Impacts of longwall mining on surface water and groundwater, Southern Coalfield NSW

Greg McNally and Rick Evans

Prepared by eWater CRC for
NSW Department of Environment and Climate Change

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Executive summary

Conflicts between the needs of underground coal mining and those of surface catchment protection have been active on the Southern Coalfield for over a century. The mining companies and their regulator, now the Department of Primary Industry, have argued the economic benefit of mining (a one metre advance of a longwall face can cut coal with a current value in the order of $70,000) and that deep mining, at 400–500 m below the surface in present-day mines, causes minimal surface damage that can be remediated or will 'self-heal' over a number of years. The Sydney Catchment Authority has raised concerns about surface fracturing, and impacts on surface flows, swamps and groundwater. Others in the environmental movement point to creek bed cracking, rock falls, loss of surface flows and swamp desiccation arising from mining-induced land subsidence.

Over the years the nature of the objections to mining have changed: up to the 1980s the main concern was with loss of stored waters into mining workings and indeed at this time a number of shallow, though non-longwall, collieries were working close to Cataract and Avon Reservoirs and seeking to mine beneath them. This fear of catastrophic drainage has been addressed by careful monitoring over many years and by evidence that deep total extraction mines remain dry, even when shallow stream flow is demonstrably being lost hundreds of metres above the workings.

This brings us to the current major concern with longwall mining, which is really an objection to mining-induced subsidence and more specifically to surface cracking and heaving caused by concentrated tensile and compressive ground strains. These phenomena are caused by the mining method itself (total pillar removal within a longwall 'panel') and also by the particular combination of geological conditions present on the Southern Coalfield: a steeply incised plateau and gorge terrain; high horizontal stress concentrations at the base of V-shaped gorges; bare, rigidly-deforming sandstone bedrock exposed along stream beds; and an enclosing 200 m thick sandstone formation composed of perched and poorly interconnected sub-aquifers. These perched water tables are easily fractured and drained by the tensile strains generated above an advancing subsidence wave, putting at risk upland swamps and other groundwater-dependent ecosystems in its path.

Improved GPS-based 3-D surveying methods, plus the expansion of longwall monitoring since the mid-1980s, have highlighted a number of other subsidence-related ground phenomena. The ground does not simply subside, it tilts, it cracks then shortens, it moves backwards and forwards and it may even twist in places. In overall terms, it tries to flow into the void left by a longwall panel, which is typically about 200 m wide by 2 km long by 2–3 m high. Assuming an overburden pile 500 m thick, mainly sandstone, the post-mining bottom 50 m or so is caved and severely fractured, while the uppermost 10–15 m is less severely cracked; the intervening 440 m or thereabouts is only slightly cracked and subsides as an entity because of its lateral confinement. In other words, there is a large increase in the porosity of the basal section and perhaps 1% dilation at the top, but very little new void space is created through most of the overburden column.

Two unexpected subsidence-related phenomena have been documented from survey monitoring results on the Southern Coalfield: small lateral movements, in the order of 20–60 mm, of structures 1–1.5 km distant from the edge of mining ('far field movements') and heaving of up to 300 mm in valley floors ('upsidence'). The former appears to have no effect on groundwater, but upsidence results in shearing and arching of bedrock layers, creating a mosaic of near-surface fractures which draw in surface water. The question which then arises is whether this loss of surface water is temporary or permanent, and how long will surface flows take to recover to pre-mining levels, if at all?

Overseas experience of longwall-induced subsidence in the USA and the UK is that streams generally recover once the new fractures are filled and spill over, but on the Southern Coalfield the jury is still out, since the longwall mining boom from the mid-1990s to the present has coincided with possibly the worst drought in 100 years. Stream beds which in normal times might have recovered their flow within a few months or years could now be taking ten years. Enter a new problem – the groundwater that does emerge downstream from the subsided area is of poorer quality. It is de-oxygenated, acid, more saline and saturated with Fe/Mn and lesser concentrations of other cations leached from the newly-exposed fracture walls. Discharge areas are consequently disfigured by large rust-like blooms and puddles of iridescent water.

What is to be done about this? One approach has been to modify the geometry of the mining panels, at the cost of reduced resource recovery, so as to limit subsidence effects. The early longwall panels under Cataract Reservoir were deliberately designed with narrow faces and wide inter-panel pillars, and subsidence was consequently small with, apparently, no loss of surface water. Another approach, being tried at Appin Colliery Area 3, is simply not to mine under major watercourses, following serious stream bed cracking, gas release and pool drainage caused by the passage of several longwall panels from Tower colliery at 430 m under the Cataract River in the 1990s. A third approach, used for example on the upper Georges River, has been to seal surface cracks with cement grout, though this is expensive, almost impossible to carry out in remote gorges, and may not be effective because of renewed cracking caused by later subsidence. (Bearing in mind that subsidence damage is cumulative over a number of side by side panels, which might take 3–5 years to complete.)

The NSW Government has responded to the public concerns by requiring longwall operators to seek approval for each new series of longwall panels and to present a Subsidence Management Plan in support. This will greatly increase the amount of surface and groundwater monitoring being performed across the coalfield, which had in any case been rising steeply for the past ten years. Yet there are many shortcomings in the present monitoring system. In the first place it is being carried out by many different authorities: mostly by four mining companies, of which the largest by far is BHP Billiton, for the Department of Primary Industry (DPI); but also for the Sydney Catchment Authority (SCA), the Department of Water and Energy and, in the past, for the Dams Safety Committee (DSC). We were unable to detect any signs of coordination in this monitoring or, indeed, any evidence that the data was being critically analysed rather than filed and forgotten. However, we have been since informed that SCA is actively examining monitoring data from the new Dendrobium Colliery, which is close to two reservoirs.

A second criticism is that the monitoring has in the past been largely reactive and confined to known trouble spots, such as the Cataract Gorge, the Georges River and, most recently, the Waratah Rivulet. Indeed, we understand that stream gauging stations upstream from reservoirs have only been set up recently. No attempt has been made to compile a picture of the coalfield hydrogeology as a whole and no monitoring of future mining areas beyond perhaps the next 2–3 years has been proposed. Indeed there is a profound shortage of baseline information, which ideally should be collected some years before mining starts and perhaps continue for up to ten years after mining in some cases.

Our key findings are that:

- Mining-induced subsidence and valley bulging causes cracking of stream beds and in places there is complete loss of surface flow.
- This loss may be temporary or permanent, and how much of the flow loss re-emerges downstream is at present unknown.
- This reduction in yield to downstream reservoirs is a major concern to SCA.
- The re-emergent water quality is generally inferior to that of surface flow.
- Overall, the impact of longwall mining on groundwater flow and quality remains largely unknown.

We propose that as a first step towards developing an improved water monitoring system for the Southern Coalfield, the existing fragmented one should be carefully examined. This would involve collation of information presently held by DPI, SCA, DSC and the mining companies themselves. The aim would be present a regional view of surface and groundwater distribution, flow and quality throughout the coalfield. As a second stage an upgraded network of observation bores, water sampling points and gauging stations should be set up, with the particular aim of providing baseline data for new or proposed mining areas up to 20 years ahead of mining.

Introduction

This report presents the results of a review carried out by eWater CRC into the impacts of underground longwall coal mining on surface water and groundwater, with particular reference to the Southern Coalfield within the Sydney geological basin. This coalfield surrounds the stored waters of Cataract, Cordeaux, Avon, Nepean and Woronora Dams near Wollongong NSW. The report is based on a selection of references listed at the end of the report, which deal with British, Australian and American research into hydrogeological changes caused by longwall mining subsidence, and on information provided by the NSW Department of the Environment and Climate Change (DECC). This report was prepared in response to a contract dated 20 June 2007 between eWater and DECC. The results of this study are to form part of the DECC submission to the Hebblewhite Inquiry into mining beneath the Southern Coalfield, which has been convened by the NSW Government. This will consider, among other matters, the impacts of present day mining on rivers, creeks and swamps.

Project aims and approach

The purpose of the project was to produce a report based on review of literature that would provide:

- an evaluation of potential longwall mining impacts on groundwater and surface water quantity and quality on the Southern Coalfield;
- an evaluation of whether current monitoring programs carried out by industry and NSW State Government agencies are sufficient to address those impacts;
- an analysis of existing knowledge gaps; and
- a framework for addressing the impacts of longwall mining on surface and groundwater quantity and quality (including a monitoring framework).

The impacts of mining-induced subsidence on riverine ecosystems and topography have not been included in the brief given to eWater.

It was intended that this study be desktop-based; in other words it would not collect original data but depend on published and unpublished material relevant to surface and ground waters in the Southern Coalfield area. We have reviewed documents provided from the resources of Sinclair Knight Merz Pty Ltd and by DECC covering:

- areas known to be affected by mining, such as the Cataract River, Georges River, upland swamps and sandstone cliff lines;
- existing data from industry monitoring reports (baseline, during and post mining);
- government agency assessments and monitoring data; and
- published scientific literature relevant to groundwater changes brought about by mining-induced subsidence over longwall panels.

Initial project workshop

A one-day briefing workshop was held at the DECC offices in Sydney on 25 June 2007 to develop the scope of the project and to discuss its aims. In attendance were representatives from DECC, the Sydney Catchment Authority (SCA), the Department of Primary Industry (DPI) and the Department of Water and Energy (DWE). A second workshop is also to be conducted at the conclusion of the study. Briefing papers were provided by:

- Dr Jerzy Jankowski (SCA) on *Current scientific understanding of longwall mining impact on water quality and quantity*, with particular reference to intensive monitoring at present underway on Waratah Rivulet, a tributary of the Woronora River upstream from Woronora Dam; and

- Martin Krogh (DECC) on *You can't drink coal* (see also Krogh 2007), which described examples of stream and swamp degradation in a number of Southern Coalfield catchments.

Discussions during the initial workshop indicated that:

- On present indications longwall mining, and its associated subsidence effects including ground heave and loss of surface waters, which now occupies only a small proportion of the Southern Coalfield, could continue for perhaps another 50 years.
- Concerns are held for the impacts of mining-induced ground fracturing, which has become very apparent along streambeds since a great expansion of longwall mining in the 1990s. Loss of streamflow into these fractures has coincided with drought conditions over most of the intervening period. Whether this loss is temporary or permanent is a key issue.
- Consequently, this eWater study will primarily consider the impacts of longwall mining on surface streams rather than on large water storages, and on shallow rather than deep groundwater.
- The issue of loss of stored water into mine workings is no longer considered to be of high importance, and indeed the lack of inflows to these deep mines was generally accepted. However, no comparison of inflows to mine workings against losses from surface streams appears to have been made.
- The contribution of upland sandstone plateau swamps to the overall catchment water balance, and its influence on the timing of stream flows has not been investigated.
- Extensive monitoring of mining impacts (such as loss of flow into subsidence cracks and water quality degradation) on surface streams and shallow aquifers is at present underway in key areas such as the Waratah Rivulet (Metropolitan Colliery), Dendrobium Colliery and Appin Colliery Area 3, in accordance with now-compulsory Subsidence Management Plans.
- However there is a lack of pre-mining surface water and groundwater baseline information both in these areas and across the Southern Coalfield generally. Monitoring for years before and after mining may be required to achieve this. Hence recommendations are required for an upgrade of the monitoring network.
- Other areas of past concern include the Cataract River (subsidence-induced bed cracking and gas release by Tower Colliery), the Bargo River (Tahmoor Colliery) and the upper Georges River, especially Marhnyes waterhole (Westcliff Colliery), and various creeks on the Elouera and Bellambi West colliery holdings.
- Finally, there is a need to convert raw monitoring data, which is at present generally stored but not interpreted, into useful input to decision-making processes.

Historical background

The stored waters dispute, 1900–1974

The possible loss of surface and ground waters into underlying coal mine voids on the Southern Coalfield has been a bone of contention between the water supply authorities and the mining companies for at least a century. According to Reynolds (1977) objections to mining on the southern catchment were first raised during the construction of Cataract Dam (1902–07). These concerns may have been based on serious mine flooding incidents in shallow workings at Fernvale and Maryville Collieries (Newcastle) during the 1880s, which later became the subject of Royal Commissions. The depth of cover at Ferndale, where a miner was killed by the inrush, was less than 20 m, only about half of which was rock (Atkinson 1902). Atkinson notes, however, that following the implementation of improved mining practices (chiefly larger pillars, narrower bords) three mines were operating safely with 45–90 m of overburden cover beneath Newcastle tidal waters in 1900.

In 1963 the Sydney Water Board (MWSDB), in line with its long-term policy, formally opposed any further mining beneath the Southern Catchment, which encompasses the greater part of the Southern Coalfield, even though mining had been taking place in this area since the 1850s. This policy was vigorously opposed by the mining companies and their regulator, the NSW Mines Department, which up to that time had granted colliery leases over most of the catchment. Some of these leases long pre-dated the MWSDB dams, which had been built between 1902 and 1941, though only a small proportion of their area had been mined up to that time.

The MWSDB position of the 1960s was that stored waters, and the ground waters that sustained them, could drain downwards along subsidence-induced cracks into mine workings. In an extreme situation this could cause catastrophic inflows which would subsequently discharge from the mine portals at the base of the Illawarra escarpment. The Board supported this contention with records of subsidence-induced surface cracking and cliff rock fall scars, and by reference to known 'wet' mines such as Nebo and Huntley Collieries. At this time, it must be pointed out, there were no operating longwall mines in Australia, although Appin Longwall 1 commenced in May 1969, and no mining activity at all, other than the driving of a few widely-spaced access tunnels, had occurred beneath stored waters.

The Mines Department replied, in effect, that only a few portions of Southern Coalfield workings were noticeably affected by groundwater inflows and that these were very shallow, generally with less than 60 m of cover, and in high rainfall areas such as the face of the Illawarra escarpment. Despite the inflow disasters of the 1880s in the Hunter River delta, at least 12 NSW mines had since operated safely beneath either the Pacific Ocean or the Central Coast lakes. Some of these had rock cover as thin as 35 m, while 45 m cover beneath waters was common for most of the period 1890–1960 (Reynolds, 1977). Nevertheless, it is likely that most of these mines were either first workings (i.e. all pillars were left) or used partial pillar extraction methods, neither of which give rise to significant subsidence.

The Mines Department also pointed out the economic importance of the Bulli and Wongawilli Seams on the Southern Coalfield. These are the most important sources of coking coal in Australia, both for the Port Kembla steelworks and for the export market. Developments in the 1960s brought matters to a head. Increased demand for coking coal caused the mining companies to advance their workings westwards from the Illawarra escarpment and to experiment, unsuccessfully at first, with mechanized longwall faces. This conflict of interests caused the NSW Government of the day to step in and appoint a judge, Mr R.G. Reynolds, to inquire into the mining of coal under stored waters and to adjudicate in the matter.

The Reynolds Inquiry, 1974–77

The Terms of Reference of Mr Justice Reynolds' commission (Reynolds 1977) required that that he assess the feasibility or otherwise of coal mining under the stored waters of five MWSDB reservoirs, and recommend any mining practices that would allow this to be safely undertaken. Evidence was presented to the inquiry on behalf of the mining proponents (four colliery companies plus the Mines Department) and the opponent (the MWSDB), in the form of written submissions from their respective mining and geological consultants. In addition, Mr Reynolds visited mining sites working under surface waters or major aquifers in the UK, Europe, North America and Japan. Finally, a limited program of overburden testing, including pre- and post-mining permeability testing, was carried out at South Bulli and Kemira Collieries.

The key issues which came to light during the inquiry were as follows:

- What is the minimum depth of rock cover needed to ensure that infiltrating surface water does not reach active mine workings in significant volumes?
- What are the minimum sizes of pillars, and the maximum dimensions of panels (groups of pillars) needed to ensure that subsidence, hence surface cracking, is kept within tolerable limits?
- What is the closest distance that total pillar extraction (hence subsidence) might approach stored waters? (This would be expressed in terms of an 'angle of draw' plus any additional standoff distance that might be required).
- What might be the effects of abnormal but penetrative geological features such as igneous dykes or faults, which could provide water conduits through otherwise impervious strata down to mine level?
- How stable are permanent pillars left to support roof strata? Could the collapse of these over decades or even centuries initiate renewed leakage from stored waters?

The inquiry report, released in 1977, concluded that MWSDB fears of a catastrophic water loss following mining were unjustified, provided that this was carried out in a controlled manner at cover depths greater than 60 m for first workings (tunnels and pillars only) and greater than 120 m for partial pillar extraction areas. Recommendations were made for pillar sizes and allowable distance from the edge of mine workings to reservoir rims. Although these recommendations were not adopted in detail, the NSW Dams Safety Committee was set up in 1978 to advise the government on, among other matters, the safety and preservation of surface stored waters above or near mine workings.

For the purposes of this study, the Reynolds Inquiry report provides a valuable statement on the relationship between geology, groundwater, mining-induced subsidence and mining practice on the Southern Coalfield, as matters stood in the 1970s. Its main shortcoming is that it deals only with bord and pillar first workings (where say 10–20% of the seam area is extracted) and partial pillar extraction (say 50–60% extracted), but not with modern longwall mining (80–90% extracted). The methods investigated by Reynolds result in little or no subsidence and therefore minimal overburden disturbance, whereas longwall mining – after the first one to three panels have been extracted – causes the maximum possible subsidence and consequently a great degree of strata cracking and permeability enhancement.

Developments, 1977–2007

The most important development on the Southern Coalfield in the years following the Reynolds Inquiry was the successful introduction of mechanised longwall mining at Westcliff Colliery in the late 1970s. Productivity gains were so impressive that this method almost completely replaced bord and pillar methods, including Wongawilli panel extraction, over the succeeding thirty years. In the process the number of collieries fell from about 20 to just eight (Appin/Tower/Douglas, Bellambi West, Berrima, Cordeaux/Dendrobium, Elouera, Metropolitan, Tahmoor and Westcliff). These mines are now mostly large longwall operations, with outputs generally in the range 1–3 Mt per annum (DMR 2000).

However the new mines brought fresh conflicts between the demands of water-supply security and efficient underground operations. First, because longwall panels are large rectangular blocks of coal, typically 150–300 m wide by 2–3 m high in the Bulli Seam and 1–3 km long. These rectangular nearly-horizontal panels, laid out side-by-side with narrow, crushable chain (inter-panel) pillars in between, do not fit well with the overlying, intricately eroded sandstone plateau and gorge landscape. In mining terms the longwall method is 'inflexible', since it cannot make the same allowance for surface features such as the highly irregular footprint of water bodies which the older, smaller-scale bord and pillar workings could accommodate.

Second, the longwall method brings with it maximum subsidence unless wide inter-panel pillars are left. This is in sharp contrast with pre-1975 mining, where there was generally little subsidence and workings could be configured to avoid stored waters. Another factor that has become much more important in predicting subsidence impacts is topography. It has become apparent over the past decade or so that in addition to vertical subsidence, which is more or less predictable, there are a number of other ground movements taking place in response to broad-scale coal removal (Waddington Kay Associates 2002):

- Valley floors rise (valley bulging or 'upsidence'). This may not be noticeable where the surface is covered by unconsolidated soil or alluvial sand, but can cause distinct cracking on rocky stream beds.
- Gorge sides close up and vertical rock faces may crack, causing rock falls, in response to high horizontal tensile stresses. These stresses are naturally present, especially in the lower portions of the gorges, but are enhanced by mining subsidence.
- Some ground surface points at the edge of panels may partly rotate, while those in the centre of panels move backwards then forwards.
- Points 1 km or more distant from the mining panel may 'flow' towards it by 10–20 mm. This distant movement, unaccompanied by any measurable settlement is referred to as 'en masse' strata displacement or 'far field movement'.

Project area description

Regional geology

The Southern Coalfield is not formally defined, but comprises that southern portion of the Sydney geological basin which is underlain by the Illawarra Coal Measures and lies generally south of Campbelltown and north of Moss Vale. The present day area of active longwall mining is smaller, lying mostly between the Hume Highway and the Illawarra escarpment. Mining is limited to the two topmost seams, the Bulli and Wongawilli coalbeds, with the former being the greater producer. On present trends longwall extraction is expected to advance westwards and northwards at cover depths greater than the present 400–500 m over the next decades.

The regional geology of the Triassic-age overburden rocks above the Bulli Seam is described in publications such as Sherwin and Holmes (1986) and Bunny (1972). The main features of the regional geology in this portion of the Sydney Basin that are relevant to the present study include:

- The topography of the area is a rugged sandstone plateau cut by steep and deep V-shaped gorges, which in places present a rectilinear drainage pattern defined by dominant joints and lineaments. These lineaments, which may be the surface expression of igneous dykes or clusters of 'master' joints and may be more than 1 km long, are sometimes associated with underground zones of enhanced lateral stress and rock mass permeability.
- The walls of the gorges are composed of massive Hawkesbury Sandstone, which formation typically extends from the plateau top to around 100 m below creek bed level. Thin soils are developed on the sandstone plateau surface, and bare rock shelves are frequently exposed in creek beds. When coupled with relatively wide-spaced jointing, this tends to concentrate surface strains and to generate conspicuous vertical fractures where undermined.
- The thickness of the Triassic overburden, which is mainly sandstone but includes finer-grained rocks at depth, varies from about 100 m at the Illawarra escarpment to 400–500 m in the vicinity of modern longwall mines to the west and north of the escarpment. The sequence dips generally to the NW at a very low angle.
- The Triassic rocks of the Southern Coalfield are intruded in places by plugs, sills and dykes of syenitic and basaltic composition. The dykes may act as conduits for surface water down to seam level, as vertical aquifers, or as groundwater dams, depending on their degree of weathering and intensity of fracturing. Faults, though present, appear to have much less impact on groundwater.

The two main units of the Triassic sequence are the Hawkesbury Sandstone, which is the cliff-forming unit seen most commonly across the coalfield, and the underlying but thicker Narrabeen Group of less prominent sandstones and shales.

Hawkesbury Sandstone

The Hawkesbury Sandstone (HSS) varies from about 100 m to 200 m thickness on the Southern Coalfield, depending on the amount of erosion; where fully penetrated by boreholes it may be 200–300 m thick. It is a massive quartz sandstone unit with a small proportion (about 5%) of shale in discontinuous beds 1–3 m thick. 'Massive' is used here in the geological sense, meaning made up of very thick beds rather than being very strong. The sandstone beds are typically 1–10 m thick, but persist laterally for only 100–300 m (i.e. they are 'lenticular' – like a lens in cross section). Their joints are sub-vertical and a little wider spaced than the bedding planes. Groundwater tends to percolate down joints and along bedding, creating a multitude of perched water tables after rain. These are vividly displayed, for example, as wet patches on the walls of freeway cuttings south and north of Sydney.

The mineral content of the HSS is relatively consistent, being made up of:

- Quartz, 50–85% (but generally 60–75%). Mostly detrital, but with some secondary silica derived by pressure solution from compressed quartz grains. Secondary silica occurs as grain overgrowths (hence some quartz grains appear sparkling and sugary-looking) and as patchy intergranular cement.
- Clay, 7–40% (but generally 20–30%). This is mostly kaolinite, but with lesser amounts of illite-smectite and illite-mica (sericite). Some clay occurs as discrete pellets, some as intergranular matrix; some is an alteration product derived from feldspar.
- Siderite (iron carbonate), 0–14% but generally 3–5%. This is generally a very fine intergranular material, not a continuous cement. It imparts grey colours to fresh sandstone and light brown or pink tones on weathering.
- Iron oxides (limonite, hematite, goethite), 1–10% (but generally 1–4%). Much of this is a weathering product derived from siderite, and along with the siderite may be the source of rust-like blooms where Fe-charged groundwater exits from the rock.

Overall, much of the Hawkesbury Sandstone is heavily compacted sand or sandrock, rather than a fully lithified and cemented rock, although the degree of cementation does vary between layers. Hence some beds outcrop more boldly than others, and this contrast between cemented and simply compacted layers probably influences their differing hydraulic conductivity (permeability) and the distribution of perched water tables.

Narrabeen Group

The overall thickness of the Narrabeen Group on the Southern Coalfield is about 300 m, of which 200 m is the Bulgo Sandstone and 24 m is the overlying Bald Hill Claystone. The latter is believed to act as an aquiclude (confining or sealing layer) between the Bulgo and the overlying Hawkesbury Sandstone. Much less petrological information is available on the Narrabeen Group sandstones than on the Hawkesbury but their main characteristics are that:

- They are quartz-lithic, rather than quartzose arenites (i.e. the grains are a mixture of quartz and fine rock fragments, rather than pure quartz sand). Sand-sized rock fragments make up 20–30% of the clastic component, which is less well sorted than the HSS.
- In the unweathered state they are more cemented, denser and less porous than HSS and the cement is largely carbonate (siderite more than calcite).
- The unweathered rock, which is usually encountered within 1–2 m below the ground surface, is light to dark grey in colour, imparted by very fine siderite cement. The HSS, in contrast, is usually weathered and orange-brown to depths of 30 m and more.

However the Narrabeen sandstones are usually distinguished from the Hawkesbury Sandstone in having more continuous bedding (especially, having shale beds more horizontally persistent than 100 m); little or no cross bedding; and less conspicuous cliff lines.

Sandstone hydrogeology

Although the Hawkesbury Sandstone hosts hundreds of registered water bores throughout the Sydney Basin, very little has been published on its groundwater characteristics. However, a vast amount of data resides in geotechnical and hydrogeological reports held by government agencies, consulting firms and the borehole owners. Some of the available information has been summarised in McKibbin and Smith (2000), although it should be noted that almost all of this refers only to the top 10–100 m of a 200–300 m thick formation which is, overall, an indifferent aquifer that is only significantly exploited in a few areas such as the Southern Highlands and the Kulnura-Mangrove Mountain district. Their main conclusions are that:

- The Hawkesbury Sandstone is a thick multi-layered complex of sub-aquifers (perched water tables), which are connected to varying degrees by vertical joints and horizontal bedding plane partings. Groundwater moves, in effect, by stepping downwards through this ladder-like network of rock mass defects. As drilling proceeds, successively lower standing water levels are encountered, since perched groundwater drains into unlined boreholes. The main regional water table may only be present at a depth in the order of 100 m beneath plateaus.

- Water quality is generally potable (total dissolved salts, TDS <500 mg/L) close to recharge areas, but becomes more saline (up to TDS >10,000 mg/L) towards the centre of the Sydney Basin. However the great bulk of the available hydrogeological information on this aquifer has been obtained close to the basin margins and very few deep water boreholes have been completed. (In fact, we are not aware of a single fully-penetrating groundwater well away from the margins of the HSS outcrop.)
- Its porosity and hydraulic conductivity are largely secondary in origin, mostly due to jointing and, in places, solution cavities ('sandstone karst'). Nevertheless primary or intergranular porosity is significant in the Southern Highlands, which overlap the Southern Coalfield and have the highest-yielding wells in the basin.
- Well yields range from <1 L/s (about 0.1 ML/d) generally to around 40 L/s, in the Southern Highlands (SCA, 2006). However the latter figure, obtained from recent SCA well testing in their Upper Nepean project area is exceptional and the bore yield range is more usually 1–2 L/s.
- In a sampling of 70 packer (Lugeon) test results by McKibbin and Smith, 75% were found to be <5 Lu (5×10^{-7} m/s or 0.05 m/d). (However in our experience even these values could be on the high side for the Hawkesbury Sandstone, outside the SW corner of the Sydney Basin.)

The Department of Land and Water Conservation (now DWE) groundwater database recorded only 19 pump tests within the Hawkesbury Sandstone for which transmissivity results had been calculated. These ranged from 0.02 to 9.2 m^2/d and averaged 2.8 m^2/d.

Hydrogeological information for sandstone units within the underlying Narrabeen Group sandstones is much sparser than for the Hawkesbury Sandstone. However, the limited data available suggests that these sandstones are even tighter, perhaps one order of magnitude less permeable, and their porosity is entirely due to widely spaced fractures and bedding. The Narrabeen Group rocks are about 300 m thick in the Southern Coalfield, and composed of about two-thirds sandstone to about one third finer grained rocks such as shale. Hence they are hydraulically more compartmentalised than the Hawkesbury Sandstone, due to the presence of these persistent shale and claystone beds.

The finer-grained rocks are not much less permeable than the sandstones in the undisturbed state (Reid, 1996), because under natural conditions they fracture in a brittle fashion like the sandstones. However under rapid loading and at large strains induced by mining subsidence they are believed to deform plastically and may also swell in contact with water. In this putty-like condition, it is argued, they act as aquicludes, effectively sealing the base of cracked sandstone formations.

The results of a more quantitative study of groundwater in the Hawkesbury Sandstone, though covering a smaller portion of the Sydney Basin, are given in Tammetta and Hewitt (2004). Their paper is based on results from 150 boreholes, mostly less than 80 m deep, from several Sydney tunnelling projects. Importantly, 20 of these boreholes were logged using 3-D acoustic methods which allow unbiased information to be collected on fracture orientation, vertical spacing and aperture. The data set also included results from 450 packer permeability tests and two pump tests in the sandstone. The principal findings from this study were that:

- The bulk permeability in the top 80 m of the Hawkesbury Sandstone, based on hundreds of packer tests, averages about 5 Lu (5×10^{-7} m/s or 0.05 m/d), which is consistent with the average hydraulic conductivity value quoted by McKibbin and Smith (2000) using different data sources. The mean hydraulic conductivity diminishes with depth, from 10 Lu close to the surface to 0.2 Lu at 50 m depth. The average intact rock permeability, from 6 core samples, was found to be 0.0019 m/d or 2×10^{-8} m/s, or about one magnitude lower than that of the rock mass. (Other sources suggest an even lower intact rock value of 10^{-9} to 10^{-11} m/s).

- However the results of two 48-hour pump discharge tests in the sandstone indicated that bulk hydraulic conductivity of the rock mass, as determined by this method, is four times greater than that predicted by packer testing in nearby boreholes. In other words the Lugeon (packer) test greatly underestimates bulk permeability, partly because it makes no allowance for vertical flow. (We are unaware of any other comparison of this type made in the Sydney Basin.)
- From acoustic logging the bedding plane spacing in the sandstone ranges from 0.01 m to 10 m, with a mean value of about 1 m. Aperture of bedding plane partings decreases with depth and is invariably narrower than 0.3 mm below 30 m depth.
- Joints have a similar spacing range, but the average is 1–2 m (that is, just greater than the bedding plane spacing). Joints in the sandstone rock mass are ‘stratabound’ (i.e. they extend vertically from one bedding plane to the next and terminate against bedding) and have a vertical continuity of 1–3 m. Their horizontal continuity is given as 2–20 m.
- The principal joint set in the central Sydney Basin trends NNE, with a conjugate set at right angles (‘orthogonal’) trending ESE. (This pattern can be observed generally on the Southern Coalfield as well, giving rise to the rectilinear pattern of many watercourses.)

Subsidence and mining practice

The following conceptual model attempts to explain the hydrogeological response of coal measures overburden to longwall panel extraction. It is based partly on references such as Booth (1986, 2002), Farmer (1985) and Whittaker and Reddish (1989), and partly on general experience of mining geomechanics in NSW underground coal mines (Holla and Barclay 2000). The interpreted sequence of events following the cutting of coal from a longwall face is described below.

Subsidence mechanisms

As a longwall face moves forward, typically at 5–10 m per day, the roof strata collapse or slide into the mined-out seam cavity behind the face, such that a slow-moving subsidence wave, located more or less directly above, travels across the ground surface at the same rate. As this wave advances the ground surface is first stretched (tensile phase of the subsidence cycle) then tilted, then lowered, and finally squeezed together again (compressive phase). At the edges of the mining panel some rotation and horizontal (backwards and forwards) movement of the surface may be measurable. The process causes considerable disturbance to the strata between the seam and the ground surface, though the intensity of this is greatest at the top and bottom of the overburden sequence.

Rapid subsidence and hence the most severe rock mass disturbance takes place in the tensile phase, which typically extends from a few metres in front of the longwall face to 30–40 m behind it. This constitutes the crest of the subsidence wave, a vertical section through which reveals, from the surface down to the seam:

- A *near-surface zone* 10–15 m thick, which may exhibit cracks that open directly above the face. These do not extend to seam level and mostly close up as the face moves away. These cracks may be highly visible on bare rock outcrops, but are not detectable beneath soil cover.
- An *intermediate, constrained or elastic zone* in which the strata are initially in tension, bending and sagging into the subsidence trough, but are subsequently compressed and remain tightly confined by the surrounding rock mass and lateral stress field after mining.
- A *fractured zone* above the extracted seam, typically about 30–50 m thick, in which strata are laterally continuous but sagging, severely cracked and exhibiting bed separations of up to 50–100 mm. The upper limit of the fracture zone often coincides with a distinct bedding plane separation which may be 100–200 mm wide.
- Finally, at the base of the overburden strata, there is a *caving zone* typically 5–10 m thick, immediately above and behind the longwall face, in which the immediate roof beds are thoroughly fractured, rotated and collapsed onto the mined-out seam floor. The highly-disturbed caved plus fractured zones are collectively referred to as the goaf.

However in shallow longwall mines, say those with less than 100 m of cover, the caving zone, fractured zone and near-surface zone can coalesce. This creates a much larger volume of cracked rock mass to be saturated and provides conduits from surface waters to the mine workings, which are then in danger of flooding. Nonetheless, current longwall mining depths on the Southern Coalfield are much deeper, in the order of 400–500 m; hence the intermediate or constrained zone makes up most of the overburden thickness.

As the tensile phase is succeeded by the compressive phase, some joint and fracture closure occurs, along with self-weight compaction, but the overburden rock mass will never fully consolidate to its pre-mining state. Surface water will slowly infiltrate down to the mine workings, eventually flooding them (although this process may take many years and will be further retarded by gas pressure of desorbed methane in the goaf).

The preceding remarks apply to the ground traversed by the advancing subsidence wave. At the sides and rear of the longwall panel, however, the tensile phase remains ‘frozen’ in place unless overlapped by later panel. Along these edges (panel ‘ribs’) between the mined and virgin coal, open cracks may persist long after mining has ceased. These cracks do not penetrate more than a few metres down, and would reach only the shallowest of workings, but can act as recharge zones for near-surface aquifers.

Hydrogeological consequences

A conceptual model showing the impact of longwall mining on groundwater in overlying strata is illustrated in Booth (2002). This demonstrates the standing water level variations experienced in a single borehole as a longwall face moves from right to left beneath it. Stages 1 to 5 might occur from a few days before to a week after the face passes beneath the observation well, while the recovery stages (6 and 7) might take months or even years.

In the Sydney Basin the maximum subsidence – which might only be achieved after several parallel panels have been mined over a period of years – is about half the thickness of coal extracted (Holla and Barclay 2000). Hence mining 2 m of the Bulli Seam will eventually generate about 1 m of subsidence, with the balance taken up by dilation of the overburden rock mass. For workings 400 m deep, this amounts to only about 0.25% overall volume increase (in the form of cracking), but the dilation is much greater in the 10–20 m above the seam and probably around 1% in the topmost 10–20 m.

As a direct result, longwall-induced subsidence causes many changes to the groundwater system within these strata.

- Water levels in wells may drop by many metres, as water is drawn into the surrounding rock mass to fill newly-created fractures. Some of these are so narrow that the water is retained permanently under capillary suction, but in wider cracks water can move in or out under gravity.
- Hence some wells dry up completely, while water levels in others fall then recover over succeeding months or years. In extreme cases well casing may be bent, distorted or even sheared, and submersible pumps may cease to function due to loss of verticality.
- Groundwater quality may decline through mixing of fresh water in shallow aquifers with more saline water from deeper ones, or by reaction between oxygenated surface water and newly exposed fresh rock in subsidence fractures.
- Shallow bodies of surface waters such as upland swamps may partly drain; streams may diminish or cease to flow altogether.
- Perched aquifers within the seam overburden may be cracked and drain downwards, or downwards and sideways along bedding planes, sometimes to create new spring lines in unexpected places.
- Gas stored in seams and porous rock above the coal measures may be released and flow to the surface.

The final condition of the near-surface zone is therefore likely to be one of enhanced hydraulic conductivity and groundwater storage capacity. Overseas experience is that water levels eventually return close to their pre-mining state, although this may take several months to a year; nevertheless, some bores never recover. Post-mining bore standing water levels below their pre-mining depths may reflect improved rather than degraded aquifer conditions - increased hydraulic conductivity, greater storage, increased bore yield and flatter hydraulic gradients.

Very little of the near-surface water is transmitted through the elastic zone, which in a typical Australian longwall mine at depth 400 m might be over 300 m thick. The impermeability of the elastic zone is enhanced where there is a high proportion of impervious, plastically-deforming mudrocks (shales, siltstones and claystones) in the overburden. The deeper caved and fractured zones, though greatly increased in permeability, are generally dry because they are not in contact with any water source.

Influence of topography

With the availability of precise GPS surveying equipment it is now possible to easily measure horizontal (X and Y) as well as vertical (Z) subsidence movements, and to measure these in steep gorges as well as open plateaus. With this capability, and the volumes of subsidence monitoring data that have become available over the past ten years, it has become apparent that steep terrain has a great influence on subsidence mechanisms and ground movements. (Though this had been suspected decades earlier, it had not actually been demonstrated on the Southern Coalfield.)

In brief, overburden is now known to 'flow' like an extremely viscous fluid towards the mining void created by longwall panel extraction. Ridge lines 'split' under concentrations of tensile strain, while valley floors bulge upwards from the effects of shearing, generated by high compressive strains acting along bedding planes. Some of these displacements are large enough to be caught on time lapse photography and their results are apparent in the form of valley floor uplift ('upsidence'), rocky creek bed cracking and spalling, cliff failures and cross-valley closure. These mechanisms are thought to be particularly active on the Southern Coalfield as a consequence of the plateau and gorge terrain, the extent of total-extraction mining and the high horizontal stresses within the bedrock mass.

Valley bulging is actually a natural process associated with erosional stress relief in steep V-shaped gorges and is believed to have affected many such features in the Sydney Basin. For example, it caused uplift, shearing and large water inflows into the foundations of Mangrove Creek Dam near Gosford (McNally 1981) and has probably affected foundations of many earlier Sydney Basin dams including Warragamba, despite the absence of mining near these structures. Undermining valleys, even at depths greater than 400 m, reactivates and hugely accelerates this natural process. Such movements have been the subject of two research projects funded by the Australian Coal Association Research Program (Waddington Kay Associates 2001, 2002), whose findings are summarised by Waddington and Kay (2001). This paper includes several observations relevant to the present study:

- The depth of stream bed cracking caused by upsidence is given as 10–15 m and this figure is quoted in many references, yet although plausible it is not backed by hard evidence. (On the other hand direct observations of natural stream bed heaving in numerous large diameter boreholes and slimholes at Mangrove Creek Dam indicated that severe fracturing occupied a stream bed zone about 20 m wide and about 10 m deep, with lesser cracks to depth 25 m.)
- The base of the Cataract River gorge experienced 250 mm of net uplift following the mining of several Tower Colliery longwall panels 430 m below. At the same time the valley walls closed up by 280 mm and the effects of upsidence were detectable 300 m into the gorge walls on either side of the river. The upsidence was accompanied by stream bed cracking and draining of natural ponds (of which more later).
- Undermining near Brennans Creek Dam (a small coal washery storage) by longwall panels of Westcliff Colliery 300–600 m away resulted in 35 mm of uplift along the embankment crest and 80 mm of abutment closure, but without affecting the performance of the structure. A nearby tributary stream bed situated directly above one of the longwall panels experienced a cumulative uplift of 250 mm.
- Distant horizontal displacements, also referred to as far field movements, were measured in the Sydney Water Corporation's Cataract Tunnel (65 mm of movement at 1 km distance 39 mm at 1.5 km) from longwall panels of Appin Colliery. Similar movements have been noted elsewhere on the Southern Coalfield, for example at South Bulli Colliery (30 mm at 0.9 km, 25 mm at 1.5 km). At present it appears, however, that there have been no groundwater impacts as result of these far field movements.

United Kingdom experience

British interest in the effects of longwall mining on groundwater systems dates back to the 1970s, when mining under the waters of the North Sea and beneath a major Permian aquifer in north east England raised concerns about mine safety. At least one large longwall mine, at Selby in Yorkshire, suffered serious flooding in 1983 when extracting coal only 80 m below a major aquifer (Dumpleton, 2002). However groundwater entry is not normally considered a potential problem, since most UK longwalls operate at much greater depth, 600–1000 m, and in less permeable rocks than is usual in the coal measures of Australia and the USA.

British practice of longwall mining beneath aquifers in the Northumberland and Durham Coalfields of north east England is summarised by Farmer (1985):

- Overburden cover must be not less than 140–150 m.
- Subsidence-induced tensile strains should be not more than 6–7 mm/m at the base of the lowest major aquifer, which should also be not less than 45 m above the worked seam.
- The immediate roof strata to a height of 30 m from the seam being worked should not contain more than 35% of sandstone beds. Sandstone beds are considered more likely to crack than the more prevalent and plastically-deforming mudstone beds.

Special care should also be taken in the vicinity of major faults and beneath abandoned mine workings of higher seams, both of which may cause water inflows to active longwall panels.

Whittaker et al. (1979) compared the results of monitoring groundwater changes in response to longwall extraction at a 587 m deep colliery in the East Midlands and at an unusually shallow mine (54 m) in Yorkshire. Their general conclusions were that:

- Large increases in overlying strata permeability occur close to and immediately behind an advancing longwall face. In deep workings these changes extend laterally from the face to about 40 m behind it, and to a height of 40 m above the face. Behind the face the subsided beds close up during the compressive phase of the subsidence cycle, reducing permeability once again but not back to pre-mining values.
- In very shallow workings the changes can affect the surface, and their onset may be detectable 60 m ahead of the face, peaking 0–40 m behind the face. Step-like changes in packer (water injection) test results indicate that joints and bedding planes are in turn opening and closing, in response to the tensile and compressive phases of the subsidence wave.
- The subsidence-enhanced permeabilities were 10–100 times greater than their pre-mining values during the tensile phase of the subsidence wave, but diminished to 20–40 times during the compressive phase for a shallow longwall panel.

United States experience

Longwall mining came late to the US, as it did in Australia, becoming the preferred method in large mines only in the 1980s. Interest in the hydrogeological consequences of longwall and other total extraction methods arose out of their impact on rural bore water supplies in Pennsylvania, West Virginia and Illinois. Of these the, the first two areas are especially relevant to the Southern Coalfield, since longwall mining there occurs beneath rugged topography.

A recent study on surface impacts of underground coal mining in western Pennsylvania covers about 16,000 ha of land undermined during the period 1993–1998 (Pennsylvania DEP 1999). Landowners in 28.2% of the 1884 affected properties reported loss or contamination of water supplies, while 10.2% reported surface cracking or fissures. Two-thirds of the water loss complaints were resolved, presumably by well deepening or provision of alternative supplies.

Moebs and Barton (1985) report on the results from monitoring a line of 45 m deep observation wells laid out across a longwall panel in southwestern Pennsylvania. The bores were intended to simulate domestic wells tapping shallow aquifers. The site has certain similarities to the Sydney Basin, with a mining depth of 225–300 m and surface relief of 120 m across the test panel, although the overburden strata appear to be less stiff than the sandstones of the Southern Coalfield. The surface underwent maximum subsidence of 1.07 m, but no strain values are mentioned. Water level readings were taken approximately weekly for six months prior to mining and for 12 months afterwards. Water samples were taken over the same period. Surface flow from permanent streams and springs was also measured.

The main findings of this study were that:

- Water levels in undermined bores fell by 3–7.5 m and one bore drained completely as the longwall face passed beneath it. Some of the well levels recovered during the 12 months post-mining observation period.
- Water quality was only slightly affected by mining, the only consistent change being a slight increase in pH.
- Wells located more than 150 m beyond the edge of the longwall panel were unaffected by mining.
- There was no discernible impact on the flow of surface streams crossing the panel, once seasonal effects were allowed for.

Walker et al. (1988) report on the later stages of this US Bureau of Mines (USBM) research project, after three adjoining longwall panels had been extracted. The maximum water level drop was 35 m and four out of five wells recovered to within 3 m of their original levels within months of undermining. Water levels dropped most over the centre of panels, and continued to fluctuate when adjacent panels were mined. Levels began to decline about 60 m in front of the face and fell most rapidly as the face passed beneath the borehole.

NSW Southern Coalfield experience

Information on subsidence-induced hydrogeological changes on the Southern Coalfield is much less comprehensive than that available in the American and British published literature. This is partly a result of the lack of research funding, but also reflects the very high cost of drilling and water pressure testing in this area, where mine workings are 300–500 m deep. Borehole access in rugged country and the difficulties of drilling through fractured caved ground are other inhibiting factors on the Southern Coalfield. Furthermore, there was until recently a lack of test sites: only a few longwall panels had been allowed prior to 2000 under any of the SCA's southern reservoirs, at Bellambi West Colliery from 1998. Longwall mining had been carried out in the 1980s close to the small Brennans Creek Dam (a colliery dam, not an SCA water supply storage), with bord and pillar mining under the dam itself (Reid, 1990). Finally, a time frame of 5–6 years of monitoring may be required from the pre-mining drilling to the completion of the several longwall panels, when subsidence reaches its maximum extent.

Despite these constraints, sources of information on Southern Coalfield hydrogeology comprise results from:

- Initial boreholes and permeability testing carried out at Wongawilli and Kemira collieries during the mid-1970s Reynolds Inquiry (Reynolds 1977). The results of some supporting studies are summarised in this document, but we have not had access to the original reports.
- Follow-on studies commissioned by the Dams Safety Committee (DSC), which are summarised in Anderson et al. (1989).
- A brief summary of the available borehole permeability test results obtained from various sources up to the mid-1990s by the DSC (Reid 1996).
- Incidental mentions of groundwater in relation to longwall subsidence on the Southern Coalfield in papers by the former Department of Mineral Resources subsidence engineer, Dr L Holla (Holla and Barclay 2000; Holla and Buizen 1991).
- Investigations carried out by BHP Billiton (BHPB) in connection with the planning of longwall mines at Elouera and Dendrobium in the 1990s. However the results of these are not available to us at present.
- Hydrogeological investigations carried out by other mining companies for the expansion of longwall mining at Westcliff, Metropolitan, Bellambi West and Tahmoor collieries. Some of these reports have been provided to eWater for this study, but most were not sighted.
- Public domain documents dealing with subsidence-induced cracking of the Cataract River bed above the workings of Tower Colliery during the 1990s (Everett et al. 1998).
- A summary report on SCA drought-relief groundwater drilling near Avon and Nepean Dams, and in the Kangaloon area, 2003–2006 (SCA 2006).

Submissions presented to the Reynolds Inquiry in 1974–77 pointed out that, other than close to the mine portals and where overburden cover was less than 60 m, the mine workings were generally dry. However small, exceptional flows of up to 2 L/min (say 3000 L/d) were encountered close to faults, dykes and joint clusters. The 60 m minimum thickness was confirmed in a subsequent but unrelated ECNSW/CSIRO investigation at Huntley Colliery (ECNSW 1988). This was a notably 'wet' mine located beneath a variable thickness of well-jointed Hawkesbury Sandstone in a high rainfall area.

The most useful, and disinterested, submission to the Reynolds Inquiry was said to be that from Mr WH Williamson of the Water Conservation and Irrigation Commission, whose findings were later published in Williamson (1978):

- Falling borehole water levels with depth drilled in Hawkesbury Sandstone boreholes are characteristic in both mined and unmined areas. They are signs that successive perched water tables have been breached and are draining downwards through uncased boreholes to the 'true' (i.e. regional) water table, but do not mean that this water is entering mine workings.

- Aquifers in the upper two-thirds of the overburden thickness (i.e. all of the Hawkesbury Sandstone and most of the Narrabeen Group) are largely unaffected by caving and fracturing below this depth.
- Ground water flow within these Triassic cover rocks is very much greater in the horizontal direction (i.e. along bedding) than vertically (along joints). Calculated vertical bulk permeabilities, based on measured inflows to mine workings, ranged from 1.3×10^{-10} m/s (1.1×10^{-5} m/d) to 5.2×10^{-9} m/s (4.5×10^{-4} m/d), which in hydrogeological terms is almost impermeable.
- Field investigations carried out for the inquiry included four boreholes over goaf at Wongawilli Colliery, where subsidence cracks were visible on the surface, and two boreholes at Kemira Colliery over adjacent mined and unmined areas (Reynolds 1977). The Wongawilli results were eventually rejected by the inquiry, but water pressure (injection) tests revealed that permeabilities above the non-longwall mined panel were 100 to 1000 times greater than in the same strata outside the mined area. Mr Reynolds concluded that, notwithstanding the large increase in horizontal permeability over collapsed goaf in both mines, the presence of aquicludes or aquitards continued to inhibit vertical flow. Furthermore, he noted that the workings of both mines were dry.

Pre-longwall subsidence investigations

- The report of the Reynolds Inquiry did not satisfy all parties and further hydrogeological research was commissioned by the Dams Safety Committee following its inception in 1978. The results of work carried out over pillar-extraction panels in its first ten years are summarised in Anderson et al. (1989). At that time no longwall panels were allowed close to stored waters, hence these limited-subsidence workings had to suffice for research purposes. DSC projects completed during this time were:
- Drilling of eight boreholes at Corrimal Colliery for water level recording over fully caved panels adjacent to Cataract Reservoir. During three years of observations (1983–86) it was confirmed that a stable water table did exist in the Hawkesbury Sandstone after mining and there was no evidence of leakage to the goaf beneath.
- Numerical and physical modelling of subsidence mechanisms and groundwater flow by Australian Coal Industries Research Laboratories (ACIRL) (for BHPB) and by CSIRO. These studies using 1980s programs had not produced satisfactory results up to the time of the DSC report in 1989, though present-day numerical models might provide more useful results.
- A study of the distribution, spacing and persistence of joints and major discontinuities in the overburden rocks, largely based on surface outcrops and airphoto interpretation of master joints or ‘lineaments’ (Regan 1980). One major concern with this work was to assess the risk that certain major ‘through-going’ geological discontinuities, such as faults and dykes, could provide leakage paths from stored waters down to seam level, even though the bulk of the overburden was impermeable.

The DSC also carried out two projects which included extensive monitoring of relatively shallow partial extraction (panel and pillar working, not longwall) close to or beneath stored waters. The first (Whitfield 1986, 1988) involved mining of 80 m wide panels in 1983–86 at cover depths of 230–320 m in Bulli Colliery. Portions of these workings were under the waters of Cataract Reservoir, while the remainder were under the margins. The panels were found to be cut by vertical igneous dykes, which might (or might not) have acted as water conduits. The panels remained dry during working, with inflows for the whole mine only 1120 L/hr or less; at times the mine experienced water losses, probably into floor strata, of up to 1900 L/hr. (More recent CSIRO research suggests that subsidence cracking may extend 80–90 m into the floor, as deep below the seam as it reaches above.)

Maximum surface subsidence over the active panels was only 114 mm, with tensile strains at the surface generally less than 1 mm/m. Shallow piezometers in the Hawkesbury Sandstone, 300 m above the seam, failed to register any response to caving. However standing water levels in deeper piezometers, only 150 m above the seam, dropped 40 m during pillar extraction phase.

A similar trial was carried out by the DSC at Wongawilli Colliery, at the head of Avon Reservoir in 1982–84. At this site mining conditions were much less favourable: the cover rock was only 80–100 m thick, and was disturbed by igneous dykes and a sill; the seam itself (the Wongawilli Coal) is an aquifer; and valley bulging may have further fractured the overburden layers. Water inflows during first working (pillar development) were not excessive, but increased during pillar extraction up to 100,000 L/hr (2.4 ML/d) and stabilised at 80,0000 L/d. Eventually, this section of the mine had to be abandoned before all pillars had been taken because of the large inflows.

A spirited debate then arose over whether the source of the water was from the reservoir (the DSC view) or from a combination of regional ground water and heavy rain infiltrating in the vicinity of the mine entries. Much of the argument turned on whether algae found in the mine water were from the stored water, or might have entered the workings in ground water. The company (BHPB) view is put by Doyle and Poole (1986) and the DSC view is given in Whitfield (1986, 1988). Whitfield considers that the igneous dykes act as conduits rather than as underground dams, as claimed by BHPB geologists. Both authors note that despite the low overall tensile strains at the surface, an 80 mm wide crack appeared close to a dyke – a reminder that small strains can be concentrated at widely-spaced discontinuities in massive rocks. Doyle and Poole argue that the Wongawilli Seam itself is a sufficiently permeable aquifer to supply this water, and that the algae could have arrived other than in water infiltrating from the surface. This coalbed is known to be partly intruded, and the combination of fractured dolerite sills and cindered coal, plus the loosening effects of coal de-stressed during mining locally increase the seam’s permeability and storativity.

The main interest in the brief paper by Reid (1996) is the implied suggestion that little additional groundwater investigation had been carried out on the Southern Coalfield between 1989 and 1995. The results that he quotes from earlier testing comprise 297 borehole injection (packer or Lugeon) tests and one pumping test. They confirm that the Triassic overburden rocks cover a wide range of horizontal permeabilities, but are generally in the range 10^{-5} to 10^{-8} m/s, and that there is little difference between the sandstones and the shales. However the Hawkesbury Sandstone is usually a little more pervious, say 5×10^{-6} to 10^{-7} m/s (0.4 m/d to 8.6×10^{-2} m/d) than the Narrabeen Group rocks, but is still an indifferent aquifer in this part of the Sydney Basin.

Subsidence over longwall panels

A considerable amount of subsidence monitoring, including ground water observations, was commissioned by the Southern Coalfield mining companies after the mid-1990s, in response to relaxation of constraints on longwall mining. The volume and scope of this monitoring has increased greatly since the early 2000s but little of these results has reached the public domain, though fragments have been published in Conference Proceedings of the Mine Subsidence Technology Society (1995, 1998, 2001 and 2004).

Case history – Bellambi West Colliery

The importance to this study of Bellambi West Colliery, formerly South Bulli Colliery, lies in the fact that it was the first mine permitted to operate longwall panels under SCA-controlled stored waters, in this case those of Cataract Reservoir. Successful longwall extraction of the first five panels, it was claimed, recovered 2.5 million tonnes of coal and extended the mine life by eight years (Singh and Jakeman 2001). As described in Holla and Barclay (2000), longwall mining commenced in 1993 in a suitably cautious fashion, with narrow panels (110 m) and wide inter-panel pillars (66 m). The Bulli Seam at this location was 2.5 m thick and at a depth of 320–430 m below the surface.

A comprehensive program of surface subsidence and groundwater monitoring was conducted during the three years of panel mining. After extracting six panels the maximum subsidence had reached 173 mm, only 7% 0f the seam thickness, and surface strains did not exceed 1 mm/m. The results of the groundwater monitoring from eight piezometers have been described by Reid (1995) and Singh and Jakeman (2001). These may be summarised thus:

- The maximum height of fracturing reached to at least 85 m above the Bulli Seam (equivalent to 34 times the seam working height, and to 325 m below the surface. At this height the lowest piezometer drained to the caved goaf and remained dry.
- Piezometers set in the overlying Bulgo Sandstone continued to function, but experienced a drop in static water level, although they later recovered to near pre-mining levels. This indicates that an aquiclude below the piezometers, presumably the Stanwell Park Claystone, cracked during the passage of the longwall face beneath but subsequently closed up, allowing groundwater pressures in the Bulgo Sandstone to rise again.
- Groundwater levels in the Hawkesbury Sandstone, at the top of the overburden sequence, were unaffected by this mining almost 300 m below. It is presumed that the underlying Bald Hill Claystone, or other shale layers, retained their water-tightness despite being deformed by subsidence movements.
- On the evidence of mine pumping rates, no abnormal groundwater flows were recorded into the workings during extraction of the six longwall panels. In fact more water was generally pumped into the mine, for dust suppression, than was withdrawn. However it is likely that low mine inflows during the caving of the first longwall panels may have been due to drainage through older mine workings (i.e. the true inflow was not measured).
- Chemical analyses of mine water, performed to determine its origin (i.e. whether from direct infiltration through the overburden, from the stored waters of Cataract Reservoir, or from regional groundwater) were inconclusive.

Seedsman and Kerr (2001) and Singh and Jakeman (2001) continue the story with monitoring results from later panels with progressively wider longwall faces at Bellambi West. Five 150 m wide panels, still with relatively wide (66 m) chain pillars were extracted at a depth of 400 m, in 1998–2001. This resulted in a maximum surface subsidence of 240 mm, which was lower than the predicted 390 mm, and tensile strains of only 0.5 mm/m.

This group of panels is of interest because, like its predecessors, the subsidence was sub-critical (i.e. minimal because of the narrow face and wide pillars), in contrast to super-critical mining geometries involving multiple side-by-side panels and narrow pillars employed elsewhere on the coal field. Few details of the later groundwater monitoring program are given, which we understand was carried out by Douglas Partners, although it is stated that there was again no loss of water to the workings.

Case history – Dendrobium Colliery

Dendrobium Colliery is the newest longwall mine on the Southern Coalfield, located close to the edge, but not under, the stored waters of Avon and Cordeaux Reservoirs, within a pristine restricted access catchment area (Dendrobium COI, Cleland and Carleton, 2001). The colliery has been operating for about five years and is at present completing its third longwall panel. The Wongawilli Seam (2.8–3.5 m) is mined at depths which vary from 300–400 m beneath the sandstone plateau, to as little as 140 m in the vicinity of Kembla Creek. Large inflows of up to 8 ML/d into the mine workings have been reported in the past few weeks (June 2007), although there were no significant inflows during extraction of the first two panels. It is believed that these large flows may have occurred in a low cover section, possibly near Kembla Creek (M. Hughes, SCA, pers. comm.). This is the only large inflow to longwall workings at depths greater than about 100 m which has come to light during the present study.

Another potential hazard to mining at Dendrobium is that deep workings may also take in water from igneous sills, which have intruded seams and cindered the coal (Sinclair Knight Merz, 2001). Flows from these sources may be very high initially due to their great permeability, but diminish with time because of their limited storage (limited, that is, by the area of the sill and the volume of its cracks). Dykes may act either as groundwater dams (where unfractured, or where weathered to clay), or as vertical aquifers where fractured and fresh. Dykes are usually only minor sources of water in deep workings, though large flows are possible at depths less than about 100 m.

The permeability of the Cordeaux Crinanite in Area 2 at Dendrobium, which is yet to be mined, is unresolved. Large doleritic plugs or sills of this type may be closely fractured in their pre-mining state, yet have low hydraulic conductivity (bulk permeability) due to the tightness and lack of connectivity of the fractures. This could change during mining subsidence, as the fractures dilate and extend. Hydraulic conductivity increases with the cube of joint width, so dilation from an average of say 0.1 mm to even 1 mm could result in substantial flow increments. The Dendrobium COI has restricted mining within Area 2 to avoid subsidence cracking up to the Cordeaux Crinanite (Cleland and Carleton 2001).

The short term effects of subsidence on shallow aquifers in the Dendrobium area could be considerable and negative, though becoming positive in the longer term (Sinclair Knight Merz 2001). These fractured rock aquifers provide the stored groundwater which maintains base flow in catchment area streams between major rainfall events. Additional subsidence-induced cracking increases both their pore space and hydraulic conductivity, but because the volume of stored water does not increase (until the next storm, that is), water levels drop. Level recovery usually occurs within a few weeks or months, but it is usual for the post-mining water table to be flatter than before due to enhanced permeability. One consequence of this is that wells distant from discharge points along streams tend to have lower standing levels than before; another is that the water table profile below hills becomes of lower relief than previously.

The effect of mining-induced surface cracking on upland swamps at Dendrobium could be severe, where these bodies are in effect perched water tables dependent on ponded rainfall on top of thin clay or shale floors. Rupturing of these seals is quite likely, especially where they rest on bare rock rather than on deep soil, or where they occur close to cliffs. However their groundwater conditions are likely to vary greatly and should be assessed on a site by site basis.

Case history – Cataract River Gorge, Tower Colliery

The undermining of the Cataract River gorge by longwall panels (LWs) of Tower Colliery in the early 1990s (LWs 6–8 and 10) became a public controversy, encouraged by TV news footage of gas flames, dry swimming holes and conspicuous cracks in the bare sandstone stream bed. A summary report on streambed cracking, loss of stream flow and the release of hydrocarbon gases has been compiled by Everett et al. (1998), while the mining and subsidence aspects are briefly described in Holla and Barclay (2000). The issue of water losses into new fractures was complicated by the effects of drought and of controlled but irregular discharges by the Sydney Water Corporation (SWC) from the upstream Broughtons Pass Weir and spillovers from Cataract Dam.

Longwall mining of the Bulli Seam at a depth of about 430 m below the river bed was initiated by Tower Colliery in 1988. The first five panels (1988–91) were relatively narrow, only 110 m, with 40–48 m wide inter-panel pillars. Mining subsidence increased with each panel extracted, up to 325 mm for the fifth one. This represented only about 13% of the seam thickness of 2.5 m, a low figure for multiple panels on the Southern Coalfield, and ground strains were generally less than 1 mm/m. Probably due to these low subsidence parameters, no streambed losses were reported from these initial panels under the Cataract River.

The subsequent five panels (1991–93), located about 1 km downstream, were widened to 155 m. The maximum subsidence increased to 475 mm, 19% of seam thickness, by the tenth panel. During this period cracking became noticeable in the river bed, many rock pools drained and flow ceased altogether in 1994. A task force was set up to study the problem in 1996 and investigations were commissioned by BHP (the mine owners), the NSW Department of Mineral Resources (the mining regulator) and SWC. A large number of consultants' reports was produced and although we have not been able to access these, we have been provided with the summary report by Everett et al. (1998). The conclusions from the study were that:

- Flow in this reach of the Cataract River is greatly influenced by SWC water management practices, especially the timing and amount of discharges from Broughtons Pass Weir.
- The in situ rock mass along the river floor has been affected by pre-mining release of horizontal stresses and by the natural joint system, which have imposed a rectilinear course on the stream bed.
- This natural orthogonal joint pattern, which is common throughout the Southern Coalfield, has been overprinted by mining-induced subsidence fractures that are typically about 20 mm wide at the surface and are considered to be 5–20 m deep (though this depth has not been proven).
- The regional water table was found to be about 20 m above the river bed level at about 200 m into the gorge sides. The level of the water table does not appear to have been much affected by longwall mining 430 m below.
- The Hawkesbury Sandstone consists of stacked sub-aquifers, which are poorly interconnected in their pre-mining state. For example, a confined sub-aquifer was located by drilling 6 m below a surface pool; once intersected, groundwater rose 2 m in the borehole. The surface flow in this area was perched, in effect, on top of the groundwater system.
- During test discharges from Broughtons Pass Weir the river was found to have gained and lost water in different sections of the stream bed. Pools that had been considered permanent in pre-mining years were found to have emptied within 1–2 months after cessation of the test discharges.
- Flammable gas flows (methane, ethane) issuing from stream bed cracks were measured at up to 20 L/s. These were readily ignited and visible as columns of bubbles in pools. CSIRO investigations suggest that this gas was sourced from reservoirs in the Bulgo Sandstone, rather than from the underlying Bulli coalbed.

Case history – Waratah Rivulet, Metropolitan Colliery

Waratah Rivulet is a major contributor to storage at Woronora Reservoir and in recent years it has become the main focus of environmental protest against longwall mining-induced subsidence on the Southern Coalfield. A series of longwall panels extracted since the early 2000s has crossed beneath the catchment of Waratah Rivulet and its tributaries, causing serious stream bed cracking, loss of surface flow and extensive rust-like iron discharges at groundwater exit points. Public concern at this prompted the NSW Government, via the DPI, to commission a risk assessment prior to granting permission for Metropolitan Colliery to proceed with longwall panel LW 12 (Galvin 2005). The main relevant findings of the Galvin report were that:

- Upsidence has already (in 2005) led to periodic cessation of flow in portions of the Waratah Rivulet. All flow could be diverted underground during the mining of LW 12, but not into the mine workings because these are too deep. Some stream bed damage is 'inevitable' with the mining of this panel.
- Water losses filling mining-induced fractures could amount to 2–4% of average daily stream flow during drought periods and 0.5% of normal flows. Upsidence (valley floor bulging) due to mining of the previous LW 11 panel resulted in 4–4.5 ML/d being diverted underground. Fractured rock bars within the stream bed leaked and ceased to function as natural weirs.
- Visual evidence of surface water degradation is already apparent in the form of iron oxide blooms on the bare rock of the stream bed. It is estimated that natural amelioration of these waters could take 5–10 years.
- Remedial measures proposed by the colliery include sand-filling of fractures, in preference to cement grouting which is regarded as being rigid and likely to crack

during subsidence induced by extraction of future panels. However this is an experimental technique and its success is not guaranteed.

A presentation by Dr J. Jankowski of SCA at the 25 June DECC meeting gave some details and preliminary findings from a current joint research project being undertaken at Waratah Rivulet by SCA and consultants Parsons Brinckerhoff (Jankowski, 2007). This three year project covers longwall areas subsequent to those reported on by Galvin (2005) and will be completed in 2010. Hence the findings at present are largely tentative.

The study area covers about 3.5 km^2 of the Waratah Rivulet catchment and includes two of its tributaries. It is situated immediately above longwall panels LW 10–16, which are currently being extracted. Unfortunately there is little pre-mining flow or water quality data, so comparisons have to be made with similar pristine catchments elsewhere in the Southern Coalfield.

The scope of the project includes more intense monitoring of water balance (stream recharge/discharge relations), surface-groundwater interactions and geochemical changes to surface water than has been attempted previously on the Southern Coalfield. Within a small catchment two surface flow gauging stations (one upstream and one downstream of the active mining area), 12 observation boreholes and 9 water sampling points have been set up. The research program includes extensive water sampling and testing, the use of four subsurface flow tracers and water dating (to determine whether it has resided a long time in the groundwater system or has only recently leaked from surface flow).

Preliminary findings from the study suggest that:

- There is a lack of baseline flow and water quality data for this catchment. Ideally monitoring should commence at least two years before any mining and may have to continue for ten years afterwards, as the groundwater system recovers towards its equilibrium. Recovery to 80% of pre-mining levels might define a practical duration for the monitoring program.
- During river low stages, upstream flows are greater than those gauged downstream (i.e. surface water is lost into subsidence-induced fractures where the rocky bed of the Waratah Rivulet crosses the longwall panels). In places this loss approaches 100% of flow. Post mining recovery of groundwater levels is likely to take more than seven years. The opposite is true during high flow periods – downstream flows exceed those upstream.
- Some of Dr Jankowski's diagrams implied that mining-induced fractures could extend to 60 m depth. (This is at odds with the generally accepted fracturing depth of 10–15 m; however his estimate may be based on better information.) In the top 10 m or so the rock mass fracture porosity may increase from an assumed pre-mining value of 20% to as much as 45% during mining. (In our opinion these figures are much too great, and rock mass porosities are unlikely to exceed a few percent.)
- Water salinity in the surface flow increases from about EC 200 to 350 μS/cm while crossing the subsided area, though some recovery is effected by downstream dilution.
- Other indicators of increased salinity due to downstream discharge of groundwater back into surface waters include increases in Ca content (up three-fold), Fe (concentration up 3–4 times), Mn (possibly up ten-fold) and large increase in Ba and Sr content. Conspicuous efflorescences of rust-like Fe/Mn oxides and hydroxides have developed at stream bed groundwater discharge sites, providing dramatic visual evidence of the problem.

Impacts on surface waters

Impacts on flow

Many of the reports consulted (such as Galvin, 2005) reported large losses of surface flow when streams crossed cracked and heaved ground above mined-out longwall panels, even where the depths of cover to seam level were more than 400 m. In some instances during recent drought years a complete loss of flow was observed, although this has not been quantified by stream gauging data. We understand that the SCA only commenced gauging of streams entering water storages in 2006, though local gauging may have been performed at mine sites such as Bellambi West before this date. An SCA research project is at present being conducted on the Waratah Rivulet above longwall panels of Metropolitan Colliery, and will address this issue as well as water quality changes (Jankowski 2007).

Impacts on quality

This surface water quality assessment of the impact of longwall mining in the Southern Coalfield is based on two reports:

- Final Report of the Cataract River Taskforce (Everett et al. 1998); and
- Hydrological and water quality assessment of the Cataract River, June 1999 to October 2002 (2003) (Bennett et al. 2003).

The impacts of longwall mining on surface water quality have been monitored in the Cataract River by numerous organisations, under various flow scenarios and at locations downstream of Broughtons Pass Weir. Monitoring data were collected between 1996 and 1997 and 1999 to 2002 (excluding 2001). A summary of the key water quality data are provided below:

- Dissolved Oxygen (DO) levels varied along the length of the river. Under low flow (i.e. no releases from Broughtons Pass Weir), DO was generally low, failing to comply with the ANZECC/ARMCANZ (2000) guidelines for protection of aquatic ecosystems, particularly in the lower part of the Cataract River and around the ‘Longwall 10 Bubble Pool’.
- Data indicated that immediately downstream of Broughtons Pass Weir and upstream of the lower mined area of the Cataract River, DO levels were within limits. Flow releases from Broughtons Pass Weir generally improved dissolved oxygen concentrations along the length of the river, although the lower reaches and the Bubble Pool continued to have unsatisfactory DO levels. In these reaches flow was generally non-existent or significantly reduced compared to upstream sites and was largely made up of groundwater inflow.
- Temperature data in the reports is limited, with extensive sampling at one site only (the Bubble Pool) and longitudinal sampling of the river limited to one event. The data obtained is seasonably variable. Therefore there is insufficient data to confidently assess the water quality in terms of temperature.
- Iron concentrations were measured both prior to and during flow releases. Prior to the test flow releases, iron was recorded at concentrations significantly in excess the ANZECC/ARMCANZ (2000) guidelines. Following flow releases, iron concentrations reduced considerably, but remained high in the downstream reach near the Bubble Pool. Observations during site visits supported the presence of iron, with areas showing thick growths of iron bacteria. At the lower reaches surface flow included a large proportion of groundwater.
- Metal concentrations were monitored, although data is limited. Of the samples collected surface water was found to be high in manganese, silica and sodium. All data were collected during flow releases.
- Total nitrogen data is limited, but results indicate elevated concentrations throughout the Cataract River, which were significantly higher prior to flow releases. High nitrogen

levels are not uncommon in the Cataract River, with high levels detected upstream of Broughtons Pass Weir and in the Nepean River itself.

- The colour of the Cataract River was compared to that of the Nepean River during a field trip in September 2001. Immediately upstream the colour was noticeably reduced and continued to become more yellow with distance upstream (to about 500 m upstream of the confluence). Whilst this data is limited to one occasion, discolouration of the Cataract River has been observed since 2000.

Generally the water quality prior to weir flow releases was very poor, improving with increased flow and dilution. The downstream reaches of the Cataract River continued to have poor water quality, which coincided with significantly reduced surface flows (compared with upstream) and the upwelling of groundwater. It would appear that the quality of water at these sites is heavily impacted by groundwater inflow, although with limited groundwater data, this cannot be confirmed.

The water quality monitoring data reviewed has been limited and erratic. There has been no consistency in sites monitored between organisations. The frequency of sites monitored has also varied, with data at particular sites significantly more abundant than others. For example a site known as the Bubble Pool or 'Longwall 10' was heavily monitored between 1999 and 2002, although other sites on the Cataract River were limited to one sampling event. Sampling data is also patchy due to equipment failure and the unreliable quality of the data. Such ad hoc sampling limits the veracity of the data.

Gaps in existing knowledge

Groundwater in general

- Groundwater investigations done prior to 1987 were entirely concerned with small, areas of shallow, non-longwall, limited-subsidence pillar extraction. In contrast, mining carried out in 1987–2007 was mainly by longwall methods and these were much larger scale, deeper, full-subsidence operations. The later mining would have had a much greater effect on groundwater flow and quality.
- Little published information is presently available from groundwater studies on the coalfield over the past 20 years. What groundwater monitoring has been done was for mining companies and was unpublished, though copies of some reports may have been lodged with the DSC or DPI.
- Studies throughout the past 30 years have focused on small, localised problem areas – the Cataract River gorge, the headwaters of Avon and Cataract Reservoirs, plus limited scope investigations close to active or planned longwall panels (or as directed by the DPI or the DSC).
- Hence no coalfield-wide hydrogeological baseline study is available. Presently investigated areas cover perhaps 10% of the field. We are unaware of any systematic long term groundwater monitoring being carried out at present.
- Because of the preoccupation with potential stored water losses to deep mine workings, little attention has been paid to the problem of loss of upstream flow to shallow aquifers in the Hawkesbury Sandstone. This has developed into the key hydrogeological issue on the coalfield.

Shortcomings in groundwater investigations

- Nearly all of the permeability carried out testing to date has been based on narrow borehole (say 75–100 mm diameter) Lugeon or injection tests, which record horizontal rather than vertical permeability.
- Some comparison with pump discharge tests are required to calibrate the Lugeon test results, since the former are more reliable indicators of the gross hydraulic conductivity of the overburden rock mass. Limited experience elsewhere suggests that the Lugeon tests, though quicker and cheaper than discharge tests, may greatly underestimate hydraulic conductivity in the Hawkesbury Sandstone.
- There are few before and after comparisons of unmined vs mined overburden permeability tests. However overseas experience suggests that mining-induced subsidence may increase the hydraulic conductivity by one to three orders of magnitude, though these effects diminish with distance above the mine workings.
- We are unaware of any long term monitoring of shallow aquifers in the Hawkesbury Sandstone, or even of any publicly-accessible regional study of these aquifers. (However this may emerge from present drought supply groundwater investigations by the SCA.)

Shortcomings in surface water monitoring

The following remarks refer to the monitoring of the Cataract River only, since we have no information on other watercourses.

- There appears to be limited data on groundwater - surface water interaction, despite groundwater having a significant contribution to surface flows in the lower reaches of the Cataract River. Groundwater and surface water are often closely linked and there is a risk of over-estimating the total resource by treating them as separate entities (Evans, 2007).

- Flow data and water quality data appear to be poorly linked in the monitoring carried out to date, with flow gauges not directly linked to sampling sites and missing flow data. (We could not confirm whether this is due to no flow or equipment failure).
- Environmental flow releases from Broughtons Pass Weir appear to be insufficient to keep surface flow in the Cataract River. This limits the ability to obtain water quality data.
- There is inconsistency between the sites and water quality variables monitored prior to flow releases and after flow releases.
- Colour was monitored on one sampling event via Secchi depth. Considering the reports of discoloration, a more rigorous test should be undertaken which includes the collection of a filtered sample.
- Hydrogen sulphide was tested for only once, despite numerous reports of its odour.
- A more rigorous and structured monitoring program needs to be undertaken. Defined sites need to be selected and monitored routinely for a range of parameters including physical parameters, metals (iron, manganese, silica etc), true colour, dissolved methane, hydrogen sulphide and odour.
- Likely constituents of groundwater based on geology (in the Hawkesbury and Bulgo Sandstones) such as fluoride and chlorine should be sampled in the surface water, to aid in determining its groundwater contribution.
- We need to know what amount of flow is required in the river to improve the surface water quality so that it complies with relevant guidelines.

Surface water and groundwater monitoring systems

Previous water monitoring

Prior to about 2003 some groundwater monitoring had been carried out intermittently over the previous thirty years at a few collieries such as Corrimal, Huntley, Kemira, South Bulli (later to become Bellambi West), Tower and Westcliff. In general this was done in response to reported stream bed damage, or in support of applications to introduce or to widen longwall mining. We do not the extent to which this network is still being monitored, but the available information suggest that this could be confined to just three sites: Appin Area 3, Metropolitan Colliery (Waratah Rivulet) and the Cataract River. The monitoring results were submitted to DPI and possibly to other NSW Government agencies such as the DSC, and some of this data has been published (for example, Reid, 1995; Singh and Jakeman, 2001). In addition, we understand that:

- The SCA is now gauging streams flowing into its reservoirs, but that this was only commenced in 2006.
- Some stream gauging may have been performed close to subsided longwall workings by individual collieries, although we have no details of these investigations.
- DWE and SCA may be monitoring a network of observation bores within the Southern Coalfield and nearby areas, but we have no details at present of either the borehole locations, nor the monitoring methods and results.

In short, the water monitoring system on the Southern Coalfield up to the early 2000s was generally very limited, particularly with respect to gathering baseline (pre-mining) data. The monitoring regime had been developed on an ad hoc basis and even key elements, such as stream gauging stations, have only been set up in recent years. Groundwater monitoring was carried out by individual collieries for the DPI, and by DWE and SCA for their own purposes. It appears that the results were largely filed and forgotten, and that there has been no attempt made to integrate these results into a regional picture.

A more rigorous, though still uncoordinated monitoring system is now in force through the introduction of Subsidence Management Plans for proposed longwall mining areas. This is discussed below.

Subsidence Management Plans

In the past five years the DPI has responded to public criticism of subsidence damage along watercourse such as the upper Georges River (Marnhyes Waterhole, Westcliff Colliery), the Cataract River gorge (Tower Colliery) and the Bargo River (Tahmoor Colliery) by initiating a system of pre-mining Subsidence Management Plans (SMPs). These form part of the requirements for gaining extraction approval for each group of longwall panels. An End of Block Report is further required on completion of each panel, detailing actual (as opposed to predicted) subsidence measurements, compliance with conditions imposed as part of the SMP approval process, and the effectiveness of any remedial measures carried out.

One current example of an SMP was examined as part of this study. This SMP was that for Appin Colliery Area 3, consisting of three short longwall panels expected to be mined in the period 2005–2007. One end of these panels is located adjacent to the Cataract River upstream from Broughtons Pass and Jordans Pass Weirs (Comur Consulting 2005). The full extraction (hence maximum subsidence) area has been configured such that it does not intrude beneath the Cataract River – hopefully avoiding stream bed damage similar to that caused when Tower Colliery drove several panels beneath the river about 3 km downstream in the early 1990s. However the panel access roadways (tunnels) do run beneath the river, though at a depth of around 500 m.

The Area 3 SMP is a substantial document, with about 200 pages of text plus a similar thickness of appended specialist consultant reports. It covers such issues as:

- The proposed mining system, its location, the need for maximising resource recovery, land ownership and approval requirements.
- The physical conditions of the site, including overburden geology, existing groundwater regime, river bed geomorphology and ecosystems, and the likely impacts of mining-induced subsidence upon these.
- Surface features, both natural and man-made, to be protected.
- Proposed subsidence management and monitoring programs.

On the key issue relevant to the present study, the SMP identifies possible hydrogeological effects arising from mining-induced subsidence as:

- Release of saline Fe/Mn rich groundwater, either via springs at the top of the Hawkesbury Sandstone, or into sub-aquifers in the upper part of the sandstone. However it is expected that the small volume of this groundwater will be greatly diluted by surface water flows.
- An increase in the horizontal hydraulic conductivity of the sandstone through shearing along bedding, but with little change in the vertical flow.
- Possible diversion of some surface water from the stream bed into shallow sandstone aquifers to a maximum depth in the order of 10 m, though BHPB points out that the depth to mining is about 500 m and no total extraction will occur under the river bed.

In the SMP the company acknowledges that both groundwater flow and geochemical processes within the Hawkesbury Sandstone are poorly known, and therefore proposes baseline hydrogeological investigations to improve this situation. The elements of this program would comprise:

- Drilling a fully cored borehole in the sandstone, to about 10 m below river level. (However it is not clear whether this hole is to be collared at plateau level or at river level, i.e. whether it is to be about 60 m deep or only 10 m.)
- Fully logging the core to determine sedimentological facies and stratigraphic details (and hence, we presume, to provide information on sub-aquifers and aquitards within the sandstone).
- Water pressure (packer) testing to determine horizontal hydraulic conductivity at intervals through the sandstone. The SMP suggests that the total tested interval is to be the topmost 30 m in the borehole.
- Completion of this borehole as a groundwater observation hole with a vibrating wire piezometer.
- Drilling of a second piezometer hole (type unspecified) nearby, to monitor upper high permeability zones identified by logging and packer testing.
- Periodic determination of water quality in samples extracted from the boreholes. Details of the proposed water quality monitoring program are given in a separate BHPB document which has not been made available to us.

Though the groundwater monitoring proposed in this SMP represents a considerable advance on what has been the practice in the past, it is vague on details – especially the duration of monitoring before and after mining, and its frequency. Furthermore only a single site is to be monitored, though the proposed mining could affect a 2–3 km length of the Cataract River.

Framework for impact monitoring

This suggested framework is geared towards assessing the near-surface impacts of mining-induced subsidence, including valley floor lifting and fracturing, on surface water and shallow groundwater. Although much of the Southern Coalfield groundwater and surface hydrological data has not yet become available for review, it appears that a wider and more intensive monitoring network needs to be devised for the future. In parallel with this a better data management system needs to be devised, to ensure that the vast amounts of water monitoring results that are becoming available, and the even greater quantities that will come to hand in the future, are properly analysed and used effectively.

Following discussions at the 25 June workshop and the findings of this report it appears that the development of this framework for monitoring might include:

- Better defining the limits of the project area. This might coincide with the Metropolitan Special Catchment Area, or it could be wider. The Southern Coalfield is much more extensive than the special area and areas likely to be affected by future longwall mining are distant from SCA storages.
- Improving the coordination, collection and storage of monitoring data, which is at present handled by numerous regulatory authorities, mining companies and their delegated consultants.
- Identifying all existing groundwater observation bores within the project area, including those no longer operational but for which past monitoring data are available.
- Locating, assembling and summarising this groundwater data and presenting it in spatial form.
- Identifying all existing surface water sampling and flow gauging sites within the project area for which data is available.
- Locating and summarising this data for storage and presentation in spatial form.
- Critically reviewing the observation borehole and gauging station data, such as it is, to characterise the existing situation and prepare a regional hydrogeology report.
- Highlighting deficiencies in terms of the spread of data points, the monitoring methods, duration and frequency of monitoring.
- Using this report, in conjunction with discussions with relevant authorities and interested parties, to facilitate planning for an upgraded network.
- Devising an exploration strategy, drilling and water testing program to overcome identified deficiencies.
- Performing numerical modelling of groundwater and surface water flow in response to mining-induced subsidence, and quantifying surface-groundwater interaction.
- Reporting periodically during the setup phase of the monitoring and devising strategies for long-tern data collection, processing and retrieval.
- Devising management procedures for impact assessment and remedial actions.
- Reviewing the operation and effectiveness of the upgraded monitoring network at, say, five year intervals.

We consider that the proposed monitoring network could include perhaps 100–200 new observation boreholes, located so as to cover the project area with particular emphasis on areas likely to be mined in the medium term, say the next 5–20 years. The drilling program would be directed towards monitoring changes in shallow groundwater (say less than 20–30 m depth) in both quantity and quality. Boreholes should generally be located close to watercourses, but especially near important hydrological features such as gauging stations and upland swamps. A few deep holes below plateau surfaces will also be required, to intersect a regional water table that might be present at >100 m.

Another priority task should be the investigation of fracture flow (stepping downward from joint to bedding to joint) and the nature of stacked sub-aquifers (perched water tables) in the Hawkesbury Sandstone. This is especially important in the study of ‘hanging swamps’.

Conclusions

1. The key hydrogeological issue on the Southern Coalfield is the loss of stream flow to shallow fractured sandstone aquifers, say to those less than 20 m deep. At this stage it is not certain whether this loss is temporary or permanent, and analysis of observations is complicated by the impact of the present drought. Overseas experience suggests that falling stream flows and borehole levels induced by mining subsidence are generally short term, from a few months to several years. A considerable amount of research is being carried out at present, particularly along the Waratah Rivulet, which flows into Woronora Dam, and more definite conclusions should be possible within a few years.
2. Water quality in surface flows is also being influenced by upstream infiltration into subsidence-induced cracks. These cracks result from the effects of valley floor bulging or ‘upsidence’ caused by shearing and flexing of rocky stream floors. Such forces are generated by subsidence-induced compressive strain concentrations, possibly exacerbated by naturally high lateral stresses. High Fe/Mn and other cation concentrations, caused by movement of oxygenated surface water through newly-exposed rock on the fracture walls, are highly visible as rust-like blooms at downstream discharge points. Subsidence-affected stream reaches may also be cloudy in appearance due to suspended matter.
3. The potential loss of surface water into deep (400–500 m) mine workings appears to be much less of an issue on the Southern Coalfield than was the case thirty years ago, at the time of the Reynolds Inquiry. In general, leakage of surface waters and shallow groundwater into workings is likely to be considerable only where the mining depth above total extraction (de-pillared) panels is less than about 100 m. No longwall workings, present or planned on the Southern Coalfield, are this shallow.
4. Below about 200 m depth, however, this flow has been found to be generally negligible due to the presence of more than 100 m of largely intact strata between the heavily fractured goaf and the cracked near-surface zone. In effect, longwall subsidence creates two separate fractured zones, one in the top 10–15 m (due to the lack of rock mass confinement) and another in the lowest 10–50 m due to caving. Normally there is only a tenuous hydraulic connection between the two, so they function as separate aquifers if saturated.
5. However deep workings may rarely experience large inflows from the surface, where major penetrative discontinuities such as dykes and faults are intersected. The presence of such features on the Southern Coalfield is often indicated by major lineaments visible on airphotos, which also carry surface streams along linear gullies – thus the lineament may act as both water source and conduit to deep workings.
6. Deep workings may also take in water from igneous sills, which have intruded seams and cindered the coal. Flows from these sources may be very high initially due to their great permeability, but diminish with time because of their limited storage (limited, that is, by the area of the sill and the volume of its cracks). It is speculated that large inflows at Dendrobium Colliery in the past weeks may have been of this type. Dykes may act either as groundwater dams (where unfractured, or where weathered to clay), or as vertical aquifers where fractured and fresh.
7. The effect of mining-induced surface cracking on upland swamps could be severe, where these bodies are in effect perched water tables dependent on ponded rainfall on top of sandstone bedding planes. Rupturing these perched water tables by joint extension or fresh cracking is quite likely to occur during the tensile phase of subsidence movements. However their groundwater conditions are likely to vary greatly – some sites may flourish from increased inflows, while new groundwater dependent ecosystems may develop in response to the changed conditions. These should be assessed on a site by site basis.

8. The present monitoring system for both surface water and groundwater is limited in geographical extent, has been set up on an ad hoc basis, and is overseen by a number of public authorities. There appears to be no attempt made to analyse the data collected or to integrate it into a regional framework. The amount of information collected has been greatly increased in recent years due to the introduction of Subsidence Management Plans for each new group of longwall panels, but its collection and storage is still uncoordinated. In particular there is a need for pre-mining baseline studies.

Recommendations

1. As a first step towards developing an improved water monitoring system for the Southern Coalfield, the existing fragmented one should be carefully examined. This would involve collation and analysis of information presently held by the Department of Primary Industry, the Sydney Catchment Authority, the Dams Safety Committee and the mining companies themselves, especially BHP Billiton. The aim would be present a regional view of surface and groundwater distribution, flow and quality throughout the coalfield.
2. Plan and implement an upgraded network of observation bores, water sampling points and gauging stations. Such a network would primarily be directed towards:

- Investigating surface-groundwater interaction, flow and water quality in shallow sandstone aquifers, stream beds and upland swamps.
- Providing baseline data for new or proposed mining areas up to 20 years ahead of mining.
- Providing post-mining assessments of water in and around closed mines, the extent of natural remediation and potential groundwater hazards.
- Devising consistent and cost-effective monitoring and sampling techniques for both groundwater and surface water.
- Performing numerical modelling of surface and groundwater as required.

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References

Anderson D., Stapledon D.H. and Mattes N.S. 1989. Coal mining beneath reservoirs in NSW, 1979–1989. Unpublished report for Dams Safety Committee.

ANZECC/ARMCANZ. 2000. Australian and New Zealand guidelines for fresh and marine water quality. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand. http://www.mincos.gov.au/pub_anzwq.html

Atkinson A.A. 1902. Working coal under the River Hunter, the Pacific Ocean and its tidal waters near Newcastle NSW. Transactions of the Institution of Mining Engineers 23: 622–667.

Bennett S., Keenan S. and Butler S. 2003. Hydrological and water quality assessment of the Cataract River, June 1999 to October 2002: implications for the management of longwall coal mining. NSW Department of Infrastructure, Planning and Natural Resources, Sydney.

Booth C.J. 1986. Strata movement concepts and the hydrogeological impact of underground coal mining. Ground Water 24: 507–515.

Booth C.J. 2002. The effects of longwall coal mining on overlying aquifers. In: Younger P.L. and Robins N.S. (editors). Mine water hydrogeology and geochemistry. Geological Society of London Special Publication 198. p. 17–45.

Booth C.J. and Spande E.D. 1992. Potentiometric and aquifer property changes above subsiding longwall panels, Illinois Basin Coalfield. Ground Water 30: 362–368.

Bruhn R.W. 1988. Influence of deep mining on the ground water regime at a mine in northern Appalachia. In: Proceedings 2nd workshop on surface subsidence due to underground coal mining, Morgantown WV, June 1988. p. 234–248.

Bunny M.R. 1972. Geology and coal resources of the southern catchment coal reserve, NSW. Geological Survey of NSW Bulletin 22.

Cleland K. and Carleton M. 2001. Dendrobium underground coal mine project. Report of Commissioners of Inquiry to the Minister for Urban Affairs and Planning.

Comur Consulting. 2005. Appin Colliery longwall panels 301A to 302 [Area 3] – Subsidence Management Plan application. (3 volumes). Report prepared for DPI. BHP Billiton, Melbourne.

DMR. 2000. NSW coal industry profile. NSW Department of Mineral Resources, St Leonards NSW.

Doyle J.F. and Poole G.R. 1986. An investigation into a water inflow at Wongawilli Colliery, Southern Coalfield NSW. In: Aziz N. (editor). Ground movement and control related to coal mining. AusIMM conference, Wollongong, Aug 1986. p. 24–31.

Dumpleton S. 2002. Effects of longwall mining in the Selby Coalfield on the piezometry and aquifer properties of the overlying Sherwood Sandstone. In: Younger P.L. and Robins N.S. (editors). Mine water hydrogeology and geochemistry. Geological Society of London Special Publication 198. p. 75–88.

ECNSW. 1988. Huntley/Robertson coal exploration program – report on hydrogeological investigations. Electricity Commission of NSW, unpublished geotechnical report GEO 5.

Everett M., Ross T. and Hunt G. 1998. Final report of the Cataract River Taskforce. Report to Upper Nepean Catchment Management Committee, Picton NSW.

Evans R.S. 2007. The impact of groundwater use on Australia's rivers – exploring the technical, management and policy changes. Land and Water Australia, Canberra.

Farmer I.W. 1985. Coal mine structures. Chapman and Hall, London.

Forster I.R. 1995. Impact of underground mining on the hydrogeological regime, Central Coast NSW. In: Sloan S.W. and Allman M.A. (editors). Engineering geology of the Newcastle-Gosford region. Australian Geomechanics Society, Newcastle. p. 156–168.

Holla L. 1997. Ground movement due to longwall mining in high relief areas in NSW. International Journal of Rock Mechanics and Mining Science 34: 775–787.

Holla L. and Barclay E. 2000. Mine subsidence on the Southern Coalfield NSW. NSW Department of Mineral Resources, Sydney.

Holla L. and Buizen M. 1991. Ground movement, strata fracturing and changes in permeability due to deep longwall mining. International Journal of Rock Mechanics and Mining Science 28: 207–217.
Jankowski J. 2007. Current scientific understanding of longwall mining impact on water quality and quantity. Presentation on current Waratah Rivulet SCA research project, given at DECC, 25 June 2007.
Galvin J. 2005. A risk study and assessment of the impacts of longwall mining on Waratah Rivulet, Metropolitan Colliery. Unpublished report by Galvin and Associates for DPI.
Krogh M. 2007 (in press). Management of longwall coal mining impacts in Sydney's Southern Drinking Water Catchments. Australian Journal of Environmental Management.
Liu J. and Elsworth D. 1997. Three-dimensional effects of hydraulic conductivity enhancement and desaturation around mining panels. International Journal of Rock Mechanics and Mining Science 34: 1139–1152.
Matetic R.J.; Liu J. and Elsworth D. 1995. Modeling the effects of longwall mining on the groundwater system. US Bureau of Mines Report of Investigations RI 9561.
McKibbin D. and Smith P.C. 2000. Sandstone hydrogeology of the Sydney region. In: McNally G.H. and Franklin B.J. (editors). Sandstone City – Sydney's dimension stone and other sandstone geomaterials. EEHSG of Geological Society of Australia and Conference Books, Springwood NSW. p. 83–97.
McNally G.H. 1981. Valley bulging at Mangrove Creek Dam. NSW Geological Survey Quarterly Notes 42.
Moebs N.M. and Barton T.M. 1985. Short-term effects of longwall mining on shallow water sources. In: US Bureau of Mines Information Circular IC 9042. p. 13–24.
Pennsylvania DEP. 1999. Impact of underground coal mining. DEP issues report. Pennsylvania Department of Environmental Protection, Harrisburg PA.
Regan W. 1980. Report on the nature of the defects in Narrabeen Group rocks in the Southern Coalfield. Unpublished report by Coffey Partners to NSW Dams Safety Committee.
Reid P. 1990. Summary report on mining within the restricted zone of Brennans Creek Dam [by Westcliff Colliery]. Unpublished report to NSW Dams Safety Committee.
Reid P. 1995. Controlled mining under Cataract Reservoir. In: Proceedings 3rd Mine Subsidence Technology Society Conference, Newcastle. p. 179–187.
Reid P. 1996. Effect of mining on permeability of rock strata on the Southern Coalfield. In: McNally G.H. and Ward C.R. (editors). Symposium on geology in longwall mining. Conference Books, Springwood. p. 273–280.
Reid P. 2001. Further analysis of horizontal movements around Cataract dam, 1980–1997. In: Proceedings 5th Mine Subsidence Technology Society Conference. p. 211–218.
Reynolds R.G. 1977. Coal mining under stored waters. Report of an inquiry for the NSW Government on coal mining under stored waters of Nepean, Avon, Cordeaux, Cataract and Woronora Reservoirs, NSW.
Sherwin L. and Holmes G.G. 1986. Geology of the Wollongong and Port Hacking 1:100,000 sheets 9029 and 9129. NSW Department of Mineral Resources, St Leonards NSW.
Sinclair Knight Merz. 2001. Effects of longwall mining on groundwater and aquifers [at proposed Dendrobium Colliery]. SKM Report EN01120.071 to Sydney Catchment Authority submission to Dendrobium Colliery Commission of Inquiry.
Singh R.N. and Jakeman M. 2001. Strata monitoring investigations around longwall panels beneath the Cataract Reservoir. Mine Water and the Environment 20: 55–64.
SCA. 2006. Groundwater investigations for drought water supply. Technical overview report by Sydney Catchment Authority.
Seedsman R. 1996. A review of the hydrogeological aspects of Australian longwalls. In: McNally G.H. and Ward C.R. (editors). Symposium on geology in longwall mining. Conference Books, Springwood. p. 269–272.
Seedsman R. and Kerr G. 2001. Coal extraction beneath Cataract Reservoir: mining at Bellambi West from 1998 to 2001. In: Proceedings 5th Mine Subsidence Technology Society Conference. p. 199–210.
Tammetta P. and Hewitt P. 2004. Hydrogeological properties of Hawkesbury Sandstone in the Sydney region. Australian Geomechanics 39: 93–108.

Waddington A. and Kay D. 2001. Closure and uplift in creeks, valleys and gorges due to mine subsidence. In: Proceedings 5th Mine Subsidence Technology Society Conference. p. 49–61.
Waddington Kay Associates (WKA). 2001. Impacts of mine subsidence on the strata and hydrology of river valleys. In: Management guidelines for undermining cliffs, gorges and river systems. Report C8005 by Waddington Kay and Associates to ACARP.
Waddington Kay Associates (WKA). 2002. Management information handbook on the undermining of cliffs, gorges and river systems. Report by Waddington Kay and Associates to ACARP.
Walker J.S. 1988. A case study of water level fluctuations over a series of longwall panels in the northern Appalachian coal region. In: Peng S.S. (editor). Proceedings 2nd workshop on surface subsidence due to underground coal mining Morgantown WV, June 1988. p. 264–269.
Whitfield L.M. 1986. Monitoring and investigation of water inflow into a coal mine in NSW. In: Cripps J.C. (editor). Groundwater in engineering geology. Geological Society Engineering Geology Special Publication 3. p. 417–421.
Whitfield L.M. 1988. The effect of coal mining on the hydrological regime of the Southern Coalfield NSW. In: Proceedings, 5th ANZ Geomechanics Conference, Sydney. p. 78–82.
Whittaker B.N., Singh R.N. and Neate C.J. 1979. Effect of longwall mining on ground permeability and subsurface drainage. In: Argall G.O. (editor). Mine drainage. Proceedings of international mine drainage symposium, Denver CO. p. 161–183.
Whittaker B.N. and Reddish D.J. 1989. Subsidence: occurrence, prediction and control. Elsevier, Amsterdam.
Williamson 1978. Hydrogeological aspects of coal mining under stored waters near Sydney, Australia. In: Proceedings of international symposium on water in mines and underground works, Granada, Spain, 1978. p. 309–328.

Acronyms

ACARP. Australian Coal Association Research Program.

BHPB. BHP Billiton.

CSIRO. Commonwealth Scientific and Industrial Research Organisation.

DECC. NSW Department of the Environment and Climate Change.

DPI. NSW Department of Primary Industry.

DSC. Dams Safety Committee.

DWE. NSW Department of Water and Energy.

EC. Electrical conductivity (a measure of salinity).

ECNSW. Electricity Commission of NSW.

HSS. Hawkesbury Sandstone.

LW. Longwall panel.

MWSDB. Sydney Water Board (previously Metropolitan Water, Sewerage and Drainage Board).

SCA. Sydney Catchment Authority.

SMP. Subsidence Management Plan.

SWC. Sydney Water Corporation.