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title: **The investigation of groundwater-surface water linkages using environmental and applied tracers: a case study from a mining-impacted catchment**

author(s): **Wendy McLean**
Parsons Brinckerhoff, Australia, `wmclean@pb.com.au`

Elizabeth Reece
Parsons Brinckerhoff, Australia, `ereece@pb.com.au`

Jerzy Jankowski
Sydney Catchment Authority, Australia, `jerzy.jankowski@sca.nsw.gov.au`

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INTRODUCTION

Longwall mining can have a significant impact on surface hydrology, groundwater systems and water quality as a consequence of subsidence (Booth, 2003, 2006). In the vicinity of creeks and rivers, mine subsidence can reactivate existing fractures, joints, lineaments and faults, and cause new fractures and fracture zones. The impact of subsidence on surface waterways is characterised by fracturing of riverbeds and rockbars, resulting in diversion of surface water to subsurface flow, changes to stream alignment, increased interaction between surface water and groundwater and deterioration in water quality (Kay et al., 2006). Depending on the depth of coal mining, and vertical extent of cracking, surface water may either be lost permanently or temporarily from longwall mining impacted waterways with the possibility of some water re-emerging downstream of mining related subsidence area.

Numerous surface waterways, including creeks and swamps, in Sydney's drinking water supply catchments, located in south-eastern Australia, have been affected by longwall mining activities and subsequent subsidence. One affected catchments, the Waratah Rivulet catchment, was selected for a detailed investigation to provide a more comprehensive understanding of long-wall mining impacts on groundwater and surface water connections. A three year study using environmental isotopes including both stable isotopes (oxygen-18 (^{18}O) and (deuterium (^{2}H)) and radiogenic isotopes (radon-222 (^{222}Rn), radiocarbon and tritium), and applied tracers was undertaken to assess changes in groundwater-surface water linkages and quantify surface water loss (if any) in the mining-impacted part of the rivulet.

ENVIRONMENTAL SETTING

The Waratah Rivulet catchment is located approximately 45 km southwest from Sydney in the southern part of the Sydney Basin (Figure 1).
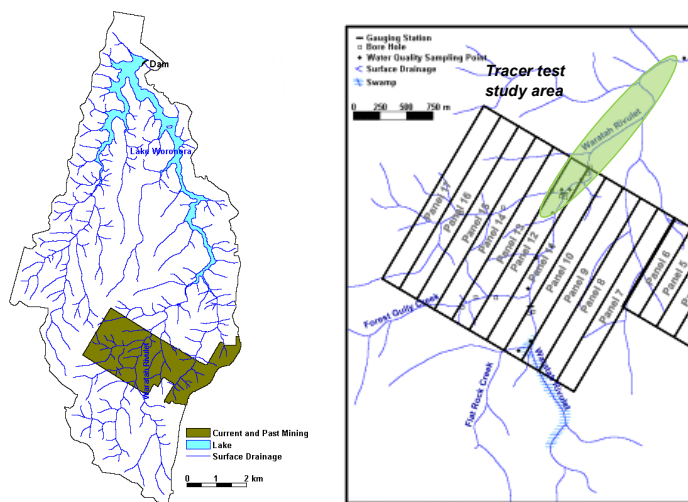

Figure 1. Study area location, longwall panel layout and location of tracer test

The catchment terrain is characterised by sandstone ridges, steep slopes and valleys, and the surface topography ranges from 170 metres Height Datum (AHD) to 360 m AHD. The geology of this area is primarily Permo-Triassic sedimentary sequence (Parkin, 2002) which is underlain

by undifferentiated sediments of Carboniferous and Devonian age. The surface geological unit exposed through much of the catchment is the Triassic Hawkesbury Sandstone which has a thickness of greater than 100 m and overlies sandstones, claystones and shales of the Triassic Narrabeen Group. The Narrabeen Group has a thickness of more than 430 m and over lies the Permian Illawarra Coal Measures. The target seam for longwall extraction, the Permian Bulli Seam, has a thickness of 3.2–3.6 m across the catchment.

The main surface waterway in the catchment is the Waratah Rivulet which flows and discharges into Woronora Lake, one of Sydney's water supply storage systems. Seventeen longwall panels have been mined to date and are located directly underneath the catchment in southwest-northeast direction, 400–500 m below ground level (Figure 1).

From 2001 longwall mining progressed beneath the Waratah Rivulet catchment and its tributaries. By 2006 the impacts of mining subsidence on the bed of Waratah Rivulet and adjacent creeks was evident, with extensive cracking and tilting of the sandstone bed and rock bars occurring as a result of upsidence and subsidence. Particularly under conditions of low flow and rainfall large sections of the Rivulet were without surface water flow, in addition, rapid declines in pool levels were also recorded.

Analysis of the surface water in the Waratah Rivulet has shown elevated electrical conductivity and metals (mainly iron and manganese) and reduced dissolved oxygen content. The change in water quality can be attributed to loss of surface water through cracks to the subsurface, resulting in enhanced water-rock interactions between oxygenated and slightly acidic surface water recharge and newly exposed rock in fractures and bedding planes. The change in water quality has resulted in the precipitation of iron and manganese oxides and hydroxides and development of large, thick bacterial mats during low flow conditions.

METHODOLOGY

Surface water and groundwater samples were collected on a quarterly basis for two years for stable isotopes (^{18}O and ^2H) and ^{222}Rn analysis. Samples for radiocarbon and tritium analysis were collected on one sampling occasion. Groundwater samples were collected using a 12V submersible pump after purging a minimum of three well volumes. The stable isotopes of water ^{18}O and ^2H were analysed at CSIRO Land and Water Laboratory, Adelaide, Australia. This laboratory analysed samples using a Europa Scientific Geo 20-20 isotope mass spectrometer. Tritium was analysed at GNS Science Tritium and Water Dating Laboratory, Lower Hutt, New Zealand, using low-level liquid scintillation spectrometers, with a detection limit of 0.03–0.04 TU, Bq/kg (0.004–0.005). The carbon-14 activity of groundwater and surface water samples was determined by atomic mass spectrometry (AMS), at the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences at Lower Hutt, New Zealand. Samples for radon-222 analysis were collected in 1.25 L PET bottles, ensuring no air bubbles or head space remained. The radon-222 from the 1.25 L groundwater and surface water samples was concentrated into mineral oil in 20 ml vials prior to sending to CSIRO Land and Water Laboratory in Adelaide, for analysis using a Qantulus scintillation counter.

Two applied tracer tests were undertaken; the involved the application of fluorescent dye (fluorescein) to the shallow groundwater system and monitoring breakthrough. 20 L of fresh water spiked with 600 g of powdered dye was injected into two monitoring bores. The dye solution

was flushed through the boreholes with a further 1,000 L of fresh water obtained from Waratah Rivulet. Breakthrough was monitored at various locations along the riverbed, and in down-gradient monitoring bores. Concentrations of fluorescein dye (Abbey Color) were determined using a dual channel, Turner Design Aquaflor Fluorometer.

The second tracer test involved application of a salt solution to surface water in Waratah Rivulet. A volume of 250,000 L was spiked with a brine solution to produce a final tracer solution with an EC of 1,000 µS/cm. The tracer was applied to the rivulet at a rate of 12 L/s and breakthrough monitored at various surface water and groundwater monitoring locations. EC was measured continuously using Greenspan EC sensors.

ENVIRONMENTAL ISOTOPES

The stable isotope results (Figure 2) show clear mixing between shallow groundwater and surface water in the mining-impacted part of the rivulet. Stable isotopic signatures for shallow groundwater are more enriched in the impacted zone (average $\delta^{18}O$ = -4.92‰, δ^2H = -22.03‰) than the non-impacted zone (average $\delta^{18}O$ = -5.08‰, δ^2H = -23.19‰) due to mixing with surface water which has an enriched isotopic signature due to evaporative enrichment (average $\delta^{18}O$ = -4.58‰, δ^2H = -19.97‰).
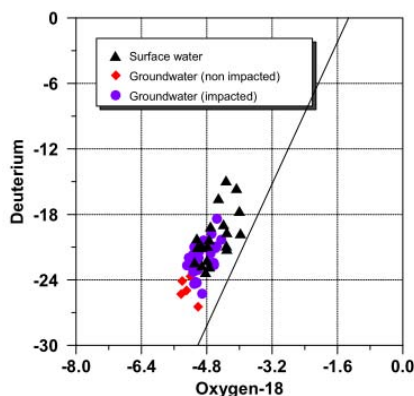

Figure 2. Stable isotope data, showing mixing between groundwater and surface water in the mining-impacted zone

Tritium and ^{222}Rn values also confirm groundwater-surface water mixing in the mining-impacted zone. In groundwater in a non-impacted part of the catchment, tritium and ^{222}Rn values are approximately 0.4 TU, and 20 Bq/L, respectively. In the impacted part of the catchment, tritium values in groundwater range from 1.0 to 1.3 TU, and are similar to surface water values (1.35 TU to 1.6 TU). Radon values in the impacted zone are much lower, due to mixing with surface water, and range from 4 to 16 Bq/L. Corrected radiocarbon ages also indicate that groundwater in the shallow aquifer system is modern (<50 years BP).

Radon mass balance calculations were undertaken for each monitoring round to estimate the fraction of groundwater present in the stream (or vice versa, stream water loss to groundwater) according to Equation 1.

$$R_s (Q_s) = R_{gw}(Q_{gw}) + R_b(Q_s - Q_{gw}) \tag{1}$$

where R_s = ^{222}Rn concentration in the stream; R_{gw} = ^{222}Rn concentration in groundwater; R_b = background concentration of ^{222}Rn in the stream, based on estimated loss of ^{222}Rn resulting from gas exchange; Q_s = stream discharge; Q_{gw} = groundwater discharge and Q_{gw}/Q_s = fraction of stream discharge that is surface water.

The results presented in Table 1 show that over a 2 km stretch of the rivulet there is a net loss of surface water, ranging from 0.20 ML/day and 0.48 ML/day. These calculations were undertaken during relatively low flow conditions (<12 ML/day), and indicate that not all surface water lost to the subsurface through fractures in the creek bed has returned by the most downstream gauging station.

Table 1. Radon mass balance calculations for Waratah Rivulet.

Monitoring period	Stream flow (ML/day)	Calculated stream flow reduction (ML/day)
Sep 2007	5.57	0.47
Jan 2008	2.81	0.30
Mar 2008	6.35	0.20
Sep 2008	10.0	0.48
Dec 2008	1.58	0.28
Feb 2009	11.82	0.38

APPLIED TRACER TESTS

The fluorescent dye tracer test was undertaken to assess the connectivity of the fracture system, measure solute transport regime, identify groundwater discharge zones and quantify groundwater baseflow. This test was completed under high flow conditions. Visual breakthrough of fluorescein tracer from the shallow groundwater system into the surface water system was incredibly fast, with breakthrough occurring 15 min after injection, at a location 50 m downstream of the injection point. Breakthrough in the downstream monitoring bores occurred within 1.5 hours, at a distance 250 m down-gradient from the injection bores. These results equate to a groundwater velocity of 4,000–4,800 m/day. Breakthrough curves (Figure 3) showed strong peaks with very little tailing, indicating limited dispersion of the dye as it moved through the shallow groundwater system. Numerical integration of the tracer breakthrough curves indicate that 100% of the fluorescein was recovered at the most downstream surface water monitoring point (located 2 km downstream of injection point) within 48 hours.
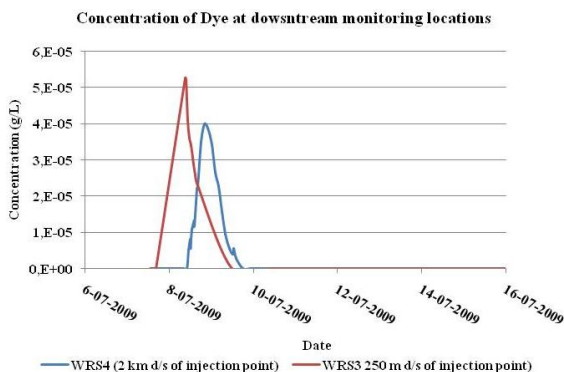

Figure 3. Dye tracer breakthrough curves.

The salt tracer test was undertaken to quantify stream loss (if any) to the subsurface. Break-through occurred within 12 min at the first surface water monitoring location, 50 m downstream of the injection point. Numerical integration of the breakthrough curves indicate that approximately 100% (94%–100% recovery of salt tracer) of the salt is present at the first surface water monitoring location (50 m downstream of injection point), but between the first and second monitoring locations (50 to 250 m downstream of injection point) around 20% of the surface water is lost (80%–86% recovery of salt tracer). However by the final monitoring location all of the surface water that had been lost to the subsurface had returned (100% recovery measured).

The two applied tracer tests were undertaken during a high flow event, with a total flow of 78.08 ML/day over of the three days of tracer testing. The results show that under high flow conditions, any surface water lost to the subsurface has returned by the most downstream surface water gauging station, and there is no net loss in surface water flow. If any loss of surface water occur is possibly masked by high flow during the time of tracer test.

CONCLUSIONS

The environmental isotopes and applied tracer tests provided new data which enhanced the understanding of groundwater-surface water interactions in the Waratah Rivulet and provided quantitative data on groundwater-surface water fluxes in the mining impacted area under different flow conditions. Applied tracer studies have demonstrated that in the Waratah Rivulet, secondary permeability has been enhanced by subsidence in the shallow aquifer system and the primary mechanism for groundwater-surface water interaction (both gains and losses) is through fracture zones within the riverbed. Radon mass balance calculations have shown that under relatively low flow conditions (<12 ML/day) there is a net surface loss within the mining-impacted part of Waratah Rivulet. The applied tracer studies showed that under high flow conditions (>50 ML/day) there was a net loss of surface water in sections of the rivulet, but all lost surface water had returned by the most downstream gauging station within the study area.

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AGH University of Science and Technology