Mine Subsidence Induced Hydraulic Connection Tested by Geochemical and Geophysical Tracing Techniques

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Abstract

Changes in surface and groundwater hydrology induced by mine subsidence near surface fracturing can also subtly alter the geochemistry. More rapid drainage of surface and groundwater along fracture pathways may lower the standing water level allowing air to penetrate further, accelerating rock weathering and leaching reactions. However, these sulphide oxidation and carbonate dissolution reaction products are normal constituents of groundwater and their presence does not necessarily indicate an impact of mine subsidence. Changes to the groundwater recharge – discharge regime due to fracturing will also affect the age of the groundwater. Whilst the groundwater age is not a significant water quality parameter it may unambiguously distinguish changes to the hydrology, where conventional chemistry may be difficult to interpret.

Mine subsidence fracturing may also cause hydraulic connection between previously isolated aquifers or ultimately between the surface and the mine. Isotopic geochemical dating (^{35}S, ^{3}H, ^{14}C) and tracing ($\delta^{13}C$, $\delta^{2}H$, $\delta^{18}O$, $\delta^{34}S$) techniques are used to distinguish the origin of the groundwater and potential isolation or fracture connections. Isolated groundwater may show a dissolved gas signature similar to petroleum gas within the Bulgo Sandstone.

To identify the geochemical impact of mine subsidence fracturing, pre and post mining profiles are being assembled for comparison. Groundwater age profiles also help to constrain and verify groundwater flow models. However, to produce useful ^{14}C dates from carbon dissolved in groundwater differences between carbon species (DIC dissolved inorganic carbon, DOC dissolved organic carbon and dissolved methane / ethane) caused by interaction with siderite in the aquifer are recognised and addressed.

A nuclear geophysical logging technique, Prompt Gamma Neutron Activation Analysis (PGNAA) is also used to trace the flow of an injected salt solution into fractures and into the porous and permeable sandstone surrounding the borehole. The variable distance the salt tracer moves into the porous rock under a known pressure increase (above standing water level), over a known time and tracer volume allows calculation of hydraulic conductivity at 20cm increments along the length of the borehole. If there is significant flow of the tracer into fractures and beyond the PGNAA measurement range a relative tracer movement distance is provided by the PGNAA log, rather than hydraulic conductivity. Other relevant lithological and hydraulic parameters such as porosity may be derived from measured Si, H, Cl, ±Fe, ±Al elemental abundance provided by PGNAA borehole logging.

Borehole sampling of aquifer water at narrow discrete intervals for geochemical profiling requires isolating the aquifer segment or individual fracture flow from the rest of the borehole. A dual packer apparatus is used to take narrow (2, 5, 10m) discrete interval samples or measure individual fracture flows.

Key words: groundwater dating, ^{35}S, ^{3}H, ^{14}C, PGNAA geophysics, borehole logging, aquifer connection

Introduction

Sandstone aquifers above the Illawarra's coal seams contain significant amounts of groundwater suitable for extraction and augmentation of Sydney's potable water supply. Some naturally fractured zones have been targeted as potential bore-fields. Mine subsidence induced fracturing has the potential to hydraulically connect near-surface meteoric groundwater systems to deeper hydraulically isolated aquifers containing connate groundwater and ultimately to the mine.

Geochemistry

A wide variety of chemical and isotopic compounds are available to characterise water and to trace the source, mixing and chemical evolution of the water in response to interactions with the atmosphere, soil, aquifer host rock or stream environment. Only those tracer compounds that occur within the environment at measurable levels without tracer addition, termed environmental tracers, are considered here.

Groundwater dating ^{35}S, ^{3}H, ^{14}C

The rarely used radio-isotope dating technique (^{35}S $t_{1/2}$ = 87.1 days) has been applied to Illawarra catchments. ^{35}S is a cosmogenic isotope produced in the upper atmosphere by cosmic rays. ^{35}S is suitable for determining the residence time of sulfate in surface drainage and rapid flow groundwater discharge in steep coastal catchments with timescales from months to 2 years (Michel and Turk 1996). An estimate of water residence time can be derived by application of sulfate retardation factors for stream and groundwater systems. Retardation factors are refined with the aid of other isotopic markers such as sulfate-$\delta^{34}S$, $\delta^{18}O$.

Rainfall sulfate ^{35}S was sampled from 2 sites, Mittagong in the upper Nattai catchment (av 8.1 Bq/g) and a near coastal site at Mt Keira in Wollongong for over 20 individual rain events from May 2005 to February 2006. A wide range of ^{35}S values from 49 stream samples (0.08 – 1.8 Bq/g. av. 0.47 Bq/g equivalent to 12mths) reflects a variable sulfate soil - groundwater transmission time to stream, dependent upon the sample location in the catchment. For any particular catchment location affected by near-surface mine subsidence fracturing, ^{35}S can gauge the change in soil - groundwater transmission time.

Tritium is extremely useful in identifying modern groundwater <50yrs and is not easily contaminated by mixing with small volumes of contaminant or water with a high concentration. However, tritium in rain has not been constant over the last 50yrs because of atmospheric input from nuclear weapons testing. Ambiguities arise as a consequence. ANSTO has measured tritium in monthly composite samples for the Global Network for Isotopes in Precipitation (GNIP) base stations since 1960. Over the last 10 years the tritium concentration has stabilised at 2-3 TU. However, the monthly composite samples mask the extent of variability in tritium from one rain event to another. Seventeen Mittagong rain samples average 2.7 TU with a range from 0.9 – 5.3 TU (σ = 1.2 TU). Fifteen Mt Keira rain samples average 3.4 TU with a range from 0.9 – 5.7 TU (σ = 1.6 TU). Precise age dating is reliant upon an assumption of constant tritium concentration in rain before decay with time. This is the tritium input function into the hydraulic system. Individual rain events show significant tritium variability adding uncertainty to a precise age date based on tritium alone.

The only practical dating technique for groundwater greater than 50 years is $^{14}C_{DIC}$. However, because the standard ^{14}C technique relies upon analysis of dissolved inorganic carbon (DIC) serious errors can arise from groundwater dissolution of carbonates. The Hawkesbury Sandstone frequently contains siderite ($FeCO_3$) at greater than 3 wt % hence contamination of DIC from dead carbon is a serious issue for ^{14}C groundwater dating.

Siderite ^{14}C inheritance

Shallow groundwater discharge has been sampled and measured as less than 2yrs (^{35}S) and modern (<50yrs from ^{3}H), yet standard $^{14}C_{DIC}$ ages are variably in the thousands of years range (Waring et al. 2007a). These inconsistent results are attributable to slightly acidic (pH 5-6) soil water dissolving siderite and inheriting DIC depleted in ^{14}C.

The noted deficiency with $\delta^{13}C$ and alkalinity corrections for the standard DIC ^{14}C age dating procedure applied locally has stimulated investigation of the feasibility ^{14}C CH_4 and DOC for age dating (Waring et al. 2007a). Methane's lower concentration in soil and lower saturation solubility in water provide new challenges for sampling and analysis.

PGNAA geophysical logging

A new method of measuring the continuously variable hydraulic conductivity at 20 cm increments surrounding a borehole is described (Waring et al, 2007). The method requires injection of a tracer solution and measurement of the variable distance the tracer has moved by prompt gamma neutron activation analysis (PGNAA) geophysical logging. CSIRO Exploration and Mining build and supply PGNAA logging tools. Gamma spectra collected by PGNAA logging from 0.16 to 10 MeV are analysed to provide a relative abundance of elements H, Si, Al, Fe, Cl and possibly others if sufficiently abundant. The distance a NaCl or KCl tracer solution has migrated into the rock surrounding the borehole is calculated from the greater energy attenuation of a 1.95 MeV low energy Cl gamma emission compared to a 6.1 or 7.4 MeV high energy Cl emission. The differential gamma attenuation is verified by experiment (Waring *et al*, 2007).

Current methods for calculation of hydraulic conductivity are based on the Darcy's law, which relates the rate of fluid flow to the applied hydraulic gradient. In practice these methods typically require measurement of changing pressure or head height difference with time. A difficulty with this approach is the measurement only provides a single average hydraulic conductivity value over an isolated screened interval or over the entire borehole beneath the standing water level. Multiple zones cannot be isolated for measurement in a single borehole without considerable difficulty and expense. If multiple aquifers or significant lithological heterogeneity is anticipated, multiple boreholes are often drilled for individual assessment of target zones. Significant or even the dominant flow zones in a borehole may be missed if not targeted for measurement. Higher flow rates from fractures cannot be distinguished from distributed porous media flow when averaged across significant measurement intervals.

A simple method for estimating porosity surrounding a borehole is also presented by measuring the elemental abundances of common rock forming minerals and water, allocating elements to minerals and presenting a water/rock ratio. Many boreholes of hydrological interest are drilled into sedimentary rocks and alluvium dominated by abundant quartz and clay, which can be quantified by relative Si and Al. Similarly, many sedimentary lithologies may be defined by variations in their mineralogy reflected in proportional changes in elemental abundance. Subtle variations in lithology not apparent by visual inspection such as degree of cementation or clay pore filling in sandstone may also be detected. Porosity and lithology estimation by PGNAA geophysical logging does not require a tracer solution to be injected and may be measured through borehole casing with screened or unscreened intervals.

Sandstone aquifers within the Sydney Basin have been identified as a significant source of emergency groundwater supply for Sydney that may be affected by longwall mine subsidence. Considerable variation in flow rates under pump tests is observed for closely spaced boreholes (SCA 2006). The variability may be due intersection of fractures or interpreted as significant variations in sandstone composition and intergranular fabric. Distinction between these interpretations and definition of preferential flow paths is possible with the high spatial resolution offered by the PGNAA logging technique. Hydraulic conductivity, porosity and lithological measurements from PGNAA logging of boreholes in the Hawkesbury Sandstone are compared to pump test and laboratory measurements.

Discussion

To determine the source of extracted groundwater, samples should be taken from discrete intervals covering stratigraphic and isolated fracture zones and then subjected to analysis using the dating and tracing techniques described above. Open bores will draw water predominantly from the most permeable zone, often including fractures and an unknown volume from the connected near-surface rapid interflow and groundwater storage system, giving an unknown volumetric mixture of water sources.

Reliable, undisturbed vertical age profiles of groundwater through Hawkesbury Sandstone have not yet been established, with mixed water dates ranging across <5yrs 10's yrs 100's yrs to 1000's yrs suggesting a crude exponential increase with depth.

Assessing the impact of longwall coal mining on groundwater flow regime is possible with construction of a valid flow model, which can only be achieved with reliable input data including reliable aquifer age profiles, hydraulic conductivity profiles and known fracture connections.

Ground subsidence due to undermining can cause near-surface fractures in addition to cracking and collapse of overlying rock into the coal extraction void. Steep surface drainage lines allows potential sandstone block movement towards creeks and opening of the near surface fracture network. Waratah Rivulet near Helensburgh provides an example of stream water loss into the near surface fracture network causing drying of the creek bed for several hundred metres. Conventional stream gauging and water quality monitoring provide a direct measure of the volumetric and water quality impact from longwall mining.

To determine whether more subtle effects such as changes to sub-surface flow characteristics or potential hydraulic connection to the underground workings are present in the affected catchment special techniques are used. These techniques include; profiling of discrete interval hydrochemistry for dating and environmental tracing, profiling of hydraulic conductivity, tracer injection and flow tracking and profiling of discrete interval hydraulic pressures within formations.

Conclusions

Environmental dating and isotopic tracing techniques provide important geochemical discrimination between:

- modern meteoric groundwater flow systems with a variable age structure,
- immobile (age >> 10,000 yrs) groundwater in the Bulgo Sandstone
- groundwater in contact with coal seam gas, or evidence of fracture connection between these different sources of dissolved gas.

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