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Wendy Timms
Deakin University

Devmi Kurukulasuriya
Deakin University

Bill Howcroft
Deakin University

Ellen Moon
Deakin University

Karina Meredith
ANSTO, Institute of Environmental Research

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WATER TRACER TECHNOLOGIES TO DETECT SOURCES OF SEEPAGE AND PROTECT ENVIRONMENTAL ASSETS

Wendy Timms[1], Devmi Kurukulasuriya[1], Bill Howcroft[1], Ellen Moon[1] and Karina Meredith[2]

ABSTRACT: Water tracer technologies can help optimise water management in coal mining operations and improve outcomes from environmental studies and controls to protect sensitive assets. ACARP project C28024 (Stage 1) is demonstrating how tracer analysis of groundwater and surface water can provide information on whether systems are hydrologically disconnected, partly connected or well connected. This stage of the project is focusing on conventional tracers that are often used by other mining industries around the world (e.g. iron ore, potash) and in groundwater resource studies. Stage 2 of this project proposes to test new artificial tracers combined with suitable conventional tracers that are particularly useful for identifying seepage sources for control actions.

This paper will demonstrate and discuss the benefits and limitations of major groups of conventional tracers that are commonly measured naturally in water. These include: field parameters (e.g. electrical conductivity, temperature), major and trace ions (e.g. metals), stable isotopes of oxygen and hydrogen, industrial compounds (CFCs and SF6) and dissolved carbon isotopes (i.e. inorganic and organic forms). In addition, this paper will discuss radioisotope tracers (e.g. tritium, carbon-14 and radon-222), as robust and proven tools to help differentiate shallow and deep groundwater where there is a contrast in water residence time (groundwater 'age'). These tracers can provide useful information on seepage, despite higher analysis costs and turn-around times for laboratory results.

Key findings from demonstration mine sites show the importance of combining physical water measurements (e.g. water levels and pumping rates) with a suitable combination of water tracers, depending on the site specific issues or study questions. For example, artificial tracers that are added to water sources are most suitable for identifying seepage and rapid flow pathways that can be a risk to underground operations. However, common artificial tracers such as added salts and dye tracers can also raise community concerns, such as producing flourescent green creeks. Novel artificial tracers are able to overcome these risks. For example, synthetic DNA with uniquely designed fingerprints can be released at different times and locations to identify the sources of water to excavations can then be controlled.

Commensurate with the risks of the project, a combination of suitable tracer technologies of different types can increase the confidence in identifiying water sources and flow rates underground. However, the costs, limitations and practical challenges of each proposed tracer should be considered in planning tracer studies. The outcomes of these ACARP projects will assist coal mining operators in deciding on the suitable combinations of tracers for different types of operational and environmental risks associated with underground mining, and show how tracer technologies can be used to check possible flow paths in conceptual and numerical models.

BACKGROUND

Water tracer technologies can help identify seepage sources for target controls and improve the outcomes for environmental studies and controls to protect sensitive assets. Underground mining assets need to be protected from flooding of the workings, whilst water resource assets such as surface waters and wetlands can be sensitive to relatively small losses of water. Identifying the source of groundwater flows to excavations, for example, from a mix of lateral inflows in a coal seam, and vertical seepage from specific overlying aquifers, is a first step in adaptive management of groundwater.

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[1] *School of Environmental Engineering, Deakin University, Waurn Ponds, VIC, 3216, Australia. Email:* wendy.timms@deakin.edu.au *Tel: +61352278692*

[2] *Australian Nuclear Science and Technology Organisation, Institute for Environmental Research, NSW 2232, Australia*

Water tracers are naturally occurring hydrochemical, isotope or dissolved gases in water or soil water. These environmental tracers can be used to 'fingerprint' water sources and can show distinct zones of water due to hydraulic separation or partial disconnection. Importantly, these tracers are averaged over time (eg. years, decades), and spatially at scales that can be useful to verify numerical models. Water tracers provide a missing link between current hydrogeological-geomechanical approaches and environmental conditions. The resource industry would benefit by quantifying flow and mixing that cannot be distinguished by other methods with the accuracy and confidence of multiple tracer technologies.

This paper is part of ACARP project C28024 (Stage 1) providing background information on types of water tracers, along with applications and benefits. Examples of mine locations where water tracers have been used are presented, along with steps to decide on suitable water tracers. Two water tracers studies at underground coal mines in Eastern Australia demonstrate selected water tracers for the purpose of a) evaluating potential for surface water-groundwater interactions and b) evaluating how much modern water has seeped to a deep coal seam that would naturally contain 'old' water that is drained for longwall operations.

Applications and benefits of water tracers in mining

Water tracers have many applications that can benefit mining at various stages from feasibility to operations and to mine closure.

Some of the applications for water tracers include the following:

1. Identifying source(s) of flow to a void
2. Evaulating hydraulic connectivity and surface water-groundwater interactions
3. Evaluating hydraulic disconnectivity - effectiveness of aquitards and hydraulic barriers
4. Aquifer recharge - age or residence time, sustainable yields
5. Aquifer interference – estimating seepage between aquifers
6. Water mixing - quantifying water mixes, discharge or baseflow in surface waters

Water tracer tools should be considered commensurate with risk, with water tracers increasingly utilised if there are operational risks of inflow to mining voids, and/or there are environmental risks to water assets (Timms et al. 2012). For example, water tracers could complement water information as part of the evaluation of proposed projects or expansions near particularly sensitive water resources and Groundwater Dependent Ecosystems (GDEs).

State of the art in water tracing tools means choosing from an increasing number of different water tracers, and the latest in appropriate tracer technology that will be useful to quantify water flows and aquifer storage. However, requirements for proponents to use specified tracers (e.g. carbon-14) may may limit useful outcomes (e.g. water-coal effects on carbon-14 may require advanced data interpretation). The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) has provided advice to decision makers for a number of coal projects in NSW and Queensland that, rather than being prescriptive, a range of suitable environmental tracers can be considered for some projects (advices are publically available at www.iesc.environment.gov.au).

Some of the many benefits of using water tracers include:

- support corporate environmental responsibility and social licence to operate
- contribute to regulatory and community engagement using leading water technologies
- strengthening the science around potential environmental effects of mine water
- evidence of different water sources in mining voids, reduce risk to operations
- improve effectiveness of water treatment technologies by quantifying source types
- differentiate non-mining and mining effects on surface waters near mine sites

- constrain computer models where parameterisation and boundary conditions are often uncertain with a range of possible model outcomes
- improve evaluation of differences in empirical and model predictions and a gap between geomechanical and hydrogeological approaches
- assist with evaluating potential aquifer interference and cumulative impact
- contribute to multiple lines of evidence on the degree of hydraulic connectivity or disconnection

While there are clearly many possible benefits to using water tracers in mine water studies, multiple lines of evidence are essential. Thus water tracers can complement, not replace, other geological and hydrological information including monitoring of water levels and flows.

International and Australian mining examples of water tracers

Water tracers are increasingly utilised in mining studies locally and internationally (Figures 1-2), and across several mining sectors including iron ore, uranium, metal and coal mining. There have been several coal mining related water tracer studies in China, the USA and Australia. These selected examples of tracer studies in mining areas include feasibility studies for mines, operational mines, and sites closed and being restored, however may not be comprehensive, particularly as some water tracer studies are not publically available.

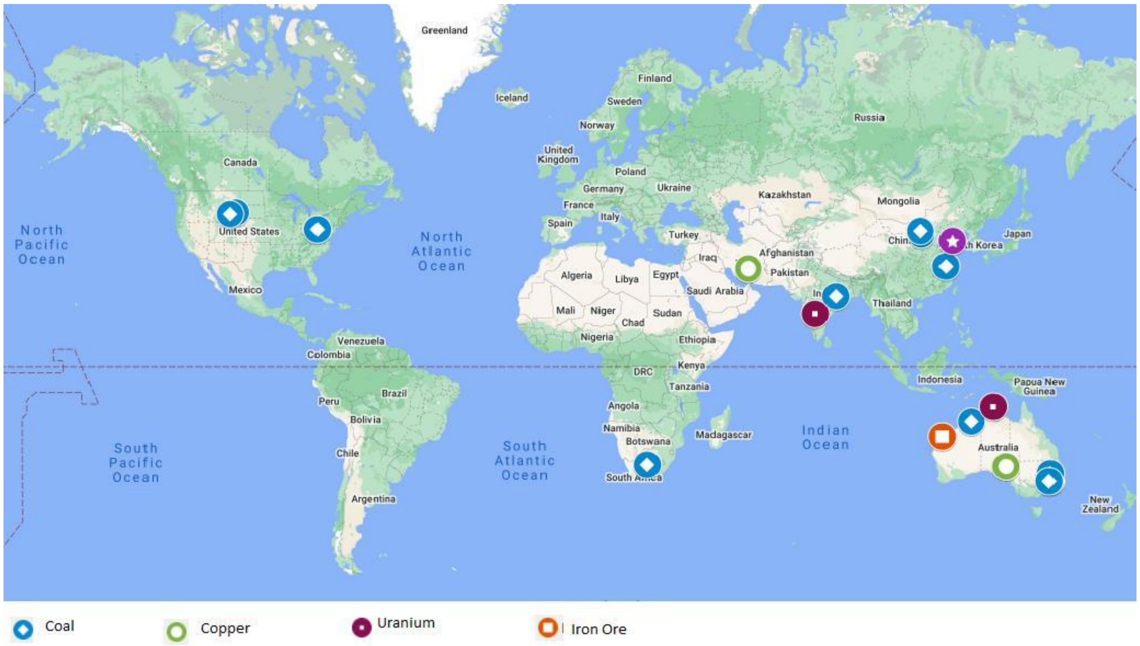

Figure 1: International examples of mine study locations using water tracers

Open cut coal mines have used hydrogeochemical tracers while other resource industry studies such as ACARP C11050 have recommended tracer and isotopes forfor management of mine closure. Isotopes have been used to trace biogenic nitrogen ($^{15}N/^{14}N$) in coal seam gas (Saghafi et al. 2012)) and helium gas to evaluate connectivity above a longwall panel . A more comprehensive review of publically available reports of water tracers applied in the various mining resources sectors is currently being finalised.

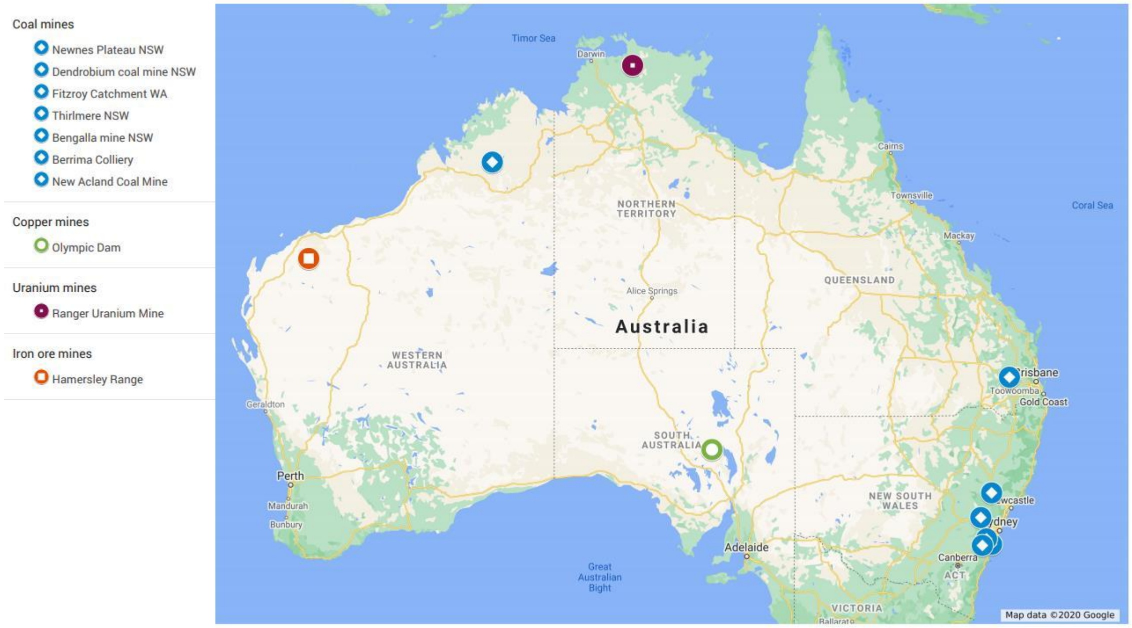

Figure 2: Australian examples of mine study locations using water tracers

CONVENTIONAL TRACERS

Conventional tracers use physical aspects of the water molecule, dissolved ions or dissolved gases in water, even if influenced by human activity. In contrast, artificial tracers involve the intentional addition of chemicals or substances such as a dye or salt tracer. This stage of the project is focusing on conventional tracers. Table 1 summaries general groups of conventional water tracers, provides examples, relative costs and priority questions or applications for each mine site.

Field water quality parameters (Electrical Conductivity (EC), pH, temperature, dissolved oxygen (DO)), are widely employed in hydrogeologic investigations, are low in cost and, can be measured at the time of sampling using a calibrated, hand-held water quality meter.

Other major groups of water tracers include major and trace ions (e.g. cations including metals, anions including bicarbonate), stable isotopes of oxygen and hydrogen, industrial compounds (CFCs and SF_6) and dissolved carbon isotopes (i.e. inorganic and organic forms) and radio-isotopes (e.g. ^3H). The presence of young water in mines can be assessed via the sampling and analysis of the young water tracers: tritium (^3H), chlorofluorocabons (CFCs) and/or sulphurhexafluoride (SF6). Tritium can be used to determine mean residence times (MRTs, the average time since recharge) up to about 150 years, while CFCs and SF6 can be used to determine MRTs up to about 70 years (Cartwright et al. 2017).

Analytical costs for investigation and advanced tracers tend to be high, laboratory turn-around times may be long, and interpretation of the data is typically requires use of lumped parameter models (LPMs) such as TracerLPM (Jurgens, Böhlke, and Eberts 2012). Radio-isotopes are robust and proven tools to help differentiate shallow aquifers and deep groundwater where there is a contrast in water residence time. These tracers can provide useful information, despite higher analysis costs and longer laboratory turn-around.

Fact sheet guides are currently in preparation for the resource industry that provide a useful summary of the major types of basic and investigation tracers, sampling and preservation requirements and interpretation. These will also consider limitations of tracers, such as assumptions for interpretation.

Standard water sampling protocols, particularly for groundwater, need to be considered when designing and implementing a water tracer sampling campaign (Sundaram et al. 2009).

Table 1: Water tracer groups and examples

Tracer group	Which water samples?	Example water tracers	Application questions
Basic	all water, on site measurement	Field water quality parameters (e.g. EC, Temp, DO)	1-6
Basic	all waters	Major cations and anions (including bicarbonate)	1-6
Basic	all waters	Stable isotopes (e.g. ^{18}O, ^{2}H)	1-6
Investigation	all waters	Trace elements (e.g. Sr, rare earth elements)	2, 3, 5
Investigation	selected samples, on site measurement	Radon-222 (^{222}Rn)	1, 2, 6
Investigation	selected samples	Dissolved Anthropogenic gases (e.g. CFCs, SF_6)	4
Investigation	selected samples	Radio-isotopes (e.g. tritium ^{3}H)	4
Advanced	selected samples	Radio-isotopes e.g. chlorine-36, carbon-14 (including dissolved inorganic and organic carbon)	4
Advanced	selected samples	Trace element isotopes (e.g. Si)	2, 3, 5
Other possible tracers	surface & shallow aquifers	Nutrients, total carbon and dissolved organic carbon, natural flouroesence, advanced dissolved gases, e-DNA (environmental DNA), dissolved noble gase isotopes (e,g, ^{39}Ar), compound specific isotopes e.g.; algae-biomarkers	1-6
Artificial tracers	added to waters on site if flow directions/rates known	Flourescent dye tracers, salts (e.g. chloride), micron scale particles, xeno-DNA (synthetic DNA markers)	1, 2, 3, 6

Steps to selecting suitable water tracers

This project has developed and tested a decision framework to assist in selecting suitable water tracers for mine sites. This framework will boost the cost-effectiveness of tracers that are applied, partly by providing reasons why some tracers that are recommended or familiar, may not be suitable, depending on site specific applications, risks and available information.

Steps that are part of deciding on water tracers for a mine site include the following:

1. What are the key risks and questions for mine water at the site?
2. What are a suitable suite of tracers, commensurate with risks to mining operation and risks to environmental assets?
3. How can these tracers complement and extend other water information that is available such as flow directions and water levels?
4. What are the costs and sampling requirements of suitable water tracers?
5. What are sampling locations, aquifer depths and reference (non-mining) sampling sites are needed?
6. Is a once-off sampling campaign sufficient, or is repeat sampling of water tracers needed?

7. Are there distinctive ‘end-members’ or variations in water tracer concentrations or activities across different waters and aquifers at the site?
8. Are the tracers mostly non-reactive, or it is possible to account for decay and/or geochemical interactions along the flow path?
9. What information and assumptions are required for interpretation of water tracer results and modelling that may be required?
10. How will water tracer data be used to improve confidence in mine water decisions and modelling of surface water and groundwater systems?

This decision framework was tested as part of this project, to determine that some tracers that were not suitable (e.g. nutrients) at a demonstration site. This process included considering whether nutrients found in surface waters and wetlands could be useful as a tracer of downwards seepage into shallow fractured rock aquifers. However, a review of available water quality data from the site revealed very low concentrations of nitrate and phosphorous. This information, combined with the fact that nutrients are reactive, and not an ideal tracer unless at high concentration with distinctive end-members, led to a decision that it was not a suitable and cost-effective tracing method in this case.

Coal contains ‘old’ carbon. When groundwaters migrate through this material, the addition of ‘dead’ carbon can occur. Therefore, it has also been found that uncertainties yet to be resolved can occur when using carbon-14 to date water from coal seams. Further research is needed to quantify the addition of ‘dead’ carbon during water-coal interactions to develop more reliable groundwater age models.

Water tracers for evaluating hydraulic connectivity

Mining excavations below the water table, subsidence, and withdrawal of water consequently result in high fracture porosity, permeability, altering of hydraulic connectivity, gradient and the flow network between the surface water and the subsurface aquifers. Therefore, mining has the potential to intensify the natural surface water groundwater interactions and affect the connected water resources qualitatively and quantitatively. Chemical characterization based on environmental water tracers is a common approach used to understand these interactions (Dhakate, Modi, and Rao 2018; Guo et al. 2019; Huang et al. 2017). Analysis of basic tracers such as major ions helps understand the hydrochemical and the geochemical processes the water had undergone and helps in determining the evolution of groundwater. This characterization and the change in water over time is used to identify possible contamination due to mining, sources of origin or mixing of end members in hydrogeological assessments.

Water quality assessments using major ions, trace element concentractions and their isotopes, and rare earth analysis helped identify discharge of saline groundwater from fractured streambeds, potentially caused by subsidence of a longwall mine by Morrison, Reynolds, and Wright (2019) and is vital information for the management of any plausible detrimental effects on ecological system of surface water streams.

Stable isotopic compositions (^{18}O, ^{2}H) help delineate the recharge sources because they can represent recharing rainfall or surface water and can be used to indentify evaporation. Having similar stable isotopic composition in groundwater and surface water in Ningtiaota Coalfield in China (Huang et al. 2017), revealed that some nearby rivers were mainly recharged by groundwater and weak inter aquifer hydraulic connection. Alternatively, Guo et al. (2019) identified the mine water sampled 5km away from a river to have similar major ion and ^{18}O and ^{2}H composition indicating drawing of river water at the dewatering bore of the mine.

Recharge rates and the impact on base flow rates of rivers can be estimated quantitatively by integrating the ^{18}O and ^{2}H data with groundwater level data and groundwater flow modelling. Similarly, the basic tracers can be used to estimate the spatial extents of the surface water-groundwater interactions, which is a critical component in assessing the impacts on surrounding water resources and narrowing down the boundary conditions in flow models. These critical insights will be very useful in water resource management and decision making on preventive measures such as mine water inrush control (Huang et al. 2017), buffer zones (Guo et al. 2019), or seepage barriers (Dhakate, Modi, and Rao 2018).

Radon can be further used to estimate the degree of mixing of surface water and groundwater (Stellato et al. 2013). Estimates of surface water groundwater interaction can be determined by multiple lines of evidence including tracers that are produced in the subsurface such as radon. Their concentrations are higher in deep groundwater whereas it degasses as it reaches surface water and it helps trace upwelling of groundwater (Baskaran et al. 2009; Cook et al. 2003).

DEMONSTRATIONS OF WATER TRACERS AT COAL MINES

Two case studies are presented that demonstrate the use of water tracers for different applications at coal mines. The applications are firstly for surface water-groundwater interactions near underground coal mines, and secondly for estimating the percentage of modern water to a coal seam at a longwall mining operation.

Water tracers of potential surface water-groundwater interactions

A new environmental tracer study is in progress to help evaluate the potential for surface water–groundwater interactions near longwall coal mines (at a depth of ~300 m) in NSW. 'The Drip', a heritage site, is also located in a national park and is considered an iconic gorge. 'The Drip' has formed within sandstone from the Triassic Period, and is a 35 m high overhanging cliff beside the river where water cascades over the rocks and drips on to the river even during dry periods.

A critical issue that emerged during this study was that the water quality parameters and the basic tracers of the river provided uncertain outcomes because treated mine water is discharged to the river. Therefore, the use of chemical and isotopic tracers in the surface water are limited since their compositions are partly derived from geochemical reactions taking place in groundwater. The use of basic tracers alone were not sufficient at this site to estimate surface water–groundwater interactions. The source of water to 'The Drip' is reported to be a shallow aquifer, however additional evidence using multiple environmental tracers is required to verify possible sources of seepage. The degree of hydraulic connectivity of 'The Drip' with shallow and deep aquifers in the area are yet to be determined.

Water chemistry, major ions and stable isotopes were used to characterise the water types at the site including groundwater and surface water and the water discharging from 'The Drip'. Chemical characterization indicates the unique composition of 'The Drip' sample deviating from the other water samples collected from other Triassic sedimentary aquifers (Figure 3).

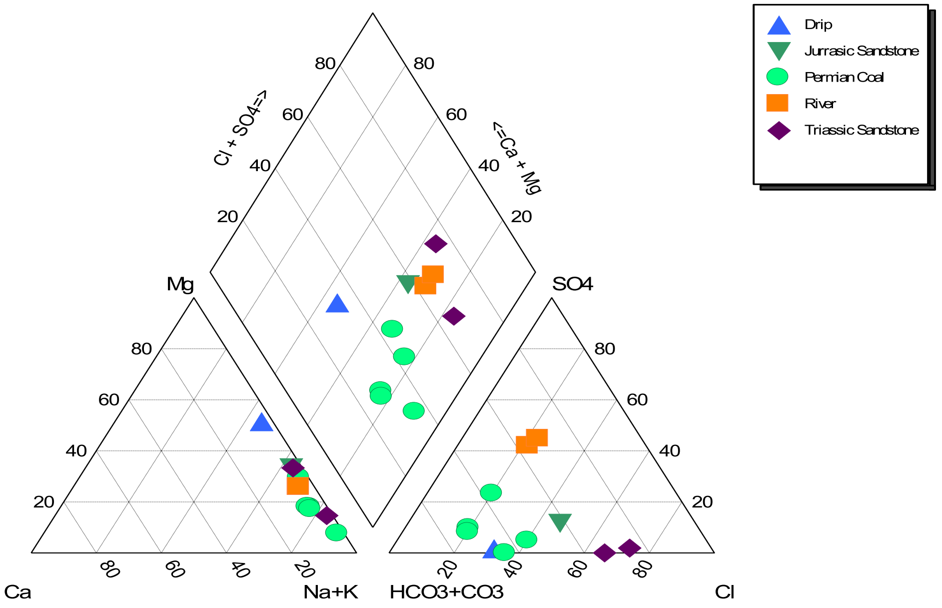

Figure 3: Piper plot of chemical facies that can trace different types of waters and mixing

The variation in pH and the EC of the water discharging from 'The Drip' and the river samples suggested that a shallow aquifer was feeding 'The Drip'. The hydraulic heads of the groundwater in the Triassic sandstone indicates that 'The Drip' could be hydraulically connected to two nearby shallow aquifers. River water had a higher ^{18}O and ^{2}H values due to evaporation whereas the groundwater was similar to rainfall with lower values. The The average stable isotope values of 'The Drip' suggests a hydraulic connection between 'The Drip' water and a shallow aquifer.

The radon concentrations in the surface water samples were below detection limit whereas groundwater indicated high concentrations. Any surface water – groundwater interactions would have been evident if the surface water samples too had relatively higher radon concentrations. These findings can be further justified by using age tracers to determine the distribution of residence times, mixing of old and young water and to calculate percentage modern water or old water in a sample.

Other tracer results that are currently being evaluated for this site include dissolved gases such as CFCs and SF_6. These compounds are very useful tracers since their concentrations re-equilibrate with the atmosphere faster and gains the "finger print" of the surface water for less complicated end member analysis (Cook and Dogramaci 2019). Non-reactive (ie conservative) tracers such as tritium are also being used to evaluate mixing of distinct waters and the percentage of seepage and mixing of shallow groundwater with surface water.

Water tracers to estimate percentage of modern water to a coal seam

Modern groundwater, can recharge, or seep downwareds into an aquifer (e.g. a coal seam) via a number of physical processes: 1) infiltration if and where the mined resource outcrops at the ground surface, 2) infiltration of water, including both precipitation and surface water, through ground deformation including fractures that develop as a result of underground longwall mining, or 3) downward hydraulic gradients, either naturally occurring or that have been increased as a result of mine dewatering. Generally, multiple age tracers are used to estimate residence times of the water samples (Clark and Fritz 1997).

Tritium and water balance methods were used to trace the seepage of modern water (<70 years) to a coal seam that would naturally contain old water at the Dendrobium mine in NSW. Over 1000 tritium samples have been collected since 2004 with the most recent data used for binary mixing models to evaluate the percent modern water present in the samples (HydroSimulations 2019). Three areas of the mine goaf (1, 2A and 3A) recorded 10-26% of modern water (Figure 4). Probability distributions of modern water in these areas were produced by statistical analysis andthe surface water component estimated using hydrograph baseflow separation technique. The results indicated a correlation between the modern water percentage and the high-volume rainfall events. However, there was little correlation between tritium content and 30-day rainfall and mine inflow rates.

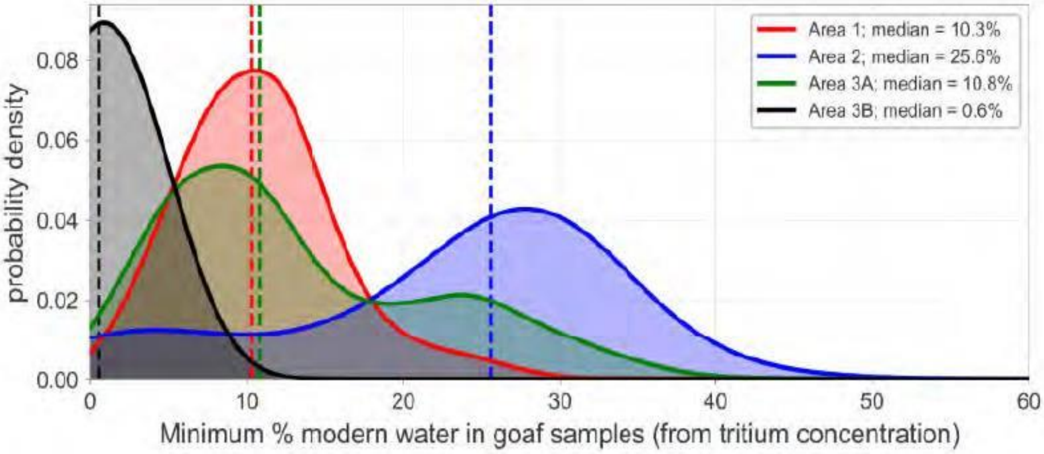

Figure 4: Use of Tritium to estimate mixing fractions of different water sources, Dendrobium Mine, NSW (HydroSimulations 2019)

Further investigation into why tritium indicated modern water in the coal seam is considering operational water, dual porosity effects and mixing of water of different ages (HydroSimulations 2019). The use of suitable multiple tracers could overcome such uncertainities by better distinguishing processes that occurring during water seepage and mixing in such complex groundwater systems.

CONCLUSIONS

This paper has introduced water tracers for applications in coal mining, including identifying sources of seepage for controls, and to help evaluate the potential risks of mining for environmental assets. Water tracers are often used by other mining industries around the world (e.g. iron ore, potash, uranium) and in groundwater resource studies, and there are several examples of water tracers used in coal mining operations (e.g. in China, USA, and some in Australia).

ACARP project C28024 (Stage 1) will continue work at demonstration mine sites to evaluate the benefits and limtiations of multiple water tracers. The steps to selecting suitable water tracers, as a decision support tool is being developed at two underground coal mine sites, along with preliminary water mix and geochemical models. Stage 2 of this project proposes to test new artificial tracers combined with suitable previously tested tracers to improve the effectiveness of tracers and to reduce environmental risks.

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