the best techniques to measure the anisotropy in hydraulic conductivity. This paper presents applying the analytical and numerical models to interpret the interference test results to determine the anisotropy in hydraulic conductivity of jointed rocks. Papadepulos (1965) formulation is one of the common analytical methods to calculate the horizontal anisotropy of the hydraulic conductivity. This formulation needs injection or pumping flow rate and head changes at observation holes and can be directly apply to the test results. For 3D tensor of conductivity, the formulation which proposed by Hsieh & Neuman (1985) is common in practice. This study discuss the limitations of direct application of these two analytical methods and present a new procedure to apply them to calculate more reliable results. Additionally, 3D numerical modelling using FLAC3D was conducted as cross check to analytical models. Comparison between numerical modelling and analytical modelling shows that the proposed analytical procedure has high accuracy. Unlike numerical modelling, the proposed procedure is easy to apply and has capability to directly determine the storativity of the aquifer.

Determining the effective hydraulic conductivity of a rock mass for modelling purposes

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It is very common in hydrogeological analysis to require a single hydraulic conductivity (K) for all or part of a model domain. In fractured rock aquifers K commonly varies by at least several orders of magnitude, however the rock mass is modelled as an equivalent idealised porous medium. It is assumed that the rock is sufficiently homogeneously fractured and interconnected such that it can be considered "an equivalent porous medium" and that at a large enough scale the small scale variation of K is evened out. Usually, in fractured rock, the properties for this idealised large scale, homogeneous porous medium are derived from statistical analysis of small scale testing, typically packer tests. This presents the problem of what is the appropriate statistic to use from a data set for use in groundwater analysis and modelling? There appears to be some difference in the hydrogeological community as to whether it is appropriate to use the geometric mean or arithmetic mean for this purpose. If variability in K is high, as is typical of fractured rock, the geometric mean can be several orders of magnitude lower than the arithmetic mean. This paper describes why the arithmetic mean is more appropriate, and use of the geometric mean can result in significant error. However in projects using packer test data, if the bias of not being able to reproduce high end K values is not corrected, then even the arithmetic mean may be invalid. The approach of Raymer and Maerz (2014) to derive a 'reconstructed' arithmetic mean to take account of this effect is described and is considered to be the most representative value. Finally, this paper examines three additional factors that need to be considered in selecting a K value; the scale effect of hydraulic conductivity measurement, problem geometry and the analysis/modelling purpose.

Reliability of spatial patterns of groundwater recharge

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Groundwater recharge is a key factor to understanding groundwater availability. Many methods have been developed with water balance modelling most straightforward. It is commonly recognised that groundwater recharge estimated for a specific site (i.e., absolute recharge) is often highly uncertain because of uncertainty in input parameters and uncertainty in observations for model calibration. However, the uncertainty in absolute recharge may become less important if we are more interested in the sensitivity of recharge to different factors such as vegetation, soil type and climate (i.e., relative recharge). It is possible that relative changes in recharge are more accurate than absolute recharge, but this has not been specifically assessed. This study aims to investigate the reliability of relative changes in groundwater recharge by estimating absolute recharge for different vegetation types, soil types and climate zones. This study chooses the Campaspe catchment in southeast Australia as a study area. The biophysically based modelling code WAter Atmosphere Vegetation Energy and Solutes modelling (WAVES) is used to perform numerical simulations. Three weather zones, two soil zones and four land cover zones are used based on the conditions of the study area. The Monte Carlo method together with the Latin-Hypercube sampling technique is employed to perform uncertainty analysis by comparing modelled results to actual observations derived from MODIS satellite imagery (i.e., actual evapotranspiration and leaf area index). The results will be recharge statistics for different combinations of climate, soil and vegetation. The recharge statistics will inform both the uncertainty in the absolute recharge and the reliability of the relative changes in the recharge.

Hydrogeological investigation and conceptual model development of the Esperance groundwater area, Western Australia

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The objective of this study was to improve the conceptualisation: of the active and potential intrusion and up-coning of saline water from the Southern Ocean and the northern saline-hypersaline lake system to the fresh groundwater resource; and increase the understanding of the aquifer geometry of the Esperance groundwater system, Western Australia. Esperance town is almost wholly reliant on groundwater for public and private water supplies, making it an extremely important resource.

Hydrochemistry sampling, aerial electromagnetic survey, down hole geophysical logging and bore hole lithological logs were used to develop a 3D conceptual hydrogeological model. The aquifer layers and groundwater contours were used to identify a potential future groundwater resource. Saline groundwater was identified through hydrochemistry sampling and the aerial electromagnetic survey. The aquifer layers and saline groundwater mapping were then used to develop a 3D layer of the saline interface.

Definition of the saline interface intruding the fresh water aquifer from the saline lake system to the north and the ocean to the south provide information about the risk of saline intrusion to the fresh water resource. New interpretation of the aquifer geometry from the development of the 3D conceptual model enabled the identification of potential future groundwater resources.

This study supports management of saline interface to ensure the fresh groundwater resource is not degraded. Additionally the study allowed for the ability to identify a potential future groundwater resource.

Groundwater abstraction, heat exchange and reinjection at the University of Auckland Newmarket Campus Innovation Centre

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The University of Auckland has a campus-wide energy use intensity target and wished to utilise natural ventilation systems as much as possible for their new campus in Newmarket. Groundwater in the unconfined fractured basalt aquifer that underlies the project site was identified as a natural renewable resource that could be used as a heat exchange medium for process cooling systems and cooling towers, and reinjected into the same aquifer to enable sustainable use of the resource.

A new bore water system was designed to abstract up to 500 m3/day from an existing water supply well. The feasibility of groundwater reinjection was assessed through 3-Dimensional groundwater modelling, in parallel with injection testing of an existing well further down gradient on site. Injection testing found the existing well to be unsuitable for reinjection and two new reinjection wells were installed. 3-D numerical modelling (using MODFLOW-2005 and SEAWAT v.4) enabled assessment of the likely magnitude of groundwater drawdown and mounding, under a range of pumping scenarios, as well as the likely extent of thermal plumes generated from reinjection of the heated water. Reinjection commenced in February 2016 following a period of baseline monitoring to assess natural groundwater temperature and level. Data logged by the Building Management System indicates that 6,634 m3 of water was abstracted and 5,420 m3 of water was reinjected in February 2016. Approximately 1,200m3 of water was used for cooling tower makeup water and irrigation, while 38.5MW of heat was rejected from the process cooling systems. City water conservation, as a result of the system is estimated to be up to 15,000 m3 /year with water cost savings of up to $75,000/year.

The groundwater abstraction and reinjection system has been successful in achieving acceptable occupants' comfort while realising energy and cost savings through sustainable use of the natural groundwater resource.

Integrated hydrogeological characterization of a groundwater-fed lake and wetland, Manitoba, Canada

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Gull Lake, a lake on a hilltop, located in Manitoba, Canada, is a groundwater-sourced lake approximately 1 km^2 within a closed catchment area of 4.8 km^2. The lake is surrounded by over one hundred holiday homes. The Gull Lake community, wishing to preserve the lake through catchment management, requested Manitoba Sustainable Development study the area's regional hydrodynamics. This included determining the source of the nearby spring-fed fen-type Brokenhead wetland. Quarrying activity located between the lake and the wetland was of concern.

The study drew upon existing forest cover, soils, climatic, hydrometric and bore data. Bore locations were field verified. Geology from drilling reports was analysed in Viewlog^{tm} software and compared to soils maps, to create a three-dimensional geological model, separating aquifers and aquitards. Water level data were used to determine groundwater flow. Heads were cross referenced to topography and reports of artesian conditions, while the dominant forest cover was used to outline recharge-discharge areas. The Gull Lake water balance was determined using lake level, groundwater level and climate data dating from the 1970s.

It was determined that Gull Lake is sustained entirely by precipitation within its catchment area, and is vulnerable to drought. The lake is surrounded by an unconfined gravel aquifer, which serves as the recharge area. Groundwater flow divides and clay aquitard beneath the lake prevent basin losses due to groundwater seepage. Lake losses are primarily due to evaporation. The Brokenhead wetland source aquifer was determined to be independent of Gull Lake. Quarries were mostly located outside the Gull Lake catchment but were heavily concentrated on the Brokenhead wetland source aquifer. Quarrying had remained above the water table and did not appear to have impacted lake or wetland hydrology.

Results were presented in the form of an atlas, as a reference tool for local water managers.

DAY 3: Thursday, 13 July 2017

SOCIAL

Keynote: The groundwater commons game: social tipping points in global groundwater management. *Juan Castilla, CSIRO.*

Changing the debate: using facts not fear to discuss groundwater science. *Liz Webb, EMM.*

Regulatory flexibility, illegal bores and the drilling industry: examining the practice and potential of NSW water bore drillers. *Cameron Holley, UNSW.*

Our knowledge of groundwater is imperfect. Regulatory and legislative structures are more effective when they acknowledge that. *Simone Stewart, Department of Environment, Water and Natural Resources SA.*

How hydrogeologists can contribute to effective stakeholder engagement in groundwater resource management. *Daniel Pierce, Department of Environment, Water and Natural Resources SA.*

Collective action in groundwater management in practice: lessons learnt from the Angas Bremer irrigation district in SA. Sarah Shalsi, *University College London.*

Breaking the hydroillogical cycle & applying socio-hydrogeology to GW management: the real-world example of Angas-Bremer irrigation district (SA). *Carlos Miraldo Orden, UCL.*

Assessment of Polar and Non-polar Material in the Groundwater of Raudhatain and Umm Al-Aish Fresh Groundwater Fields of Kuwait. *Tariq Rashid, KISR.*

Property rights in underground waters in South Australia. *Hossein Esmaeili, Flinders Uni.*

The groundwater commons game (Part I): social tipping points in global groundwater management

Juan Castilla[1], Rodrigo Rojas[1], Martin Andersen[2], Cameron Holley[2], Gregoire Mariethoz[3]

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A third of Earth's largest groundwater basins are being depleted by irrigated agriculture, yet little is still known about whether and when resource users will comply with groundwater conservation policies. Although enforcement monitoring compliance and punishing infractions is an essential part of any successful management programme, it is a costly endeavour that erodes trust between water agencies and users. Directly studying normative drivers of compliance (eg social norms and cultural values) is problematic because rule breakers are usually unwilling to reveal themselves or to discuss their motivations freely, thus bearing data on illegal activity prone to unquantifiable biases. To overcome these issues, we devised the 'Groundwater Commons Game' (GCG), an agent-based model of irrigated agriculture rooted in principles of human cooperation and collective action, grounded on the largest dataset of cultural values in existence: The World Values Survey. Simulations of three major aquifer systems currently facing unsustainable demands: the Punjab (India/Pakistan), the Central Valley (USA), and the Murray-Darling Basin (Aust) reveal 'tipping points' where collective attitudes towards groundwater conservation shift abruptly with small changes in cultural values and enforcement provisions. Our results suggest that these tipping points play a significant role in groundwater management, as they define the transition between groundwater overuse and conservation states, and because they can trigger unwanted responses across system domains. Based on these findings, we propose a three-stage approach to achieve long-term regulatory compliance: first, diagnose if the system is close to its tipping points; second, weave non-enforcement factors (social capital) to bring the system to the tipping points; and third, ensure compliance past the tipping points to build systemic resilience. Overall, our work presents new powerful modelling tools for groundwater management that can be used to evaluate how regulatory compliance is contingent upon socioeconomic, institutional, and physical constraints and conditions.

Changing the debate - using facts not fear to discuss groundwater science

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Sustainable management of Australia's water resources is a well-considered and studied science that is generally not well understood by communities. Public debates on the water related impacts from proposed new mines and coal seam gas projects rarely have relevant facts on water resources at hand. This study is specifically designed to analyse and present scientific data with appropriate context and provide these resources for our communities.

The project considers sedimentary Basins in NSW with known coal and/or CSG resources. Basins include the: Gunnedah; Sydney; Gloucester; and Murray. Data considered is; licence volumes, groundwater levels, groundwater quality, geology and hydrogeology. Results are presented with specifically designed graphics to provide context (ie maps; cross sections; and graphs). Interactive presentation of information to communities allowed for questions and active conversation on water facts and its management.

Data and results from the Gunnedah Basin and overlying water sources show how existing rights in the basin and overlying sources are distributed:

- irrigation 87%;
- town water supplies 8%
- domestic and stock 5%
- free flowing artesian bores 3%;and
- mining, CSG and industry 2%;

For the Narrabri Gas project, the volume proposed to be intercepted represents 0.0004% of the available water from the Gunnedah Basin and overlying groundwater sources. This project provides overall context, but potential impacts at the local level still need to be considered.

The project is considered a landmark for changing the debate. The initial concern over impacts of water take often change to other concerns that are not always water related. The project demonstrates the success of investing in science data and communication to promote informed debate.

Regulatory flexibility, illegal bores and the drilling industry: examining the practice and potential of NSW water bore drillers

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Drillers of water bores are a vital but often the most under-examined actor in water law and regulation. They carry out drilling, bore construction, and other work on bores on behalf of landholders to supply groundwater for stock, domestic, irrigation and town water supply purposes. The quality of drilling practices can have significant impacts on groundwater misuse, wastage and degradation. As such, Australia licenses and regulates their activities to ensure the protection of the groundwater resource and the long-term economic production of groundwater.

Beyond the need to licence drillers, drillers themselves play a unique role in providing information to landholders. Because landholders will typically engage a driller to access groundwater, drillers may often be one of the first points of contact about the landholders obligations under NSW water management legislation (e.g. to obtain a works approval). This role means the drillers have the potential to be a key party that assist or undermine water user compliance with their obligations under NSW water management legislation.

Given the limited examination for regulation of drillers to date, and their potential lynchpin role in ensuring landholder compliance, this paper examine and assess the operation of drilling industry regulation in Australia. Drawing on approximately 45 interviews with drillers and government officers in Australia, it provides insights into the effectiveness of these regulations. Its findings reveal some success, but suggest regulation remains confounded by a lack of inspectoral oversight due to geography, resourcing and driller mobility, and detailed administrative and training arrangements. The paper canvasses options for addressing these challenges, and argues that engaging individual drillers, and the drilling industry as whole, more effectively in the regulatory process requires a best practice accreditation approach.

Our knowledge of groundwater is imperfect. Regulatory and legislative structures are more effective when they acknowledge that

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The scarcity of surface water in South Australia has resulted in heavy reliance on groundwater across the state. In many of SA's 21 prescribed groundwater areas, water allocation plans (WAPs) provide the framework for sustainable management of groundwater resources.

The South Australian Natural Resources Management Act (the Act) guides the development of WAPs and requires an assessment of the water available in the prescribed area - the resource capacity, to meet the needs of environmental water requirements and consumptive demand.

Historically there has been a view that a WAP must assign a fixed volume to these components. This resulted in a number of issues which result in over-allocation of the groundwater resources. Prior to amendments made to the Act in 2009, there was no opportunity to vary water quantities identified in WAPs without undertaking a Ministerial amendment or a costly unscheduled WAP review. This led to a tendency to be overly generous with the water quantities estimated and often, in the absence of sufficient data, to rely on expert intuition to estimate volumes.

The 2009 amendments to the Act provide the ability for a WAP to acknowledge that it represents the best available science, but that as the resource and our knowledge of it changes, so too can the volume of water available and the volume allocated. The amendments allow WAPs to adaptively manage resources through annually announced allocations and allow the assignment of new volumes of water for consumptive purposes if additional science identifies there is more water available than previously assessed. These legislative changes mean that WAPs are no longer based on an expectation of complete knowledge of a complex, varying resource, but rather have the ability to respond to changes in the resource and our understanding of it, that may occur during its 10 year life span.

How hydrogeologists can contribute to effective stakeholder engagement in groundwater resource management

Daniel Pierce[1]
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There is a growing movement in South Australia, as with many other jurisdictions, for greater community involvement in the development of public policy, including in the area of water resource management. In the development and periodic updating of water allocation plans for each of the State's priority water resources, the nature of this involvement has moved away from the arrangement where government agencies, drawing on scientific advice, draft the rules, announce them to the community and then end up defending them in the ensuing consultations.

Recent experience with the Barossa Prescribed Water Resources Area illustrates how hydrogeologists can assist in opening up parts of the water planning process to be more participatory. A third iteration of the water plan for this resource is seeing, for the first time, community involvement in the determining volumes available for extraction, a determination, which was previously made solely by water planners on the advice of hydrogeologists. Hydrogeologists have made this possible by defining suitable management areas, and using numerical modelling to link the resource condition in each area to the impacts on users. Using this information, stakeholders are then engaged to determine the level of risk to the users dependent on the resource that they think is unacceptable, which then affects how much water is available for use.

In management areas where the resource is more vulnerable to short term changes in its condition, the information is also being used to develop a more responsive management regime where allocations can vary on an annual basis. As the State's water resources face the uncertainties of climate change and increased demand due to economic pressures, hydrogeologists are in a position to facilitate greater public participation in groundwater management using approaches such as these.

Collective action in groundwater management in practice - lessons learnt from the Angas Bremer irrigation district in South Australia

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2. Charles Sturt University, Albury-Wodonga, NSW, Australia

3. National Centre for Groundwater Research and Training, Adelaide, SA, Australia

Between 1981 and 2001 the Angas Bremer (AB) catchment in South Australia provided a rare example of collective action amongst irrigators to manage a groundwater resource in Australia. By closely working internally as well as with government agencies, the community successfully recovered an aquifer that was at risk of deflection and salinisation.

It is increasingly recognised that resource-user engagement in decision-making, through local collective action, is likely to offer effectiveness to groundwater management, which in turn can prevent groundwater depletion. However, the formal frameworks developed to facilitate resource-user participation in management have mainly been focusing on institutional design in isolation, often neglecting to incorporate important factors such as the social, historical and ecological context in which those institutions were created. Those specific contextual factors play a critical role in determining whether resource users are likely to work together towards the common goal of sustainably managing their groundwater resource.

The key questions of this research analyse the extent to which AB was an example of collective action, how that changed over time, why it occurred and the key outcomes of collective action. These research questions aim to identify the main factors that facilitated or impeded collective action in groundwater management in an Australian context.

Through a series of semi-structured interviews to further explore the context under which collective action arose as well as to understand individual perspectives and experiences, this presentation provides a summary of qualitative research that sets out to describe how the AB groundwater system has been managed over time and identifies lessons from that experience.

The preliminary findings show that norms and values have a strong role in determining the successfulness of management approaches. However, a two-way relationship is required, where all stakeholders involved need to exchange knowledge and have a common understanding of each other's norms and values.

1. *Afroz, Sharmin, Rob Cramb, and Clemens Grunbuhel. "Collective Management of Water Resources in Coastal Bangladesh: Formal and Substantive Approaches." Springer US, 23 Jan. 2016.*
2. *Skurray, James H. "The Scope for Collective Action in a Large Groundwater Basin: An Institutional Analysis of Aquifer Governance in Western Australia." Elsevier Ecological Economics. National Centre for Groundwater Research & Training, Adelaide, SA, Australia, 1 Apr. 2015.*

Breaking the hydro-illogical cycle and applying socio-hydrogeology to groundwater management – the real-world example of Angas-Bremer irrigation district (South Australia)

Carlos Miraldo Orden[1], Sarah Shalsi[1], James Hopkinson[1], Craig Simmons[2], Steve Barnett[3], Allan Curtis[4]

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The Angas-Bremer (AB) irrigation district (South Australia) is located at the lower end of the Murray-Darling Basin. It is economically supported by a thriving high-quality wine industry that relies on water availability for irrigation. This region is especially vulnerable to water crises because its water security depends on upstream management practices. Groundwater pumping in AB started in the 1950s, which lead to declining groundwater levels and rising groundwater salinities. AB faced two major groundwater crises, in the late 1970s and early 2000s (Millennium Drought), which drove the community to embrace innovative water-management approaches to survive. These approaches have been described as highly-successful and nation-leading, making the community more resilient to future water shortages. AB offers examples of integrated groundwater management (IGM) concepts, such as co-management and collective action (which will be addressed in a concurrent presentation), and hydro-illogical cycle and socio-hydrogeology, which are the focus of this study.

We aim to examine the innovative nature and success of AB's example of community-driven IGM, including breaking the hydro-illogical cycle, and successful application of socio-hydrogeology. We collected and analyzed biophysical data from the 1950s to 2015, including groundwater pumping, artificial recharge, surface water usage and rainfall. These data were integrated with a chronology of groundwater management practices and interaction between government agencies and local irrigators. From this we discuss the temporal evolution of the interaction between stakeholders – socio-hydrogeology. We show periods in which the hydro-illogical cycle was broken, but also periods that seem to show a regression back to this illogical approach to water-related issues.

From this we draw lessons for real-world IGM, the expansion of socio-hydrogeology as a discipline and how to break the hydro-illogical cycle in practice. This will benefit those aiming at resolving groundwater management problems considering the multi-disciplinary nature and different dimensions of complex socio-ecological systems.

Property rights in underground waters in South Australia

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Water resources, whether underground, on the surface, or rainwater resources, have significant importance in most legal systems and jurisdictions. Like other minerals (gold, silver, coal, iron ore, petroleum, etc.) ownership of waters and the nature of property in water is of significance in using and managing water resources. In Australia ownership of water, including groundwater, is based on the common law of England as entered and applied in Australia since the settlement as well as extensive State and Commonwealth statutory provisions. As water intensive activities (including agriculture, mining and industrial undertakings) are developing and as water resources, including underground water, are shrinking, traditional legal questions such as who owns the water and what is the nature of the ownership of the water is becoming important. Therefore, these types of issues are appearing in litigation in Australia.

This paper uses a theoretical legal research method where existing legal principles (under common law and legislation) are analysed in light of available case law. It reviews and analyses the ownership of water under the common law of Australia. This is particularly significant given that common law, unlike like its approach to mineral resources, considered water to be common property instead of recognising water resources as private property.

Nevertheless, extensive legislation and policy initiatives, by the Commonwealth and States and Territories, have significantly altered the traditional position of common law in relation to property rights in water.

This paper identifies the possible gaps where reform of the relevant law may be necessary in relation to ownership of ground water in Australia and the extensive legal framework of licencing of groundwater resources in South Australia.

A leading case on the issue of nature of property and ownership of groundwater was *ICM Agriculture Pty Ltd v Commonwealth* (2009) 240 CLR 140

DAY 3: Thursday, 13 July 2017

SOCIAL

Keynote: Updating Australia's Atlas of groundwater dependent ecosystems. *Lacey Elsum, BOM.*

What happens to groundwater ecosystems when you take out the groundwater? *Grant Hose, Macquarie University.*

Influences of agricultural practices on ecosystem services provided by groundwater microbes and stygofauna. *Kathryn Korbel, Macquarie University.*

A contemporary approach to groundwater system conceptualisation. *Sanjeev Pandey, OGIA.*

Groundwater drawdown: biogeochemical implications for streambed water quality. *Martin Andersen, UNSW.*

Impact of groundwater drawdown on stygofauna in the hyporheic zone. *Helen Rutlidge, UNSW.*

Biogeochemical trends within calcrete aquifers recharge processes: preliminary results based on historical data. *Mattia Sacco, Curtin University.*

Compound specific isotope analysis: a new tool to assess groundwater ecosystem function. Alison Blyth. *Curtin University.*

Adaptive management applied to assessment of potential impacts of CSG to GDEs distal to operations. *Chris Jones, Arrow Energy.*

Updating Australia's atlas of groundwater dependent ecosystems

Lacey Elsum[1], Eloise R Nation[1], Mark Menzel[1], Ralf-Dieter Schroers[1], Champika Wethasinghe[1], Elisabetta Carrara[1]

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The Atlas of Groundwater Dependent Ecosystems (GDE Atlas) was released in September 2012 using data collected during 2009-10. There was considerable progress in GDE mapping at the state scale since then, and some data in the GDE Atlas has become superseded. In early 2016 the Bureau, in response to stakeholders' feedback, commenced updating the GDE Atlas by integrating new state datasets to maintain the quality and relevance of this national product.

To update the Atlas, the Bureau collated state and regional GDE datasets from a number of agencies covering the three types of GDEs. Coverage was partial for most states, and datasets were created using a range of methods and no longer nationally consistent.

To convey information about differences in data source, the updated classification clearly distinguishes between pre-existing data from the national assessment and new state datasets, whilst retaining information about the GDE potential. New attributes were added to the data model to capture information about the data source.

Each dataset required a different approach for integration, and consultation with states/territories helped in determining this process. The key steps for each state update were:

1. Pre-processing of state datasets into new data model format
2. Classification of known and potential GDEs according to new classification system
3. Mapping of data, which either involves replacing existing data or using precedence rules where overlap occurs
4. Populating new data schema using state attributes
5. Running *Python* script to populate national attributes

By integrating the new state data, retaining information about the data source and highlighting the difference in methodology from the pre-existing national assessment, the quality and relevance of the GDE Atlas is improved. Now users of the GDE Atlas are accessing the most accurate and up-to-date information available for a wide range of uses, including natural resource management and environmental impact assessments.

What happens to groundwater ecosystems when you take out the groundwater?

Grant Hose[1], Kathryn Korbel
1. Macquarie University, Sydney, NSW, Australia

The removal of groundwater results in the lowering of water tables, which, for groundwater organisms, translates to reduced habitat availability and changed environmental conditions in the habitat that remains. While changes in groundwater levels may be well modelled and predicted, the impacts on groundwater ecosystems remain poorly known.

There are three key processes associated with groundwater drawdown in shallow alluvial aquifers that may threaten groundwater ecosystems. These processes are 1. the physical decline of water levels, from which fauna can be stranded in isolated or unsaturated sediments; 2. the loss of or change to habitat, particularly as water levels move through different geological strata and 3. changes in hydrological connectivity, that may influence water quality as a result of increasing distance or disconnection from the surface and other water sources. This talk will present a framework that identifies the key threats of groundwater drawdown to groundwater ecosystems and will highlight the current state of knowledge of each of these threatening processes, including new research on specific elements of the framework.

Influences of agricultural practices on ecosystem services provided by groundwater microbes and stygofauna

Kathryn Korbel[1], Grant Hose[1]
1. Macquarie University, Sydney, NSW, Australia

Groundwater ecosystems consist of simple foodwebs with microbes (archaea, bacteria and fungi) providing biofilms on which protozoans and stygofauna (highly adapted groundwater invertebrates) graze. It is apparent biota provide a range of ecosystem services significant for water quality and quantity. Microbes perform a range of metabolic functions important for biogeochemical cycling of carbon, sulfur, iron and nitrogen. Similarly, stygofauna and protozoans are believed to perform a range of functions from grazing and promoting microbial growth, through to maintaining pathways for water flow within aquifers. Thus the maintenance of these ecosystems services within groundwater resources is vital for industries such as agriculture, which in many parts of the world is heavily reliant on irrigation from groundwater.

Previous studies indicate the significant biodiversity of groundwater fauna, however relatively few studies have studied groundwater microbial communities, mainly due to difficulties in using traditional methods to culture these organisms. With advances in technology, it has now become relatively easy (albeit expensive) to study the potential microbial function and diversity within environmental data though the use of metagenomics and DNA sequencing. The study utilised a combination of both traditional (pumping and netting) techniques as well as DNA community profiling (metabarcoding) of 16S rDNA and 18S rDNA, to characterise groundwater biota (stygofauna and microbes) from three catchments within the Murray-Darling Basin, eastern Australia with data collected between 2015-2016. A number of differences in the compositional structure of biota under irrigated or non-irrigated lands were demonstrated, including differences in relative abundances of nitrogen cycling microbes and stygofauna communities. Such findings suggest agricultural activities can alter groundwater biotic composition and functions, which may in turn influence biogeochemical cycling and ecosystem services provided by groundwater ecosystems.

A contemporary approach to groundwater system conceptualisation

Steven Flook[1], Linda Foster[1], Keith Phillipson[1], Sanjeev Pandey[1], Gerhard Schoning[1], Dhananjay Singh[1], Peter Khor[1], Dean Erasmus[1], Ben Cairns[1]
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Following the rapid expansion of coal seam gas (CSG) in the Surat Basin in 2005, there has been continued investment in hydrogeological research by industry, research organisations and Government. Outcomes often challenge paradigms, but importantly improve understanding of these complex regional groundwater systems.

The Office of Groundwater Impact Assessment (OGIA) is responsible the assessment of cumulative groundwater impacts from petroleum and gas (P&G) activities in the Surat Cumulative Management Area (CMA) – an area of overlapping impacts. The role necessitates undertaking primary hydrogeological research and investigations, but also the collation and integration of hydrogeological research across all other organisations.

Extensive new information and understanding has become available in recent years. This presentation highlights how new learnings have been integrated to provide the basis for regional impact assessment. These include:

Revised basin architecture following the development of a new hydrostratigraphic model based on primary interpretation of 4,800 CSG well wireline logs and other datasets.

- Increased confidence in the estimation of unmetered stock and domestic (S&D) using a new methodology for estimating this component of the water balance.

- Applying a multiple lines of evidence approach to connectivity assessments in priority areas using multi-variate cluster analysis, geological investigations and pump tests.

- Revised recharge estimates for each aquifer based on an extension of saturated zone chloride mass balance (CMB) calculations across the whole of the CMA.

- Analysis of groundwater level data for around 12,000 bores to determine trends, develop potentiometric surface maps and determine groundwater flow directions.

- Detailed hydrogeological conceptualisation for 17 priority spring complexes.

This presentation focuses on new methods, knowledge and a contemporary approach to conceptualisation – multidisciplinary, collaborative and research guided by management needs. The conceptualisation report will be updated every three years to provide a reference point for hydrogeologists working on the GAB

Groundwater drawdown: biogeochemical implications for streambed water quality

Martin Andersen[1, 2], Helen Rutlidge[1, 2], Stefan Eberhard[3], Gabriel Rau[1, 2], Alexandra Auhl[1, 4]
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2. School of Civil and Environmental Engineering, UNSW, Sydney, NSW, Australia
3. Subterranean Ecology Pty Ltd, 227 Coningham Road, Coningham, TAS, Australia
4. School of Biological, Earth and Environmental Sciences, UNSW, Sydney, NSW, Australia

While interest in the ecological effects of depleting groundwater resources is increasing, little is known about the effects of groundwater drawdown on biogeochemical processes in the hyporheic zone. This study aims to elucidate the coupling and feedback mechanisms between flow and biogeochemistry in the hyporheic zone of three streams with different flow regimes (from intermittent to perennially gaining and losing) in the Maules Creek Catchment (NSW). The variation in flow regime is used as a proxy for groundwater drawdown. Stream reaches were characterised based on surface flow duration, hyporheic zone flow thermal regimes, inorganic tracers and head gradients. The hyporheic zone for the stream reaches was sampled at two depths 0.4 and 0.8 m for the characterisation of dissolved organic matter and inorganic redox-sensitive species. The biogeochemical conditions in the regional groundwater were characterised using a network of observation bores. The results illustrate that hyporheic zones of gaining reaches generally had oxic regional groundwater discharging into them, while losing reaches generally had steep redox-gradients and anoxic conditions (low dissolved oxygen and high Fe^{2+}) developing a few tens of centimetres into the streambed. The characterisation of organic matter revealed that while infiltrating surface water DOC may be important in driving redox-reactions, buried sedimentary organic matter plays an equally important role. Rapid degradation of organic matter leads to anoxic conditions favourable for anaerobic microorganisms. The findings have implications for the prediction of impacts to water quality in hyporheic zones and streams subject to groundwater drawdown caused by agricultural and mining activities.

Impact of groundwater drawdown on stygofauna in the hyporheic zone

Stefan Eberhard[1], Martin Andersen[2], Helen Rutlidge[2]
1. Subterranean Ecology Pty Ltd, Coningham, TAS, Australia
2. Connected Waters Initiative Research Centre, UNSW, Sydney, NSW, Australia

The objectives of this study were to understand how reductions in groundwater level and baseflow affect the ecology of stygofauna in the hyporheic zone, and thence, to develop conceptual models to aid understanding of hydroecological responses to groundwater drawdown. We examined effects of reduced baseflow permanence by sampling gaining and losing reaches of streams with varying intermittency and perenniality, in wet and dry periods. Stygofauna and hydrochemistry in upwelling and down-welling hyporheic zones were sampled from mini-piezometers <1m deep, and in the aquifer, from groundwater bores. The study was conducted in the upper Bremer River catchment in southeast Queensland and the Maules Creek catchment in northern NSW. In the Maules catchment, a rich stygofauna inhabited creek systems with deep alluvium and strong hydrologic connectivity to the regional aquifer. The Bremer catchment also had a rich stygofauna, but was contrasted by creeks with very thin alluvium (< 0.5m) overlying relatively impermeable strata, albeit still fed, to varying degrees, by groundwater discharge. In both catchments, streams with intermittent flow regimes supported a rich stygofauna demonstrating that ecosystem processes and function are maintained even during periods without surface flow. As hypothesised, losing/down-welling stream conditions supported few stygofauna. In contrast, gaining/upwelling conditions supported a rich stygofauna. The narrow vertical extent of the hyporheic zone means that only small changes in groundwater levels may switch the direction of hydrologic exchange from gaining/upwelling to losing/down-welling and thus change the ecological conditions for stygofauna and stream ecosystem function. This is relevant where groundwater drawdown from activities such as mine dewatering, coal seam gas extraction and irrigation for agriculture, potentially threaten stream ecosystem processes and function.

Biogeochemical trends within calcrete aquifers recharge processes: preliminary results based on historical data

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3. Western Australian Museum, Perth, WA, Australia
4. Australian Centre for Evolutionary Biology and Biodiversity, and School of Biological Sciences, The University of Adelaide, Adelaide, SA, Australia
5. South Australian Museum, Adelaide, SA, Australia
6. Dipartimento di Scienze Chimiche, della Vita e della Sostenibilità Ambientale, University of Parma, Parma, Italy
7. Department of Environment and Agriculture, Curtin University, Perth, WA, Australia

Groundwater ecological assessment studies have increasingly gained prominence during the last decade. In order to unravel the overall functioning of these ecosystems, it is urgently necessary to understand the aquifer recharge processes and their influence on the subsurface communities. Arid zone Western Australia calcrete aquifers have been recently found harboring a huge array of biodiversity. As well as their intrinsic ecological value, these environments represent interesting and relative pristine model systems to study several groundwater dynamics. This study embraces three main objectives: 1) recover quantified information about the geochemistry and biology of a calcrete aquifer (Yilgarn Region: Sturt Meadows aquifer), 2) investigate the ecological status of the ecosystem by using macroinvertebrates as biological indicators and 3) assess the influence of rainfall recharge events on the groundwater stygofaunal community. Based on previous investigations, physicochemical (temperature, conductivity, depth, pH, DO and ORP) and biological (α diversity) data from several years (2005, 2006, 2011 and 2015) were available. In order to decipher the recharge effect of the rainfall events on the system, we specifically focused on 2005, the only year with data from 2 different sampling periods (March and September). The physicochemical results revealed a fluctuating tendency over time, mainly due to the unpredictability of the rainfall episodes. Interestingly, 2005 trends were anomalous, with a substantial shift between wet (usually in March) and dry seasons (usually around September). Both geochemical and biological patterns revealed a strict linkage between the aquifer recharge and the ecological switches within the community. In addition, the biological diversity indexes showed specific stygofaunal community responses to the changing environmental conditions. This preliminary investigation informs responses to climate change, especially due to altered rainfall patterns, leading to a broader understanding of the ecosystem functions and the dynamics that regulate the water quality.

Compound specific isotope analysis – a new tool to assess groundwater ecosystem function

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2. Archaeology and History, Latrobe University, Melbourne, VIC, Australia
3. Zoology, Western Australian Museum, Perth, WA, Australia

Groundwater is a fundamental resource of global importance. The hydrology of Australia's aquifers is relatively well studied, but far less understood are the ecosystems they contain[1]. To understand the effects on these systems of issues such as climate change, and water extraction, we need to understand how these ecosystems function. This is a challenging question, given that the systems are dominated by invertebrates living in highly cryptic environments.

To circumvent these problems, we are applying a combined programme of compound specific isotope analysis of single amino acids, and radiocarbon dating of fauna. This will allow us to:

1) Assign trophic position to different invertebrate species
2) Identify the dominant carbon sources at the base of the subterranean food web
3) Assess changes in these characteristics with fluctuations in physiochemical parameters

We can achieve this, even in small samples, because by analysing the isotopic composition of single amino acids, we can access signatures from different parts of the trophic process. By nitrogen isotope analysis of phenylalanine and glutamic acid we can assess the signature of the base of the foodweb and the trophic enrichment, giving relative trophic position[2]. For carbon isotopes differences seen between essential and non-essential amino acids and via pairwise analysis of particular compounds which allow the type of carbon source at the base of the system to be indicated. This is enhanced by companion radiocarbon analyses, indicating the degree of carbon recycling vs fresh carbon being utilised in the food chain.

The application of cutting edge chemical techniques has particular value if combined with biological and physiochemical techniques to provide a "whole system" picture[3]. This will allow a much fuller understanding of how these cryptic ecosystems function, and a much stronger ability to assess their fragility or resilience under different natural and anthropogenic pressures.

1. *Humphreys W. F. 2006. Aquifers: the ultimate groundwater-dependent ecosystems. Australian Journal of Botany54, 115–132.*
2. *Chikaraishi Y, Ogawa N. O., Kashiyama Y., Takano Y., Suga H., Tomitani, a., Miyashita, H., Kitazato, H. & Ohkouchi, N. 2009. Determination of aquatic food-web structure based on compound-specific nitrogen isotopic composition of amino acids. Ecol Res 7: 740–750.*
3. *Humphreys, W. F. 2009. Hydrogeology and groundwater ecology: Does each inform the other?. Hydrogeology Journal, 17(1), 5-21.*

Adaptive management applied to assessment of potential impacts of CSG to GDEs distal to operations

Chris Jones[1]
1. Arrow Energy, Brisbane, QLD, Australia

Arrow Energy Pty Ltd (Arrow), as part of its Federal environmental approval conditions for its proposed Surat Gas Project, is required to undertake assessments of the potential impact to groundwater dependent ecosystems (GDEs) as a result of potential aquifer drawdown and associated reduced groundwater availability. To address these conditions, Arrow has adopted the Model – Investigate – Verify – Manage framework to assessing potential impacts distal from coal seam gas (CSG) operations.

Arrow commissioned the development of a numerical surface water-groundwater model to identify any potential impact to GDEs from groundwater drawdown as a result of its proposed operations. The model indicated that the potential impact is immeasurable (mm/annum) compared to background variations (cm/day to m/annum).

Arrow proposes to undertake investigations to confirm the status of potential GDEs identified through a risk assessment. These potential GDEs were selected using a GDE likelihood matrix based on:

- depth to groundwater data,
- vegetation mapping and site observations,
- landscape position (hydrology/geomorphology),
- ecosystem ability to adapt to changes in groundwater availability,
- the scale of the impact in the watertable aquifer.

The investigation options currently being assessed include:

- undertaking a drilling program to identify local lithology/stratigraphy,
- monitoring for seasonal groundwater level/water quality variations,
- connectivity studies of the water table aquifer and underlying aquifers, and
- use of leaf water potential and soil water potential, in combination with stable isotopes of water to determine the depth at which vegetation is accessing water.

A GDE monitoring program will then be developed based on the outcomes of the investigations and model verification which may include ongoing groundwater and ecological monitoring.

DAY 3: Wednesday, 13 July 2017

PLENARY

When a Simple Model is Better. *Dr Catherine Moore, Senior Groundwater Modeller, GNS Science, New Zealand*

When is a simple model better?

Catherine Moore[1]
1. GNS Science, New Zealand

The predictions from models that inform decision making in environmental management and assess the risk of failing to achieve a desired environmental outcome must include estimates of the uncertainties associated with these predictions. These estimates of uncertainty are based in part on expert knowledge as expressed through the construction of the model, its boundary conditions, and its parameterization. This knowledge is typically defined stochastically, as is the nature of expert knowledge in environmental systems. Uncertainty information is also encapsulated in the historical behaviour of the system and is incorporated through the history-matching process. Models more reliably predict the range of future environmental outcomes if they have sufficient "receptacles" for these sources of information.

It follows that a model used in decision-making requires three components: a numerical model, a parameter estimation process wrapped around that model for history matching, and a model predictive uncertainty estimation process wrapped around these components. When considering these components, Kitanidis (2016) suggests a paradigm shift from models as simulators to models as receptors for data important to the decision-making process. He defines a good model as one which quantifies uncertainty and supports a comprehensive risk based evaluation of alternatives. Similarly, Nowak et al (2012) apply statistical methods to test the fitness for purpose of models in respect of decision making and the worth of decision-critical data used to inform these models.

More complex models provide "receptacles" for a greater amount of information. Unfortunately, we also observe that the long run times of complex models preclude running the model the number of times required for proper stochastic analysis. These same run times, accompanied by a tendency for numerical instability, often make the task of history-matching very difficult, if not impossible. We explore the gains and costs of model simplicity in the context of decision fitness for purpose and propose some metrics to be used in this analysis.

Posters

Tuesday 11 July – Thursday 13 July

A comparative examination of microbial activity in the hyporheic zone and boreholes at Maules Creek, NSW

Alexandra Auhl[1], Martin Andersen[1], Helen Rutlidge[1], Stefan Eberhard[1]

1. Connected Waters Initiative, UNSW Australia, Sydney, NSW, Australia

While many studies focus on either the hyporheic zone or aquifers, no previous studies have sought to compare these two different ecosystems within the same study. This research aims to compare microbial activity in both the hyporheic zone and boreholes. For two 4-6 week sampling campaigns (Spring and Autumn) at Maules Creek, Namoi, New South Wales, Australia, microbial activity was measured using the cotton strip degradation method in the hyporheic zone and adjacent boreholes. In the hyporheic zone, unprimed cotton canvas was affixed to rulers which were then placed in different habitats (dry bar, riffle and pools) at three different water regimes found at different sections of the creek (perennial-gaining, intermittent, and perennial-losing). Cotton strips were also deployed in 13 boreholes located adjacent to the creek. Microbial activity was calculated based on the loss of cotton strip tensile strength. The results of the study showed that microbial activity in the hyporheic zone was greater and slightly more variable compared to the more stable borehole environment. Microbial activity in the hyporheic zone was strongly correlated with the moisture-status of the site, measured during deployment and collection of the cotton strips. These findings may have implications for environmental impact assessments. Sampling for the purposes of environmental impact assessment is often limited to borehole sampling as it remains a simple and cost effective method, while the biogeochemical conditions and ecology of the hyporheic zone have been largely ignored. Incorporating hyporheic zone studies into environmental impact statements may provide a more comprehensive understanding of the ecosystem impacts of agricultural and mining activities.

A new approach method for groundwater quality management using background concentration

Hyeon-Jin Kim[1], Young-do Yea[1], Chul-ho Choi[1], In-su Baek[1]
1. Korea Environment Corporation, Seo-gu, Incehon, South Korea

In Korea, groundwater quality is managed depending on purpose of use which is drinking, household, agriculture, fishing and industry. Since it is not considered by natural groundwater status or aquifer management, only limited action such as stop using and close wells or keep using the wells with different purpose is possible when the groundwater is contaminated. It makes groundwater aquifer being left as it is and even getting worse. The objective of this study is to research and determine the background groundwater concentration and to assess the groundwater quality. In EU and USA, Groundwater Background Levels and Threshold Values decided by statistical method have been considered as one of the significant factor for groundwater management. After review of overseas cases, groundwater quality evaluation scheme using estimation method of background groundwater concentration and Groundwater Quality Standards as shown in fig 1 and 2 is conducted. 257 samples are analyzed in study area which is about 550 km^2 and consist of metamorphic and igneous rock. 64 samples remained after pre-selection and the background concentration is calculated by Cumulative Probability Distribution (CPD) and 90 percentile. All items in drinking water standards are determined and it is reflected in assessment of groundwater status of study area; 11.7 % of the area is good status (drinkable), 68.6% is moderate (drinkable), 11.9% is poor and natural status (not drinkable), 7.8% is poor and anthropogenic (not drinkable). As a result of pilot study, groundwater quality assessment and management should be reflected by natural local background concentration based on local hydrogeological characteristics to establish efficient groundwater quality management and reasonable use of groundwater.

Keywords: Groundwater quality management, background concentration

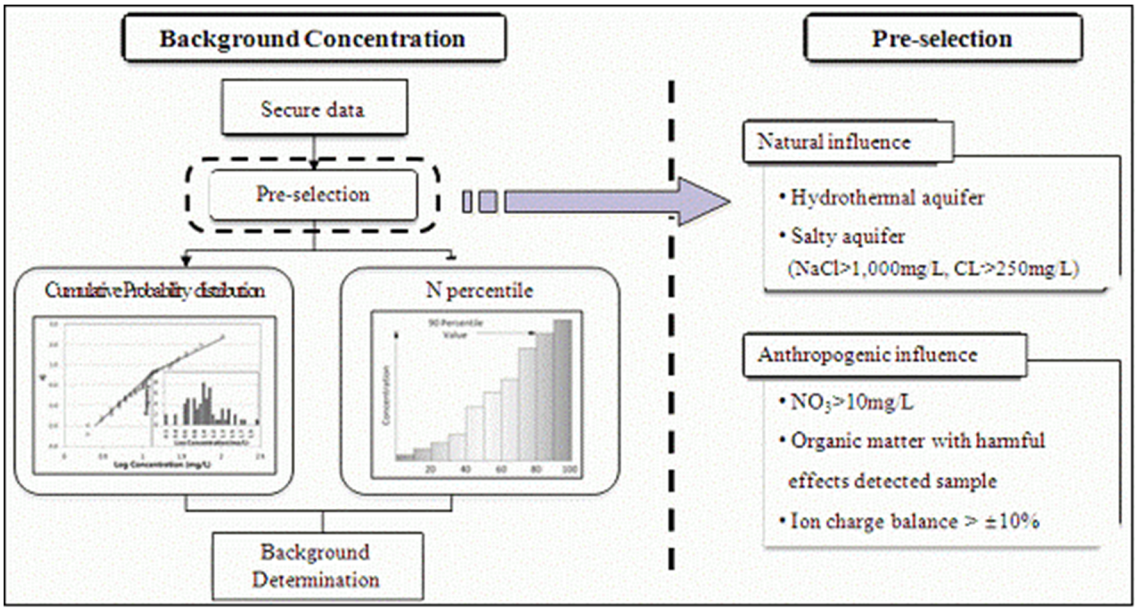

Figure 1. Background concentration determination process

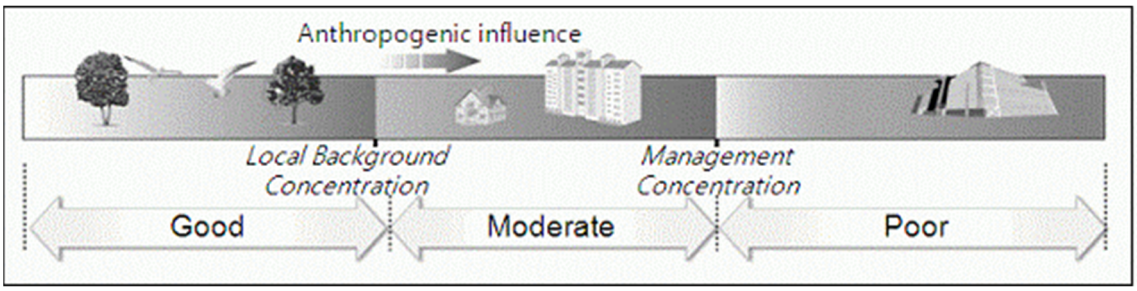

Figure 2. Assessment of groundwater quality assessment

Age and nature of calcrete accumulations in fluvial sediments: implications for regional groundwater dynamics and landscape evolution

John Magee[1], Ken Lawrie[1], Chris Harris-Pascsal[1]

1. Geoscience Australia, Symonston, Australian Capital Territory, Australia

In this study, petrographic and geomorphic analysis of unconsolidated river bank sediments was carried out to provide new insights into groundwater dynamics and lateral bank processes in the Lower Darling Valley. Quaternary geomorphology was mapped in 3D using LIDAR, AEM and temporal Landsat, validated by drilling and field observations. Riverbank calcrete distribution was mapped using boat-mounted photography; petrographic analysis used standard optical microscopy; calcrete ages were determined by radiocarbon dating. Three-dimensional mapping of the Quaternary fluvial systems has demonstrated that calcrete accumulations occur where the river incises relatively coarser-grained sediments in abandoned meander point bars, aeolian dunes or buried paleochannels. Petrographic study suggests that calcrete forms during groundwater discharge localised at river bank sites. Solutional features in calcrete and overprinting relationships with oxides and oxyhydroxides indicate that these discharge sites may also act as recharge sites for the alluvial aquifer. This supposition is supported by bore hydrograph data (Lawrie *et al.*, 2012). The age of calcrete accumulations cluster in periods of river migration identified by OSL dating of quartz grains. This study of the distribution of calcrete in the landscape demonstrates that groundwater-surface water interactions are discontinuous. This has implications for groundwater processes. Calcrete ages cluster in phases of river migration due to the greater likelihood of relatively coarser-grained sediments being exposed on the riverbank during periods of channel migration. Due to the resistance of calcrete to erosion, calcrete formation may play a significant role in controlling the morphology of the Darling River. The relationship between river morphology and calcrete accumulation in the river bank may assist in mapping and predicting sites of lateral bank recharge and groundwater discharge.

1. *Lawrie, K., Brodie, R.S.1, Dillon, P.2, Tan, K.P.1, Gibson, D.1, Magee, J.1, Clarke, J.D.A.1, Somerville, P.1, Gow, L1., Halas, L.1, Apps, H.E.1, Page, D.2, Vanderzalm, J.2, Abraham, J.3, Hostetler, S.4, Christensen, N.B.5, Miotlinski, K.2, Brodie, R.C.6, Smith, M.1 and Schoning, G. 2012 Assessment of conjunctive water supply options to enhamce the drought security of Broken Hill, regional communities and industries. Geoscience Australia record 2012/15*

An aquifer becomes an aquitard: centrifuge measurement of desaturating sandstone from the constrained zone above an underground mine

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2. Connected Waters Initiative Research Centre, UNSW, Sydney, NSW, Australia
3. Australian Centre for Sustainable Mining Practices, Sydney, NSW, Australia
4. UNSW School of Civil and Environmental Engineering, Sydney, NSW, Australia
5. University of Adelaide, School of Civil, Environmental and Mining Engineering, Adelaide, SA, Australia

Perched aquifer conditions often develop in the constrained zone overlying underground mines, due to dewatering of the mine workings. An inverted water table marks a transition from saturated un-fractured sandstone to an underlying unsaturated fractured zone. The objective of this research was to identify the relationship between vertical hydraulic conductivity (Kv), saturation (S) and suction (p) for a sandstone.

An AllegraX-15R centrifuge was fitted with custom made drainage cells (n=4) to test discs of sandstone (50 mm diameter, 5 mm thick) initially at >95% saturation with fresh water. The centrifuge speed was accelerated to provide increasing tension and drainage (300 to 2800 revolutions per minute), with the mass of drainage at the base of each cell measured after each acceleration step. The reduction of Kv with decreasing saturation (S) was observed for the sandstone (n = 8). On average, relative Kv values decreased by a factor of 10, as moisture content decreased from 16% (at maximum saturation) to 13%. For several sandstone samples, a small decrease in moisture content of 1-2% was associated with a 50% reduction in K_v values.

An empirical relationship of the volumetric water content (V), V = 0.015e^0.02p (r^2 = 0.9) was developed as a function of the suction (m H2O) applied within the centrifuge. To our knowledge this is the first time such relationships have been developed for consolidated rock. Further research is recommended to verify these observations and to model transient and non-linear drainage processes to calculate actual Kv values. These empirical relationships could be used to improve numerical models that include semi-saturated matrix flow processes. This research has demonstrated that partial desaturation significantly decreases the permeability and that the base of aquifers overlying mine workings can effectively become aquitards.

Assessing suitability of groundwater for drinking purpose - a study of Ahmadabad City

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2. Department of Civil Engineering, Pandit Deendayal Petroleum University, Gandhinagar, Gujarat, India

Witnessing lacunas in the overall water & wastewater treatment and management which includes 'unsatisfactory' treatment of Wastewater, ineffective Common effluent Treatment plant, mismanagement of Rain Water Harvesting (both groundwater Recharge and roof top rainwater Harvesting) and Depleting groundwater table, there is clear-cut indication of contamination of groundwater. As a significant portion of water demand is met through ground water, there was a dire need for a assessing the intensity of groundwater pollution across the city which host more than 75 lakh people. Addressing to need, the present study was initiated which focus on spatiotemporal analysis of the groundwater quality (in terms of Water Quality Index) the research work would give clues for the 'cause effect relationship' for groundwater pollution which would help the city administration to evolve suitable mitigation strategies.

A field campaign was done to collect the raw groundwater samples from different parts of the city representing different parts of the city representing different land use/land cover. A total of 28 samples were collected in the month of April, 2016, and were analyzed in laboratory for 8 parameters which were pH, TDS, Turbidity, Chloride, acidity, Hardness, alkalinity, Sulfate. Analysis was done by following the standard methods as presented by American public health association. Based on the observed correlation of a parameter along with the permissible limit on recommended by bureau of Indian standards, Water Quality Index was computed to assess the suitability of water for drinking purpose.

Table 1 Suitability based Classification of Water Quality Index

Water Quality Range	**Water quality**	**Number of samples**	**Percentage of Water Sample**
0-25	excellent	0	0
26-50	good	0	0
51-75	poor	9	31.03
75-100	very poor	17	58.62
>100	unfit for Drinking	3	10.34
0-100	-	29	100

Water samples were observed to have higher TDS than Desirable limit (500 ppm) that leads to higher water quality index. It shows that untreated water is not suitable for drinking purpose in urban community.

Broken Hill emergency water supply borefield investigations and production optimisation, Menindee, NSW

Nicholas Coulson[1], Marian Hart[1]

1. Water, Golder Associates, Milton/Brisbane, QLD, Australia

In 2016, in association with WaterNSW, Golder Associates assisted in the development of two emergency groundwater borefields, Menindee Lakes and the Talyawalka floodplain, to secure short term water supply for the residents of Broken Hill, Menindee and Sunset Strip (western NSW). The borefield locations were identified as a result of hydrogeological review; targeting the shallow, sand aquifer known as the Calivil Formation for water supply.

This paper discusses data collected during the drilling and hydraulic testing of the Menindee Lake borefield; as well as a GoldSim mixing model designed as an operational tool for the Menindee Lake borefield to predict the combined water quality from 12 supply bores. Groundwater variations were identified during the installation of the borefield through field parameters and water quality samples.

As there was limited total dissolved solid (TDS) data at each bore location, the TDS data was pooled into groups of bores partly based on water quality and location. The statistical distributions of these groups were input to a GoldSim mixing model as a distribution representing the range of TDS values measured within that group. This allowed for the prediction of future TDS from the borefield using a probabilistic framework that recognises the heterogeneous nature of water quality in the Calivil Formation. A stochastic data input element was used in GoldSim with resampling set at defined trigger periods throughout a model realisation. The final TDS of the mixed solution was estimated over time depending on the number of supply wells and predicted pumping rates, showing results as a statistical distribution of water quality.

The model was successfully used to predict water quality from various pumping scenarios to meet strict water treatment requirements for potable use.

Calcrete mapping and verification in the Murchison Palaeochannel system

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The Murchison palaeovalley (MPV) system is an arid basin covering an area of approximately 129 000 Km2 that was identified as one of six key priority project areas across Western Australia that required research to identify water sources to support population growth, agriculture and mining. The MPV project supports the WA Government strategic focus to assess and provide advice on groundwater availability to meet current and future demand. An airborne electromagnetic (AEM) survey was flown across the upper Murchison River catchment in early 2015. The survey collected 14,022 line kilometers of data, mapping approximately 52,000 square kilometres of the MPV system. The AEM survey data has been evaluated in association with geological and groundwater quality information sourced from more than 2000 existing boreholes across the MPV project area.

The Department of Water worked in collaboration with expert CSIRO geophysicists to process the AEM information using techniques that were developed specifically for this project.

The initial interpretation of these data indicates a wide range of saturated sediments with the value and useability of the groundwater dependent upon quality. Borehole information together with historic and observational data indicates that the best quality groundwater to be associated with calcrete outcrops located in the upper reaches of catchments. The calcrete forms transmissive horizons that enhance rainfall infiltration and groundwater storage.

The AEM data was processed with data including radiometrics and 1:250 000 geological mapping to identify near surface calcium carbonate (calcrete) deposits. A field evaluation project initiated to verify the accuracy of the mapped data showed these areas to have a complex nature and an exceedingly varied depositional history. The field evaluation project has improved mapping techniques and provides a means to better understand calcrete formation.

This paper will give an overview of the results of the field mapped versus remote sensed calcrete mapping.

Can land management intervention ameliorate the affect of geological impediments to groundwater flow in an upland NSW catchment?

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This research program aims to develop an improved understanding of natural processes of a sub-catchment undergoing landscape transformation and how the hydrology is impacted by changes in climate.

The Baldry Key Site is a 1.9 km^2 study site, located within the Little River sub-catchment of the Macquarie River. The catchment slopes to the north and is bisected by an ephemeral stream running north into Little River. The western side of the stream was planted to a eucalyptus plantation in 2001. Monitoring of components of the hydrological cycle including climate and groundwater began in mid-2003.

Equipotential lines of the fractured rock groundwater system in 12 bores indicate complex flow pattern. Initially the groundwater flows in a northerly direction in the upper part of the site. Flow direction begins to veer to the NNW approximately 250m up slope of the salt scald and flows to the NW in the middle of the scald. Water levels were similar across the slope in the upper and mid sections of the study site.

Analysis of monthly groundwater data from 2003 on the 12 boreholes using the auto-regressive model HARTT showed that the non-climatic trend was for the fractured groundwater system to fall between 136 mm/annum to 240 mm/annum. The highest and lowest rates occurred in the plantation with rates being higher on the upper slopes of study site.

The salt scald was caused by groundwater being interrupted in its flow north towards Little River by a sub-surface geological formation acting like a dam wall. The groundwater flow slowed and rose closer to the surface in the scald area as it found an alternative route down the slope. The planting of trees had little to no influence on the rate of groundwater movement, with its movement more strongly influenced by the underlying geological variability.

Carbon source and sink investigations in a Late Quaternary-age coastal limestone aquifer using radiocarbon of dissolved inorganic and organic carbon

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This study aims to investigate the inorganic and organic aspects of the carbon cycle in groundwaters throughout a freshwater lens and mixing zone of a carbonate island aquifer and identify the sources of carbon that dissolve in the groundwater. Groundwater samples were collected from shallow (5-20 m) groundwater wells on a carbonate island in Western Australia and analysed for inorganic ions, stable water isotopes ($\delta^{18}O$, $\delta^{2}H$), ^{3}H, ^{14}C and ^{13}C carbon isotope values of DIC and DOC. The composition of groundwater DOC was investigated by Liquid Chromatography-Organic Carbon Detection (LC-OCD) analysis. The presence of ^{3}H (0.12 to 1.35 TU) in most samples indicates that groundwaters on the island are modern, however the measured $^{14}C_{DIC}$ values (8.4 to 97.2 pmc) would suggest that the carbon in most samples is older due to carbonate dissolution and recrystallisation reactions. $^{14}C_{DOC}$ values (46.6 to 105.6 pMC) were higher than $^{14}C_{DIC}$ values and were well correlated with ^{3}H values. Deeper, saline groundwaters were characterised by an absence of ^{3}H, and lower $^{14}C_{DOC}$ values. The DOC composition of these groundwaters was found to be different to fresher groundwaters, with higher proportions of humic substances. The ^{3}H free, saline waters are hypothesised to be old, remnant sea water resulting from a sea level highstand that occurred between ~4.5 and 4.3 ka ago. This study shows that a combined approach utilising both DIC and DOC tracers, as well as ^{3}H, is required to identify the sources and evolution of carbon in groundwater, and the processes that effect the application of ^{14}C dating to groundwaters. This is important for understanding the evolution of groundwater resources and is essential for residence time calculations.

Characterisation and transformation of organic carbon in a connected river - groundwater system: an example from the Murray Darling Basin

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To improve catchment carbon budget models and to quantify climate change impacts we need to know where dissolved organic matter (DOM) is produced and consumed within aquifers and how it is exchanged between rivers and aquifers. Measurements of DOM in the river water, groundwater and sediments at Wellington Caves, NSW, Australia provide new insights.

Water levels in the river and aquifers were continuously measured. Water samples were collected along the river, from alluvial and karst monitoring bores, and from the caves. They were analysed for their water stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) and chloride chemistry, and we used UV absorbance and fluorescence spectroscopy to characterise the natural organic matter. The absorbance data were processed to provide the specific ultraviolet absorbance and spectral slopes. Parallel factor analysis was used to discriminate fluorescent components and assess their dynamics in groundwater and river water.

Groundwater levels are dynamic and respond quickly to changes in the river stage, and show that the river is predominantly losing. The chloride, $\delta^{18}O$ and $\delta^{2}H$ data demonstrate a direct hydraulic connection between the river and groundwater. The absorbance and fluorescence properties of DOM indicate higher molecular weight, chromophoric, and hydrophobic components in groundwater compared to river water, which has hydrophilic DOM with low molecular weight. DOM concentration, absorbance and fluorescence intensity rapidly decrease from the river water to the groundwater, suggesting the alluvial aquifer acts as a sink for the riverine DOM. We show that groundwater DOM is mostly derived from sedimentary organic matter, which has different characteristics compared to river-derived DOM. We present a conceptual DOM process model for intermittent rivers connected to karst alluvial aquifers that shows continuous processing of groundwater DOM from different sources along the flowpath. This model may be applicable to other alluvial systems and is important for research into carbon biogeochemical processing.

Characterisation of terrestrial ecosystem reliance on groundwater

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Understanding a terrestrial ecosystems' dependence on groundwater presents a significant challenge to decision makers during the development of a Project. This challenge is particularly prevalent in arid areas of Australia, where changes to the availability of groundwater may prove detrimental to the terrestrial ecosystems that rely upon it for survival. This study assess potential sources of water used by dominant flora species (Acacia papryrocarpa, Eucalyptus camaldulensis, Meleuca xerophylla) at three locations within a proposed Project site in South Australia's Arid Lands. Data collected in the field included groundwater levels, soil water potentials, leaf water potentials, and stable isotopes from soil water, plant xylem water and groundwater. Results suggest a degree of groundwater use by flora species, with indication of opportunistic uptake of rainfall and soil water when available. Groundwater utilised by the ecosystems is considered not to be from the regional groundwater flow system that the proposed Project will interact with, due to its high reported salinities. Groundwater utilised by flora species is considered to originate from surface water that has infiltrated during and after creek flow events, and entered shallow alluvial formations in the proposed Project area. Infiltrated surface water from creek flows are sporadic and typically seasonal in the proposed Project area, and therefore flora species are likely existing for long periods of time waiting for opportunistic uptake. This is considered to be the case for Melaleuca Xerophylla at Site 3, where highly negative leaf water potentials suggest a plant under stress, with its metabolic functions being kept at a minimum during a semi-dormant state. The conclusions drawn from this study were able to inform the Project owner and decision makers of the terrestrial ecosystem's dependence on groundwater, and incorporate the ecosystems potential fate in Project impact assessments.

Climate and groundwater recharge: the story from Australian caves

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Quantifying the timing and extent of diffuse groundwater recharge is crucial for our understanding of groundwater recharge processes. However, diffuse recharge is notably difficult to measure directly. Caves can be used as natural observatories of ongoing diffuse recharge processes, and speleothems (cave carbonate deposits such as stalagmites) as archives of past recharge. Cave records can improve our understanding of diffuse recharge in the context of climate change and past climate variability.

A long-term, national monitoring program of infiltration into caves has been undertaken since 2010 using a network of over 200 automated loggers. This has been supplemented by artificial irrigation experiments at one semi-arid site. The timing of past recharge can be determined from the periods of past stalagmite growth. Recharge characteristics can be elucidated from oxygen isotope composition, with increased ^{18}O likely caused by evaporative fractionation and increased ^{16}O from high intensity/magnitude rainfall events.

Automated logger data identify the diffuse recharge thresholds that vary with climate and geology. Both the logged data of natural events and the artificial irrigation experiments identify significant spatial heterogeneity in recharge in these karstified systems. Water infiltrating into the karst is often depleted in the lighter oxygen isotope due to soil and shallow subsurface evaporative fractionation. Speleothem deposition is more frequent during glacial periods, presumably because recharge thresholds are lower, and their isotopic composition provides evidence of the characteristics of the recharge process.

Caves provide direct access into the unsaturated zone. Direct observation of groundwater recharge can be used to complement data from the saturated zone (boreholes) and models. The heterogeneity of recharge in karst aquifers can be directly observed and quantified. Speleothems preserve a record of groundwater recharge that can extend back for hundreds of thousands of years, providing a long-term view on the timing and variability of groundwater recharge in Australia.

Combining geoelectrical and hydrochemical methods for dominant groundwater process determination: a saltwater intrusion study of a coastal aquifer in NZ

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Between August 2014 and August 2016, a long-term monitoring study of saline mixing within a shallow coastal aquifer along the west coast of New Zealand's lower North Island was carried out. Two main methods were used in order to determine the seawater intrusion potential and dominating seawater mixing processes at the site of interest. With geoelectrical time-lapse measurements along nine 2D profiles it could be shown that there is significant change in resistivity (± 40%), which correlates well to a seasonal change in total dissolved solids. Additionally, it was possible to show clearly opposite behavioural patterns in seasonal aquifer response between profiles situated in rural areas compared to those located in urban areas. Study of the groundwater chemistry with in-situ multi-probe and laboratory based ICP-MS measurements in 18 domestic bores was able to determine saltwater intrusion as a function of bore depth and distance from the coast. This confirmed the hydrogeological stratigraphy inferred from the geoelectrical models and supported the hypothesis of evapotranspiration/crystallisation being the dominant process within the saltwater affected part of the aquifer during summer as was drawn from the geophysical study. The combination of these methods clearly leads to a broader understanding of an aquifer system and is superior to using each method exclusively. Furthermore, the results of this monitoring project add significantly to the current knowledge about the dynamic behaviour of saltwater-freshwater systems in coastal aquifers which can be used for groundwater assessment in similar hydrogeological areas around the world.

Combining quantitative microbial risk assessment and groundwater modelling to investigate the risks of treated wastewater discharges to shellfish and bathers

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The Tanilba Bay Wastewater Treatment Plant discharges secondary treated and UV disinfected effluent via infiltration to shallow groundwater that flows to a nearby estuary of high value to the community for recreation and as an active oyster harvesting area.

MODFLOW groundwater modelling with analytical solute transport modelling and a Quantitative Microbial Risk Assessment (QMRA) were used to determine whether discharge to infiltration ponds is a safe disposal method in a highly sensitive receiving environment.

The MODFLOW numerical model determined particle residence times and pathways, which was coupled with a solute transport model to determine virus concentrations with distance using initial pathogens concentrations and biphasic decay.

Results were assessed using QMRA and compared to acceptable risk targets from the NHMRC Guidelines for Managing Risks in Recreational Water and using risk assessment models from drafts of the Australian Guidelines for Water Recycling and Australian Drinking Water Guidelines (in preparation). For the most exposed and at-risk cohort, children, the guidelines specify 0.6 viruses/L for less than 1% additional risk of gastrointestinal illness per person per event of recreational water activity.

For shellfish there is no agreed acceptable risk target, however the additional risk of gastrointestinal illness was quantified and compared to both a 1% additional risk of illness per person per meal criteria, as well as the 1 micro disability adjusted life year (mDALY) target as set out in the drinking water and recycled water guidelines (i.e.<1).

Conservative estimates of pathogen concentrations at the estuary boundary were 0.08 virus/L, more than seven-fold below the guidelines for primary recreation. With dilution in the estuary, final pathogen concentrations at the oyster leases was 0.0008 virus/L, representing a 0.14% increased risk of illness or an additional 0.7 mDALY.

Since the assessment was conservative it was therefore determined that acceptable risk benchmarks had not been reasonably foreseeable exceeded.

Concepts for groundwater level and storage condition reporting on a state-wide scale

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This project had the objective of developing an approach to reporting on groundwater levels and storage within aquifer systems throughout Victoria, to provide an understanding of the health or condition of a groundwater resource, targeting a varied audience.

To achieve this outcome, a reporting concept was developed using pared back hydrogeological principles, consultation with technical specialists, and consideration of the functionality and format of reporting outputs.

Hydrogeological principles were the focal point for both confined and unconfined groundwater systems, adding factors of influence to help 'build the story', such as groundwater development (use), rainfall recharge, depth to groundwater, proximity to waterways, saturated thickness of the (unconfined) aquifer, land use and changes to land use, and climate variability. These factors helped to define a baseline (or trigger) level on which management levels could be set, with specific confidence limits and review periods defined.

Consultation with academia and industry was paramount in developing a robust approach, or tailoring multiple approaches to specific hydrogeological settings.

Given the broad scale assessment (state-wide), this study applied statistics (normalisation of groundwater level data to provide a meaningful hydrograph output) to develop 'spatial suites' that comprise spatial areas containing groundwater monitoring bores that exhibit a comparable underlying hydrograph response. Suite hydrographs were developed and used to represent a much larger suite area. The Victorian Aquifer Framework was used as a basis in this process.

Application of principles was undertaken through 'proof of concept' case studies, which used actual groundwater level and abstraction data managed by the Victorian Government.

This project assisted the Victorian Government in developing robust techniques to report on groundwater level and storage condition. With further work, these approaches could be implemented to simplify government's management of groundwater resources, through assessment of trends and highlighting areas where conditions are 'not expected'.

Conceptualising groundwater processes of Willochra Basin, South Australia

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In light of anticipated further development in regional areas and subsequent increases in demand for water, a better understanding of South Australia's non-prescribed groundwater resources is required. There is also uncertainty of the impacts associated with a changing climate on the groundwater resources, existing developments and groundwater dependent ecosystems. As the lead agency for water resources management in South Australia, DEWNR undertakes groundwater assessments aimed at identifying new sources of water and improving our understanding of developed resources to ensure they are appropriately managed.

The Willochra Basin extends north from Melrose in the Flinders Ranges. Good quality groundwater (<1000 mg/L) in the southern half of the basin has been developed for town water supply, lucerne irrigation and stock and domestic supplies. However, the extent and recharge rate of good quality groundwater has remained uncertain. In this study, water level, salinity, hydrochemistry and radiocarbon age data were acquired to improve the conceptual understanding of the basins' hydrogeology and groundwater recharge processes.

Potentiometric contours and salinity maps have been refined. Hydrogeochemistry data and radiocarbon age dating have helped elucidate recharge processes and groundwater flow paths. Major ion analysis suggests recharge to the fractured rock aquifers in the streambed of Spring Creek, and from there it then flows into the basins' confined aquifer. All lines of evidence support a revised conceptual model of contemporary recharge of good quality water in the current climate.

The results of this study have reshaped the conceptualisation of recharge processes and groundwater flow paths of Willochra Basin. The identification of contemporary streambed recharge implies climate dependency on sustainable groundwater resource development. The sustainability of future extractions should be evaluated in light of the new knowledge.

Current and historical water use estimation for the GAB, Queensland

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As part of developing a water balance for the GAB and to inform water management policies, current and historical water use estimates were required. The historical and water use estimate involved consideration of artesian, sub-artesian bores which are utilised for a range of purposes, including stock and domestic, industrial, mining, town water supply and agriculture. Consideration in the estimate towards 'free-flowing' bores, bores capped / piped under saving schemes such as GABSI and abandoned bores was also required. For the current water use estimate, a previously developed method by OGIA for the Surat CMA was adopted, adapted and scaled to include the remaining portions of the QLD GAB and provide an estimate on a bore-by-bore basis. The historical water use involved a more complex approach, with consideration given to the declining pressure in artesian bores. The primary data used in the assessment was from the DNRM Groundwater database, utilising bore types, conditions, status, flow estimates and yields. The results of the assessment provided a water use time-series from 1900 to 2015 for the aquifer groupings adopted by the study. Due to the large spatial extent of the GAB in QLD, current water use was presented using spatial mapping comprising 50kmx50km grid of the water use. The assessment resulted in historical water use profiles, and estimates of current water use presented in visual format which has provided valuable information and an alternative approach to assist water management of the GAB in QLD.

Development of an updated Meteoric Water Line for Tehran, Iran

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The Local Meteoric Water Line (LMWL) is the relationship between the hydrogen and oxygen isotopes (δ^2H and $\delta^{18}O$ respectively) in precipitation and is the reference point for isotope investigations at a local area. The International Atomic Energy Agency (IAEA) have been collecting the Global Network of Isotopes in Precipitation (GNIP) since 1961. The GNIP is the primary source of δ^2H and $\delta^{18}O$ data in precipitation globally. The GNIP data gives critical information about the water cycle and enables a variety of hydrological processes and impacts to be studied. However, in most developing countries there is no (or limited) active stations where isotope data samples can be collected. For example, in Iran, the most recent rainwater isotope data was collected more than a decade ago in 2004. Therefore, an update of δ^2H and $\delta^{18}O$ and the LMWL is urgently needed for Iran, especially for Tehran, which is a rapidly growing urban center within Iran. In this paper, an update of Tehran LMWL is published. This update is based on one-year of data collected in 2014 and 2015 from Tehran's rainwater and analyzed by IAEA. Regression results for the 32 samples yielded a LMWL defined by the equation LMWL (δD) = 7.83 $\delta^{18}O$+5.23 (r^2 = 97%) based on ordinary least squares regression (OLSR) method and δD=8.18 $\delta^{18}O$+10.60 (r^2 = 97%) based on precipitation amount weighted least squares regression (PWLSR) method. The updated LMWL equation presented here will be useful for future studies in this area that use stable isotopes to determine surface-water and groundwater interaction and sources of groundwater recharge.

Drilling and bore construction leading to false arsenic and molybdenum positives

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Molybdenum (Mo) and Arsenic (As) are two redox sensitive ions, often associated with pyrite and organic matter in reducing aquifers. Redox conditions in the aquifer can, however, be temporarily altered through the introduction of oxygen during drilling and well construction. This can potentially lead to false positive As and Mo detections or false negatives when sampling groundwater following drilling.

Here, we present one such scenario, where strongly elevated Mo as well as As concentrations were measured following the installation of irrigation wells in the municipality of Lithia in central Florida, despite the groundwater being generally low in As and Mo (Pichler et al. 2017). In this study, we propose conceptual models, which can explain elevated As and Mo concentrations induced by the drilling process. We evaluate these conceptual models through the application of a reactive transport modelling framework which takes the mineralogical data and the geochemical time series data for the site into account. We explore the processes which can lead to false positive detections of redox sensitive species following the introduction of oxygen into anoxic aquifers due to bore drilling and construction. This includes As and Mo release following pyrite oxidation and organic matter mineralisation triggered by the drilling process. We show the time dependence of elevated concentrations and demonstrate that complexation to neo-formed hydrous ferric oxides as well as dilution due to background flow reduces concentrations over time and allow sampling of representative groundwater samples after a set time period.

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Economic, social and resource management factors influencing groundwater trade: findings from Victoria

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In Victoria, most groundwater resources are fully allocated and so opportunities for new groundwater development or substitution for increasingly expensive and scare surface water can only occur through trading of license entitlements. Even in the 2008/9 drought year, groundwater usage exceeded 50% of the available licensed volume in only a few groundwater management areas. Moreover, between 50 to 70% of individual license holders use less than 5% of their allocation each year. However, little groundwater trading is occurring at present, so this study investigated what factors were influencing the uptake of groundwater trade in Victoria

In 2015/16, 3 focus group meetings were followed by interviews with 34 groundwater license holders and 5 water brokers to learn how participants were experiencing the developing Victorian groundwater trade market and asked them to identify barriers to trade. Using social research methods, the survey data contained insights into the circumstances of each groundwater user, financial factors, experience with administrative processes and people's thoughts about the resource and trade management rules.

Water brokers and irrigators who have successfully traded noted that the demand and market is small, and there are few participants interested in trading, often due to factors such as unrealistic selling prices, expensive technical appraisals and burdensome administrative requirements and fees, especially when compared to surface water trading.

Groundwater trade could be facilitated by refining groundwater management plans, providing improved information, simplifying transaction processes and decreasing costs, as well as through demonstrating good resource stewardship and preventing third party impacts from trade. However, there are numerous individual circumstances that inhibit groundwater trading, so it is unlikely that policy and process changes alone can increase usage rates without greater demand for groundwater or more favourable farming economic circumstances.

Emerging contaminants and the science-policy nexus: a PFAS case study from Williamtown, NSW

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In NSW, water pollution is defined as introduction of anything into waters that changes their chemical, biological or physical nature. This obliges the NSW Environment Protection Authority to regulate all non-trivial impacts of water pollution on the environment, including potential impacts from emerging contaminants which lack robust environmental guideline values.

This paper outlines the scientific data informing the NSW Government's policy around per- and polyfluoroalkyl substance (PFAS) contamination originating from RAAF Williamtown. The discussion is framed in the context of the State Government's advice to minimise local community exposure to PFAS, implemented as a precautionary measure while the Commonwealth Government conducts its site characterisation, risk assessment, and remedial works at the base. The precautionary advice is underpinned by a diverse array of hydrological, toxicological, and geospatial data including Defence-commissioned studies, State-conducted investigations, and advice from the Williamtown Expert Panel and technical Working Groups.

Here, development of key scientific inputs are discussed, including: the regional-scale conceptual model of PFAS transport from the base; the maximum likely impact area from hydrological and contaminant transport principals; and, the Investigation Area boundary – a geospatial product synthesizing hydrological and cadastral data to support Government's community engagement efforts. Additionally, the challenges public-service scientists face when providing policy-ready scientific advice in the face of evolving guideline values are examined.

Factors affecting dissolved organic carbon in coastal groundwater systems

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Balancing the terrestrial global carbon budget has proven to be a significant challenge. Whilst the movement of carbon in the atmosphere and riverine waters has been extensively studied, the potential for organic carbon to desorb/adsorb from mineral surfaces and act as a groundwater organic carbon source/sink, is poorly understood.

To investigate the biodegradable component of groundwater dissolved organic carbon (DOC), groundwater samples were collected from six wells located on Rottnest Island, WA. Wells were selected to cover a range of DOC ages and concentrations in a carbonate aquifer. Water quality parameters such as pH, electrical conductivity, temperature, dissolved oxygen were measured in the field. Samples were analysed for their biodegradable DOC content using spectrofluorometric techniques at set intervals within a 28 day period.

Further to this, we examined the conditions and processes affecting DOC at a coastal wetland in Anna Bay, NSW. Four multilevel samplers (MLS's) were installed in a transect with 1m spacing, with a distance of up to 3 m from the wetland edge. Two samples were taken from each MLS and analysed for DOC, dissolved inorganic carbon (DIC), anions and cations using LC-OCD, spectrofluorometry, UV-Vis and FIA techniques.

This research forms part of an ongoing project which will assist in identifying the factors affecting the mobilisation, transport and removal of DOC in uncontaminated groundwater. By quantifying the processes, we can then determine whether the groundwater is a carbon source or sink. Importantly, this information will help guide policy and identify the need to include groundwater resources as part of the carbon economy.

Fecal indicator bacteria near the shoreline at freshwater beaches

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Beach sand near the shoreline acts as a reservoir for fecal contaminants with fecal indicator bacteria (FIB) often orders of magnitude higher than in adjacent surface waters. Elevated FIB (*Escherichia coli* (*E. coli*), enterococci (ENT)) concentrations in the surface water can lead to beach water quality advisories. This study combines field measurements with numerical modelling to investigate the physical processes controlling the accumulation, distribution and release of FIB in beach sand. *E. coli* and ENT were measured in the pore water across two beaches on Lake Huron and Lake Ontario with samples collected up to 2.3 m depth below the water table. A numerical model simulating wave-induced groundwater flow recirculations coupled with microbial transport (using colloid filtration theory) reproduced the overall measured FIB distributions at the two beaches. The model was then applied to assess the impact of various factors including beach slope, sediment type and wave height on FIB accumulation. The infiltration zone width, average infiltration velocity and infiltration rate were shown to ultimately control the amount and spatial distribution of FIB in the sand. Study findings are important in identifying factors controlling the accumulation and release of FIB in beach sand at freshwater beaches and thus ultimately reducing health risk at beaches.

Geochemical characteristics of arsenic contaminated groundwater in hydrothermal alteration zone

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Ministry of Environment (MoE) and Korea Environment Corporation (K-eco) install and operate the National Groundwater Quality Monitoring Network all over the country for sustainable management of groundwater quality. Through this monitoring network, highest arsenic concentration ranged from 0.014 to 0.083mg/L has been detected consistently since 2011 in deepest well in Muan City three wells (each depth are 10, 30 and 83m) installed in to monitor background groundwater quality in 2010. The Mann-Kendall trend test with arsenic data in confidence levels of 90% showed increasing trend, which is expected to arsenic contamination of groundwater. In this area, bedrock is located under 6.5m from surface and consists of metamorphic rock (calc-schist and dolomitic limestone) mainly. To examine the effect of interaction between groundwater and rock in aquifer, geologic survey and groundwater quality analysis such as field survey, thin section analysis, X-Ray Diffraction (XRD), Inductively Coupled Plasma (ISP), Scanning Electron Microscope (SEM) and Electron Probe Micro-Analysis (EPMA) were conducted. Pyrites (FeS_2) were found easily at overall depth of in-situ core. Pyrites were grown heavily in hydrothermal alteration zone of geologic boundary of metapsammite. Result of geologic investigation, it indicated that arsenic is observed on surface of some pyrite and weathered iron oxide. In case of groundwater, arsenic were detected 0.001~0.018 mg/L at 19 samples among totally 60 samples. Geologically, 12 samples located in metapsammitic rock area, 9 samples located in volcanic rock area, and 1 sample located in granitic rock area. Result of geological investigation and groundwater analysis shows that groundwater quality is affected by geologic environment according to the depth and oxic/anoxic environment of groundwater. In case of study area of arsenic contaminated groundwater in hydrothermal alteration zone, it could be managed strictly by prohibiting utilization and groundwater development or installing water treatment facilities.

Groundwater residence time in the Condamine River Alluvial Aquifer (SE-QLD)

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Many gigalitres of groundwater have been extracted from the Condamine River Alluvial Aquifer (CRAA) since the 1960s. These groundwater withdrawals have stressed the system and locally altered the groundwater flow paths. Isotopes can provide powerful insights into recharge pathways, flow direction, and the sustainability of groundwater withdrawals from alluvial aquifers. To address some of the regional groundwater concerns we must characterise alluvial groundwater residence time.

A total of 31 groundwater samples were collected from privately owned irrigation bores and Qld-DNRM government monitoring bores in the region between Condamine Plains and Dalby. Parameters analysed included: ^{3}H, $^{14}C_{DIC}$, ^{222}Rn, $^{87}Sr/^{86}Sr$, $\delta^{13}C_{DIC}$, water $\delta^{2}H$ and $\delta^{18}O$, sulfate $\delta^{34}S$ and $\delta^{18}O$ as well major, trace and REE elements.

Distance from primary recharge areas (rivers) provides the main control on groundwater residence time in the CRAA. This is supported by the following observations:

1) Groundwater between the Condamine River and its northern branch has low TDS (~400 mg/L), is Na-HCO_3-type and has detectable ^{3}H, indicating a proportion of modern recharge (<70 years);

2) Groundwater east of the northern branch has higher TDS (~700 mg/L) and is Na-$HCO3^{-}$ -type with increasing eastern inputs. No ^{3}H is detected and ^{14}C shows sub-modern groundwater (~500 years);

3) Groundwater along the eastern and western boundaries of the alluvium or samples retrieved from the Walloon Coal Measures (WCM) have high TDS (1,250-19,770 mg/L) and are Na-Cl-type. Residence times in the upper WCM increase along the flow path to the west from modern to 32,000 years on the western side.

Groundwater residence time distributions provide a visualisation of recharge processes and delineate areas where groundwater withdrawals are less sustainable within the CRAA.

How much does improved aquitard characterisation matter when predicting groundwater impacts from unconventional gas extraction?

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Proposals for unconventional gas developments typically involve predictive modelling of potential impacts on a groundwater flow system. The hydraulic properties of aquitards represented in such models are typically poorly constrained. The present study sought to demonstrate to what degree, if any, improved estimates of aquitard properties altered the sensitivity and uncertainty of predictions produced by a groundwater flow model.

This study used an existing groundwater flow model of coal seam gas extraction in an eastern Australian basin as the basis for the quantification of prediction uncertainty. Predictions generated by the model included the magnitude and timing of maximum drawdown in a confined aquifer. Laboratory analyses of core porosity–permeability relationships were combined with downhole neutron-density logs and upscaled using analytical and numerical methods to derive an improved basis for identifying the uncertainty of aquitard vertical hydraulic conductivity (K_V) values. Monte Carlo sampling from specified hydraulic parameter prior distributions was used to estimate the uncertainty of modelled predictions before and after improved characterisation of aquitard K_V values. Global sensitivity analysis metrics were used to assess the sensitivity of predictions to a range of hydraulic properties, prior to and following improved aquitard K_V characterisation.

The inclusion of improved aquitard properties resulted in reductions in uncertainty for three of the four predictions. These predictions were sensitive to the vertical hydraulic conductivity of one of the two aquitards represented in the model. Conversely, the uncertainty of predictions of the spatial extent of drawdown was increased after the revision of aquitard properties.

More generally, this study serves as a demonstration of the use of Monte Carlo methods for the assessment of prediction uncertainty. In addition, global sensitivity analysis metrics can be used to comprehensively identify key relationships between predictions and model parameters. Such relationships may then be used to guide future data collection.

Hydrogeochemistry applied to mineral exploration: a new initiative in northern Australia

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Mineral exploration in Australia currently faces the challenge of declining discovery rates despite continued exploration investment. The UNCOVER roadmap, produced by stakeholders from industry, government and academia, has highlighted the need for discovering mineral systems in areas under cover. This is where prospective basement is covered by regolith including transported sediments, challenging many traditional exploration methods that rely on outcrop sampling. Groundwater-rock interaction in the subsurface has the potential to impart both geochemical and isotopic characteristics to water that may persist over time and space (down the groundwater flow path). Geoscience Australia's minerals hydrogeochemistry project, part of the Exploring for the Future Programme, aims to use groundwater chemistry to better understand the bedrock-regolith system and develop new methods for recognising mineral system footprints within and below cover.

This work will be conducted in selected areas to identify the best chemical indicators to use with various mineral systems. Initially targeting areas of shallow cover near known mineral deposits and in barren areas, the project will then extend into deeper under cover regions to develop diagnostic tools. Focus areas will be up to three 1:250,000 scale map sheets, targeting existing groundwater bores that ensure good spatial coverage. The Tennant Creek and McArthur Basin regions have been identified as initial focus areas.

In addition to the standard measurements such as bulk parameters, major anions, major cations and trace elements, selected groundwater samples will be analysed for a comprehensive suite of isotopes (e.g. Sr, Cl, I, C, O, S, H, Pb, Rn), organics and hydrocarbons, and dissolved gases. All data will be released to the public. If suitable chemical indicators can be recognised and mapped spatially, hydrogeochemistry can become a successful, more widely used exploration tool in Australia with the capability to identify and target parts of mineral systems undercover.

Impact of fire on hydrological and chemical signatures in Karst Vadose Zone Water, Wombeyan Caves, New South Wales, Australia

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Impact of wildfire on karst-vadose-zone hydrology and hydrogeochemistry is hard to evaluate owing to the complexity of subsurface environment. The aim of this study is to understand the variation of hydrogeochemical components and drip discharge in response to a moderate-intensity 10m x10m experimental fire above the shallow Wildman's Cave at Wombeyan, Australia, in May, 2016. Water isotopes and cation analyses were conducted on drip waters collected pre- and post-fire. Ongoing drip water collection began in Dec, 2014. And drip rate has been monitored continuously using acoustic data loggers. Discharge into cave is discontinuous, indicative of limited soil and karst storage. The post-fire drip data demonstrate decreased duration of recharge, with approximately x3 increase in peak discharge, which we hypothesize is caused by the decrease of soil-storage capacity. Water isotope compositions have significantly changed after fire, with d^2H isotope composition up to ~56 per mil lower and $d^{18}O$ ~6.3 per mil lower in the week after fire. With time, isotopic values return to pre-fire values. We hypothesize that this temporary depletion in water isotopic composition reflects a combination of post-fire rainfall isotope composition, loss of pre-fire evaporatively enriched soil and shallow karst stored water.Drip water concentrations of bedrock-related elements (Calcium, Strontium) and soil-related elements (Zinc, Nickle) decreased after the fire. We hypothesize that these reflect the loss of soil and soil biological activity above the cave, and agree with a decrease of soil storage capacity. This research demonstrates that even in complex hydrogeological settings, understanding the impact of local wildfire on subsurface system can be improved through the combination of drip water hydrograph analysis and geochemical analysis. This will provide opportunities to broaden the insights into improved fire management in karst environments and a better understanding of the relationship between surface environment conditions and vadose zone hydrology.

Implementing an alternative to metering in the Shepparton Irrigation Region

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During the millennium drought, groundwater licence holders in the Shepparton Irrigation Region began surrendering their licences to use groundwater due to difficulty accessing the resource as water levels declined and costs to maintain their licences increases. In this region, groundwater extraction provides not only a valuable resource for irrigators to use, but also benefits land and salinity management. To maintain these regional benefits and the incentives for licence holders, groundwater resource management needed to change.

Historically, groundwater management in the Shepparton Irrigation Region, an area that applies to groundwater to depths of 25m below ground surface, was intensive and included metered extraction. Intensive management is costly to implement and cost recovery comes from licence holders.

In 2015, Goulburn-Murray Water in consultation with groundwater users and stakeholders implemented an adaptive management plan that included the removal of metered groundwater use. Switching to an adaptive style of management that included the removal of metering requirements allowed Goulburn-Murray Water to reduce the costs to licence holders substantially.

Groundwater use by licence holders in the Shepparton Irrigation Region is now estimated from a combination of historic use, climate conditions and metered use in the nearby Katunga Water Supply Protection Area.

The adaptive management approach allows for potential use outside of groundwater licences to be identified by reports of groundwater interference. Since the implementation of this approach, no reports of interference have been received.

Removing the requirement to meter groundwater use in the Shepparton Irrigation Region provides licence holders with more incentive to maintain their licences, and provides a benefit to regional land and salinity management by pumping groundwater during periods of high water tables.

Further assessment is required to determine whether licence holders are maintaining their licences and the social implications of removing metering requirements.

Improved unsaturated zone conceptualisation for more robust modelling of groundwater recharge and evapotranspiration

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In the steadily expanding world of the numerical models used for assessing groundwater, the effect of surface variables, directly correlated to groundwater recharge through the unsaturated zone, has been simulated with many different methods. Simple representations are preferred for computationally intensive uncertainty modelling, but physically realistic representations are required for accurate outputs. Finding a way to improve the representation of this correlation is of essential importance for the calculation of recharge, particularly where remote sensing data is used to improve recharge estimation. In this paper, a simplified approach to simulate the water flow through the vadose zone is linked to a groundwater model.

Specific attention is dedicated to the mechanism of evapotranspiration (ET), which is one of the most important variables in arid environments. Percolation, which eventually becomes recharge, is also extensively investigated.

It is expected that a vertical lumped approach can satisfactorily estimate the water flow through the unsaturated zone and, due to its intrinsic simplicity, will allow a straightforward calibration of parameters using, e.g., PET data that are available. A three-dimensional groundwater model is then combined with this vadose zone model, to obtain spatiotemporally distributed recharge values and water table levels.

The trade-off between the complexity and precision of such a model is examined via a test case in the Limestone-Coast and Murray-Basins in South-Australia. These areas are characterized by a heterogeneous interaction between vegetation and a generally shallow groundwater. The model is calibrated with data of potential and actual evapotranspiration, values of soil moisture, and a network of observation bores.

This paper is expected to provide a flexible model that can effectively be applied for data scarce regions where remote sensing is the only source of information, which is a useful tool for decision makers.

Increased application of the Resource Condition Limit approach to managing groundwater extraction in South Australia

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As part of a broad process of improvement to South Australia's water planning and management system, efforts have been made by the Department for Environment, Water and Natural Resources (DEWNR) to survey and synthesize the current approaches to setting extraction limits within groundwater management areas. Setting a volumetric limit safeguards the water property rights system in South Australia, and is based on defining acceptable levels of risk to the groundwater resource and associated users. The review of current technical approaches has provided recommendations that can be incorporated into DEWNR's forward work-plan for water planning, facilitating well-planned and efficient use of public funds. Specifically, a number of technical studies recently completed for the Barossa, Adelaide Plains, and Tatiara groundwater resources have highlighted the increasing use of the Resource Condition Limit (RCL) approach. This is due to the increased need to address the uncertainties that arise from the water-balance approach that has been extensively used, and to evaluate the likely impact of climate change projections. The review also highlights the potential of the RCL approach for a greater level of community engagement in the process of capping extraction from an area and in managing extractions accordingly.

Measuring multi-directional 3D-flow fields using active heat pulse sensing in the streambed

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Vertical temperature profiles using the 1D analytical solution are now widely used to determine hyporheic flow patterns and hydraulic dynamics within the shallow streambed sediment. One of the challenges in using a limited number of measurements to characterize processes that are essentially 3D has been the determination of the horizontal or lateral flow components and how these vary in magnitude, as well as spatially. This study used a portable 56 sensor, 3D temperature array with 3 heat pulse sources (the hot rod) to measure the flow direction and magnitude up to 230 mm below the water-sediment interface in sedimentary environments ranging from fine silt to coarse gravels. Short heat pulses, typically 1 minute in duration were injected at one of the three heat sources and the temperature response was monitored over a period of 20-30 minutes. Breakthrough curves from each of the temperature sensors was analysed using a heat transport equation and an optimization function was used to estimate flux in three directions to determine the dominant direction and magnitude at the point of observation. Measurements were also conducted in a sand tank under a range of controlled hydraulic conditions to validate the method and to compare the results with a numerical model. The robust design of the hot rod and use of short duration heat pulses provides a rapid, accurate assessment technique for determining dynamic and multi-directional flow patterns in the hyporehiec zone and understanding biogeochemical processes at the water-streambed interface.

Modelling of groundwater flow and geomechanical stresses near rock bolts in an underground mine

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One of the major failure modes of bolts in underground mines is Stress Corrosion Cracking (SCC) in which bolts fail due to the combined influences of tensile stress and a corrosive environment. SCC of bolts is primarily driven by groundwater chemistry and biological activity that facilitate corrosion. To investigate the conditions promoting groundwater flow and stress near installed bolts, the groundwater flow and stress in grout surrounding bolts, and surrounding rock strata are modelled using a 2D finite element technique. The model domain (15 m width by 15 m thick, with ~11,0000 elements) include a single 2m grouted steel bolt in the roof of a 5 m^2 roadway with coal, clay, sandstone, and shale as the major rock types. Forty seven different rock strata configurations and nine different grout conditions are studied. The parameters of the models are set based on data from a mine in New South Wales of Australia including material properties, hydraulic conductivity, joint properties, in-situ stresses and boundary conditions. Discharge flowrates are measured at the interface between the grouted bolt and the roof. The results indicate that coal strata contains the highest groundwater discharge flow and also existence of a clay band intersecting in the bolt results in a higher discharge flowrate. It is observed that grout failure and loss result in higher groundwater discharge and consequently enhanced SCC. It is also observed that the absence of grout in upper section of the bolt leads to a high tensile stress to the bolt suggesting that improper grouting and/or grout damage contributes to the tensile stresses and flowrate that cause SCC. The results of this study provide a better understanding on the conditions contributing to SCC failure in bolts and also assists in advancing solutions for preventing SCC bolt failure.

More than just a 'tick the box' exercise: why geology is the key to hydrogeological and hydrochemical investigations

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Geology is a major driver of hydrochemical and hydrogeological processes, including recharge and groundwater-surface water interactions. However, geology remains an under-utilised resource that is increasingly only addressed marginally in hydrogeological or hydrogeochemical investigations to 'tick the box' of providing some background geological information. Here we provide an example from the Condamine River catchment (south-east Queensland) that highlights benefits of integrating hydrogeological and hydrochemical data with a comprehensive analysis of the geological framework. This work demonstrates how such integrated approaches can help to avoid shortcomings and misconceptions in conceptual hydrogeological models.

We have developed a three-dimensional geological model through application of state-of-the-art 3D geological modelling software packages GoCAD and SKUA (Paradigm Geophysical Pty Ltd®) using information from more than 15,000 groundwater and exploration bores. Unlike previous 3D geological model developments of the Condamine River catchment (which often focused on the characterisation of deeper sedimentary bedrock units) this newly developed model provides a more accurate depiction of the geometry of shallow and deep aquifers, focusing on the important interfaces between the alluvium, volcanic bedrock and sedimentary bedrock. The conceptual understanding forms the basis for development of an initial conceptual hydrogeological model. This hydrogeological model has been tested using independent lines of evidence, including a recharge assessment, development of potentiometric surface and head gradient maps and an assessment of hydrochemistry.

The integration of multiple techniques, the refinement of aquifer geometry understanding, and the interfaces between shallow and deep aquifers have all been used to provide new insights into the spatial variability of the connectivity between shallow alluvial and volcanic aquifers and the underlying sedimentary bedrock aquifers. The study also highlighted limitations of groundwater quality monitoring bore networks, which often do not target areas identified as likely areas of interactions between shallow and deep aquifers based on the assessment of the geological framework.

Natural Sequence Farming - reconnecting the stream to its flood plain aquifer, what have we learnt so far

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Natural Sequence Farming (NSF) modifies streamflow by installing instream structures to decrease the velocity of the streamflow and re-connect it to the flood plain. This work aims to determine if these structures affect the stream-flood plain groundwater connectivity.

A series of instream structures (leaky weirs) were constructed in 2006 and 2007 along a flood plain reach of Mulloon Creek. Groundwater levels and electrical conductivity (EC) are being monitored through a network of 13 boreholes located at 3 cross sections on the floodplain, which were installed in 2008. Water level and EC are also monitored in the ponds which intersect each borehole transects.

Equipotential lines indicate that the groundwater flows in a north north-east direction towards the outlet of the study area and does not interact with the stream. However, during the wet winter of 2016 the groundwater flowed from the hills on the east and west of the stream towards two groundwater sumps located at the top and bottom of the reach. Each sump is located 30-50 m west of the stream. Equipotential lines do not indicate any connection with the stream.

Across all the bores the EC of the alluvial groundwater varied from 156-954 µS/cm. During the 2016 wet winter, EC of the groundwater varied from 76-635 µS/cm. The EC across and down the flood plain is variable.

During the 2016 wet winter, the EC of the stream increased marginally along the monitored reach from 61 µS/cm to 69 µS/cm at the outlet. When flows are low, the EC increases from 93 µS/cm to 140 µS/cm at the commencement and outlet respectively.

The connection between the water in Mulloon Creek and its floodplain groundwater is tenuous. This may be explained by the low hydraulic gradient between the stream and the floodplain and the complexities of the floodplain sedimentary sequences.

Pesticide residues in groundwater from rice, cotton and vegetable growing areas and its impact on human health

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Crop wise, in India the consumption of pesticides are found highest in cotton i.e. around 37%, followed by paddy (20%), while the vegetable consumes about 9% pesticide residues. Farmers often spray hazardous insecticides like organophosphates and organochlorine up to five to six times in one cropping season while only two applications may be sufficient. A study was thus undertaken to analyze the contamination by pesticide in groundwater samples collected from tubewells installed in the farm fields of vegetable, rice and cotton growing areas.

Groundwater samples collected from vegetable growing areas were found contaminated with 31.3% organochlorine and 19.4% samples with organophosphorous pesticides above MRL value. All the synthetic pyrethroids analyzed were found below MRL value.

Groundwater samples collected from rice growing area and the variety grown there was 11/21. Samples were found contaminated with 24% by organochlorine pesticides, 23.4% by organophosphorous pesticides and 20.8% by synthetic pyrethroids above MRL value.

Samples collected from cotton growing area 59% were found contaminated with organochlorine pesticide, 45.3% by organophosphorous pesticide and 29.2% by synthetic pyrethroids residues which were above MRL value.

Diseases caused by organochlorine pesticides are loss of sensation around the mouth, hypersensitivity to light, sound, tremors, nausea, vomiting, nervousness etc.

The adverse health effects caused by organophosphorous are increased salivation, perspiration, narrowing of the pupils, nausea, diarrhea and fatigue. Pyrethroids can cause an allergic skin response, and cause cancer, reproductive or developmental effects, or endocrine system effects.

There is need of proper extension services to educate farmers about the judicious use of new molecules of pesticides along with Integrated Pest Management approach to avoid contamination of water resources.

Qualitative and quantitative imaging analysis of fines induced permeability damage during water flow

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Fines migration is known as one of the mechanisms of permeability alteration during water disposal or artificial aquifer recharge processes (McDowell-Boyer et al). However, there is limited direct evidence of fines migration during water flow. This paper presents conclusive evidence for the fines migration and resultant permeability damage using 3D micro-CT imaging assisted experiments.

A single phase flooding experiment was performed on a Berea sandstone core plug in multiple steps. Firstly, a micro-CT image of the dry core plug was taken before flooding. Then the core plug was saturated with 4% NaCl brine, followed by the injection of deionised water. The pressure drop across the core plug was monitored during the injection of 4% NaCl brine and deionised water, and produced water samples are analysed for particle concentration and type by combining particle counting methods and SEM-EDS analysis. After the flooding experiment the core plug was reimaged and the second micro-CT image registered to the first to quantify the fines migration. Laboratory measurements show an order of magnitude drop in permeability during deionised water injection, which was associated with large concentration of produced fines in the produced water samples. SEM-EDS analysis of the core plug and fines shows that clay particles were mobilized during deionised water injection, some of which blocked the pores and others were produced. Navier-Stokes equation was solved on the 3D images to compute absolute permeability. The computed permeability on the micro-CT image before the experiment matches with the experimentally measured initial permeability. The computed permeability on the image after the experiment shows a permeability drop by a factor or 2.5 due to fines straining near the core outlet.

The proposed experimental approach can be used in designing key parameters like injection rates, well location and well completion for water disposal or aquifer recharge processes.

1. *McDowell-Boyer, L. M., Hunt, J. R., & Sitar, N. (1986). Particle transport through porous media. Water Resources Research, 22(13), 1901-1921.*

Quantifying impacts of groundwater pumping using a nonlinear transfer function time-series model in the southwest Victoria

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Assessing the impacts of groundwater abstractions is an essential part of groundwater resources management. Traditionally, the assessment has been undertaken by using numerical groundwater models such as MODFLOW. However, meaningful numerical groundwater modelling requires reliable information on hydraulic property, aquifer geometry and other data sets (e.g. recharge) which are often not available. Furthermore, numerical groundwater modelling is often resource-intensive, time consuming, and it is not practical for day-to-day groundwater management (e.g. assessing interference from pumping wells). This paper extends an approach which uses a nonlinear transfer function groundwater time-series model (Peterson & Western 2014; Shapoori et al. 2015) to assess impact of groundwater pumping on groundwater head. The time-series model consists of a soil-moisture layer to account for non-linearity between rainfall and recharge, and several pumping response functions to account for pumping from production wells (freely available in HydroSight http://peterson-tim-j.github.io/HydroSight/). With only observed groundwater hydrograph, groundwater pumping information and climate data as input data, this approach can separate the contribution of climate and each production well on groundwater level variation.

This approach was applied to the Nullawarre Water Supply Protection Area in the southwest Victoria. The model clearly separated the contribution of climate and each of over 60 production wells on groundwater level variation. The results showed that the impact of the increasing groundwater abstraction on the groundwater level trend has been negligible across the study area over the period from 1985 to 2015. The slightly declining trend in groundwater level was primarily due to climate variation. While this application has demonstrated that the time-series model was an effective and robust tool for assessing impact of groundwater abstraction, there were uncertainties associated with inaccurate input data, in particular estimates of the daily groundwater pumping rates. Accounting for these uncertainties would help to avoid unintended and undesirable management decisions.

Queensland Aquifer Framework: 2016 version

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The Millennium drought and increased demand for water throughout Australia placed the water supply infrastructure of the day under considerable stress. In response the Bureau of Meteorology (BoM) was given the role of compiling and delivering Australia's water information under the conditions set out in the Federal Water Act 2007.

To achieve this the BoM developed the Australian Water Resource Information System (AWRIS) and the National Groundwater Information System (NGIS) to support AWRIS. Implementation of the NGIS hinged on the development of a National Aquifer Framework (NAF) and each state and territory was tasked with developing an aquifer framework for incorporation into the NAF.

The Queensland Aquifer Framework (QAF) uses a three-tiered system of grouping individual geologic units. The three tiers are defined as:

- Geologic Unit (GU): Smallest mapped geological feature.
- Hydrogeologic Unit (HGU): One or more GUs with similar hydrogeological characteristics.
- Hydrogeologic Complex (HGC): A collection of HGUs with similar broad hydrogeological characteristics.

The QAF was developed using the best available geological mapping data and literature at the time to create a list of GUs that provided the foundation for creating the QAF.

Grouping and assigning HGUs to GUs was performed at group, subgroup or formation level and took into consideration age, dominant rock type, spatial extent, and geographic location of the GUs. Grouping of HGUs was performed based on age, hydrogeological characteristics and the geologic province or basin that the HGU forms part of, to create HGCs used in the QAF. Flexibility was built into the QAF to accommodate changes in geological mapping and naming.

Ongoing revision of the QAF is essential in maintaining the NAF and facilitating data migration from the Queensland Groundwater Database to the NGIS. The NGIS is a vital component of the AWRIS and underpins many groundwater products developed by the BoM.

Seasonal dynamics of residence times in a perennial, wastewater impacted stream

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Some organic micropollutants are so stable that they occur in high concentrations in treated wastewater that is discharged into streams. They also persist in surface waters for relatively long periods. Investigating the timescales over which these contaminants circulate through the streambed is a first step required for a better understanding of their persistence in our environment. Previous research has shown the importance of considering diurnal variability of surface discharge on the fate and transport of these compounds; however, seasonal changes can also be important, especially in arid climates where dilution occurs during the wet season, while summer months are characterised by high solar radiation and air temperatures.

In this study, we conducted approximately one-hour continuous salt tracer injection experiments during the wet and dry seasons (September 2016 and March 2017) in a small perennial, wastewater-impacted stream in South Australia. The data were first analysed using the solute transport model OTIS. Analysis of solute breakthrough curves over five stream reaches within approximately two kilometres showed strong variations in residence time distributions and hyporheic zone properties along this short stretch of the stream. Challenges of using this simple model included the strong correlation between transient storage and dispersion; therefore, sensitivity analysis was needed to better determine parameters. Ongoing work to better differentiate streambed parameters is discussed.

Stable isotope composition of precipitation and groundwater in a wet-dry tropics karst area (East Sumba, Indonesia)

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The present study aims to provide insight into the characteristics of carbonate aquifers supplying springs used by local households in the small coastal Larawali and Kadahang catchments of East Sumba. It is thought that the aquifers are predominantly recharged by rapid flow through fractures and that rain water and ground waters would have similar isotopic signatures. The main objective of this study was to test this assumption by analysing the stable isotope compositions of springs, shallow wells and rainfall within the catchments.

Wells, springs, rainfall collection sites and one surface stream were sampled multiple times during the wet season of 2016-17. Samples were extracted from wells and streams using a top-weighted *Hydrasleeve* no-purge sampler and analysed by cavity ring-down spectrometry (Picarro L2130-i) for δ^2H and $\delta^{18}O$ at the Environmental Chemistry and Microbiology Unit, Charles Darwin University, Darwin.

Results did not consistently fall along meteoric water lines, suggesting potentially different water sources or that groundwater samples represent a mixture of sources. Rainfall samples were depleted in $\delta^{18}O$ relative to the local meteoric water line (LMWL), indicating they may have originated from high intensity rainfall events that were depleted in the heavy isotopes (influenced by the "amount effect"). Streamwater was significantly more enriched in both isotopes than rainfall, indicating the probable effect of evaporation. By contrast early wet season well and spring samples fell on the global meteoric water line. This could indicate a different source or origin of these waters.

Stable isotope analyses in isolation cannot give us a good understanding of recharge processes. Repeated field campaigns for stable isotopes analyses with the addition of major ion analyses and geological survey will provide further insight into the characteristics of these wet-dry tropical karst aquifers.

The groundwater commons game (Part II): unravelling the evolution and dynamics of compliance with groundwater conservation

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Groundwater management depends on the effective collaboration between water agencies and users. Beyond agreeing on sustainable levels of extraction, a key challenge is that extraction rules are followed. Yet experience has shown that compliance cannot be taken for granted. Enforcement—monitoring compliance and punishing infractions—has been essential to foster cooperation and reduce illegal extractions; yet it is a costly undertaking that often erodes trust between users and authorities. These issues are exacerbated in large groundwater basins due to the sheer number of users and limited resources available for regulatory action. In this context, new methods to study rule-adherence and rule-breaking behaviour are of great interest and value to groundwater management practice globally. The "Groundwater Commons Game" (GCG) is a novel approach to explicitly address these issues and help managers to better understand how rule-breaking behaviour can be discouraged. To this end, we use agent-based simulation to synthesise well-known principles of human cooperation and collective action, and to couple physically-based groundwater models with models of human behaviour grounded on the World Values Survey. The GCG, for the first time, reveals how culture drives groundwater conservation at the global scale. We focused on quantifying the likelihood of compliance emerging under regulated and nonregulated conditions, and how cultural values affect the speed at which compliance norms spread and their stability. Our results suggest that non-enforcement measures, such as leadership programs that engage a small fraction of compliance champions, could trigger more rapid responses to groundwater depletion (and its associated impacts) compared to enforcement. Similarly, we quantified the deleterious effects that a minority of rule-breakers can have on groundwater conservation. Overall, our work highlights the need to incorporate agent-based modelling into the groundwater toolkit as a way to progress towards systematic modelling of coupled human and groundwater systems.

The nature and origin of groundwater salinity in the Muttama Catchment, NSW, Australia

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Groundwater salinity is a major issue across the world due to its adverse impacts on environment and agricultural productivity. Several types and amounts of salts from diverse sources can be dissolved into groundwater system, as this water system interacts with different processes along its flow direction. Understanding the hydrogeochemical processes or sources of dissolved salts in groundwater is vital for an effective salinity management plan. In this study, the groundwater hydrochemistry of Muttama catchment (1059km^2), in southern NSW, Australia, is used to investigate the nature and origin of solutes, causing groundwater salinity. Major ion chemistry together with physicochemical parameters of groundwater were measured at mostly two month intervals over a two and half year period (December 2013 to February 2016) from twenty two piezometers across the catchment.

Most of the groundwaters in the Muttama catchment are Na-Cl dominant except for a few, which are Ca-Cl type water. At low salinity locations weathering of aquifer substrates (up to 53% of total dissolved solids) influences the composition of the groundwater. However, cyclic or evaporated salts with minor weathering inputs are most likely the primary source of solute in the high saline groundwater. Furthermore, evapotranspiration processes could concentrate the salt concentration in some shallow groundwater systems, particularly on the western side of the catchment. The hydrochemistry in this catchment is more variable in space than in time, suggesting that aquifer substrate is a major determinant of the salinity. The outcome of this study will assist to improve the current management strategy in order to mitigate groundwater salinity in the Muttama Catchment.

The role of dissolved organic matter and groundwater biogeophysical processes in the carbon budget

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Atmospheric CO2 concentration is acknowledged to play an important role in climate change. However, quantifying more accurate predictions requires a sound understanding of the cycle and process of carbon especially in the environment. There has been extensive research on terrestrial carbon and the different conditions where it is a source or sink. However, the knowledge on whether groundwater organic matter is a carbon source or sink is limited. This work will explore the dynamic of groundwater organic matter including both its concentration and its rate and extent of biological processing and sorption. The UNSW Wellington Research Station was selected for groundwater sampling as it represents a fractured rock aquifer and alluvial aquifer for groundwater property and interaction investigation. Samples were collected from a transect of boreholes perpendicular from the river. Literature procedures were adopted for determining biological dissolved organic carbon and investigation of organic matter sorption on pure minerals (quartz sand, iron-coated quartz sand and calcium carbonate). For each sample collected total dissolved organic concentration was measured and the organic matter present was characterized by fluorescence spectroscopy and size-exclusion chromatographic technique, LC-OCD. There was greater sorption of organic matter with calcium carbonate, followed by iron-coated sand, while minimum sorption was observed with sand. This research in conjunction with similar studies in different environments will allow conclusions to be drawn groundwater organic matter and whether it is a carbon source or sink and thereby the findings can eventually have some policy application which will enable the management of the groundwater resources as part of the carbon economy.

The use of airborne EM/3d modelling to reinterpret the carbonate aquifer, and its relationship to seawater intrusion/sustainable yield in Exmouth

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Exmouth is a regional centre located 1260km north of Perth, Western Australia that relies entirely on groundwater for its water supply. The Exmouth bore field extracts groundwater from an unconfined carbonate limestone aquifer within the Cape Range Group. Groundwater flows easterly from the Cape Range to Exmouth Gulf where it discharges above a saline wedge at the base of the aquifer. The current extraction from the bore field does not have capacity to meet increased water demand due to population growth and the influx of tourists in holiday periods.

In 2016-2017, the Water Corporation decided to undertake an investigation to optimize bore field performance through improved production from existing infrastructure. A desktop review, an Airborne Electromagnetic (AEM) survey, 3D modelling, and pumping tests, helped define the extent/geometry of the saltwater interface and karstic features within the aquifer.

The AEM survey effectively mapped the location of saline water. It identified existing bores screened in areas with lower salinity and twenty four hour pumping tests of these was undertaken at rates much higher than their current extraction rate. The survey also identified existing bores in areas of higher salinity where increased extraction was not recommended.

A new conceptual 3D model was created using Leapfrog Hydro [tm] from all historic and recently acquired data. The new model identified the major karstic features within the aquifer system, as well as detail about the screened lithology for each bore, and their proximity to these karstic features.

The new model and the AEM survey have established a clear relationship between the extent of the saltwater interface and the location of the karstic features. Importantly bores have been identified which could accommodate additional sustainable extraction, and other bores where extraction rates should be not be increased, or should be reduced.

Using packers to improve loading/barometric efficiency estimates in low permeability formations

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Water levels in many open monitoring wells fluctuate in response to changes in barometric pressure. The change in water level expressed as a fraction of the change in barometric pressure is termed the barometric efficiency (BE). For a shut-in monitoring installation, the change in pore pressure divided by the change in barometric pressure is called the loading efficiency (LE). By measuring how LE or BE vary with frequency or time following fluctuations in barometric pressure, we can infer if conditions are confined, semi-confined or unconfined. In addition, specific storage and drained compressibility can be estimated from LE or BE in confined and semi-confined formations. These parameters are important for incorporating into models used to predict the impact of groundwater extractions.

Low hydraulic conductivities (K) or large monitoring well diameters increase the time for monitoring wells to equilibrate with pore pressures. These time lags may be so long that BE cannot be adequately assessed in open monitoring wells. This study shows how packers can be used to reduce time lags to enable reliable LE assessments. Two examples are presented from the Mooki River catchment, New South Wales. Estimates of BE from an open monitoring well installed in a confined, high-K formation matched shut-in LE estimates. By contrast, BE could not be satisfactorily assessed in an open monitoring well located in a low-K confining layer due to time lag. For this site, a reliable assessment of LE was made from a short, 24-day monitoring period by sealing the monitoring well with a packer. The shut-in LE response showed that conditions were confined and enabled estimation of specific storage and drained compressibility. We conclude that short periods of shut-in monitoring can enhance our understanding of hydrogeological conditions and potentially provide hydraulic parameters to improve groundwater models.

Water & mining: the importance of good geological data

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Water is critical for mining operations however, there are many competing demands placed upon water supplies including agriculture, industry, towns and the environment. Over the past decade or so the mining sector has been the centre of increased attention surrounding water use and management.

With the population of NSW expected to increase from 6.9 million to 11.8 million over the next 40 years there will be increased demands on a finite water supply. This demand is exacerbated during drought conditions, adding enormous pressure to already stressed water resources, potentially requiring difficult decisions by the water regulators regarding water allocations.

With the current and increasing pressure on NSW water resources, it is important to: (1) understand the likely water requirements for potential new mines prior to a mine development application being lodged, (2) assess the potential impacts of existing and proposed mines on the water resources, (3) develop a standardised water reporting framework, and (4) use policy and regulation to maximise water efficiency and reduce drought-related risks to supply. This will ultimately lead to improved regional water management that considers the requirements of all competing water users in a region.

The Geological Survey of NSW (GSNSW) is in a unique position, as the custodians of the State's geoscientific data, to help characterise the groundwater systems and the potential impact mining may have in those areas. In this capacity GSNSW is providing 3D geological models and geological data to the NSW Office of Water for their Water Monitoring Strategy – to better understand groundwater behaviour. The GSNSW is also assessing mine water balances to understand the water requirements and usage in coal and metalliferous mines.

Why do soil scientists and hydrogeologists so often have completely different groundwater recharge estimates? How to resolve the discrepancy

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Groundwater recharge to a hydrogeologist is equivalent to deep drainage to a soil scientist. They should be equivalent, but in many circumstances the predictions differ greatly, leading to uncertainty in system understanding and potentially unreliable conceptual and numerical models. This paper explores some of the reasons these discrepancies exist, and suggests approaches for practitioners and water resource managers to achieve alignment despite the different approaches to analyse a system.

Groundwater recharge is a key parameter that affects groundwater behaviour. Hydrogeologists commonly estimate recharge by analysing groundwater level data with rainfall data using soil-water balance methods. Soil scientists typically focus on characterising soil-water behaviour in the near surface zone, often with multi-layer soil-water balance models.

Discrepancies generated when relying on deep drainage estimates derived from lumped parameter models are often apparent when conducting impact assessment of irrigation schemes. Often these projects do not have the resources to undertake detailed soil and groundwater modelling and calibration, and therefore judgment-based decisions and interpretation are required.

There are some simple checks of model outputs that can be performed (but rarely are) to verify model predictions are reasonable. For example, deep drainage estimates could be compared to recharge estimates made using calibrated groundwater models which simulate groundwater level fluctuations (e.g. from government groundwater models).

There is no single method that will produce good estimates of recharge in all cases. However, estimating recharge using an integrated approach by linking groundwater level fluctuations to recharge would reduce uncertainty in the assessment of the sustainability of irrigation schemes.

It is important that water resource managers are aware of the different approaches used in system conceptualisation and modelling when assessing and interpreting model predictions so that the soil-water regime of the system is well represented and any outcome based decision making can be done with greater confidence.