A case study of an alternative approach to coal mine site water management:
West Cliff Colliery NSW

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A CASE STUDY OF AN ALTERNATIVE APPROACH
TO COAL MINE SITE WATER MANAGEMENT:
WEST CLIFF COLLIER, NSW.

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE AWARD OF THE DEGREE OF
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From The
University of Wollongong

By
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2007
CERTIFICATION

I, Antony John Volcich, declare that this thesis, submitted in fulfilment of the requirements for the award of the degree of Master of Environmental Science (Research), University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Antony John Volcich
ABSTRACT

The provision of water supply, its usage and discharge, are major concerns for all mines, both underground and opencut, often accounting for a significant portion of the daily running cost of mining. To reduce these costs, mines will often collect as much site runoff as possible, and recycle the water whenever economically feasible. The constant recycling of on-site waters can mean that, over time, the levels of salinity, acidity or alkalinity, or other contaminants may build up within the internal water management system to a point which may lead to problems with licensed discharge requirements.

This project investigated the water quality at West Cliff Colliery, an underground coal mine, in the Illawarra Coal Measures, in order to develop an improved system for managing water resources with minimal environmental impact. While West Cliff Colliery is totally self sufficient and independent of any town water supply, issues have arisen with the quality of water being discharged into the receiving waterways, Brennans Creek and the upper Georges River. To alleviate these issues, a new water management system (WMS) has been established to try and maintain an adequate supply of clean recycled water and to prevent uncontrolled discharges to the environment outside West Cliff’s Environmental Protection Licence (EPL) requirements.

To monitor changes in the WMS, a new operation of the system involved a daily testing and monthly sampling regime of the key water quality parameters pH, EC, temperature and ORP. These parameters were measured at designated sites within the WMS using probes and meters that had been freshly calibrated each day. Monthly grab samples were also taken from the same designated sites for laboratory analysis of trace (heavy) metals. Chemical speciation modelling was also carried out in order to determine the ecotoxicity of dissolved trace metals in the discharge water.

Operating the WMS in the new manner prescribed led to a significant reduction in uncontrolled discharges to the environment, a reduction in salinity of the WMS water, a reduction in the concentrations of potentially ecotoxic elements As, Cu, Ni, and Zn. It also maintained a high level of compliance with the mines current EPL and provided a more constant environmental flow in the upper Georges River without having to resort to much more costly forms of water treatment.
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List of Symbols and Acronyms

AMD – Acid Mine Drainage
BCD – Brennans Creek Dam
CPP – Coal Preparation Plant
CWM – Coal Washery Material
DEC – Department Environment and Conservation
Density – Grams per centimetre$^3$
EC – Electrical Conductivity
EPA – Environmental Protection Authority
EPL – Environmental Protection License
GAC – Granular Activated Charcoal
GRP – Gross Regional Product
LDP – Licensed Discharge Point
LOR – Limit of Resolution
mg/L – Milligrams per litre
ML – Megaliters
mV – Millivolts
NATA – National Association of Testing Laboratories
NOEC – No Observable Effect Concentration
O&G – Oil and Grease
ORP – Oxidation Reduction Potential
pH – Potential Hydrogen

PLC – Programmable Logic Control

PRP – Pollution Reduction Program

S.d. – Standard deviation

T – Temperature Degrees Celsius

TDS – Total dissolved solids

TSS – Total suspended solids

µg/L – Micrograms per litre

µS – Micro Siemens

WMS – Water Management System
1.1 GENERAL INTRODUCTION

Coal was first used on a commercial scale in China as early as 200 B.C. to evaporate brine in China’s ancient salt making industry (AUSIMM, 1993). The first known European reference to coal was by Aristotle who said, “Those bodies which have more of earth than of smoke are called smoke-like substances”. Around 370 B.C., Theophrastus wrote a book *The History of Stones*, which had reference to “some of the more brittle stones which became as it were, burning coals when put in a fire and continued so for a long time” (AUSIMM, 1993).

The use of coal became relatively widespread and by 1778, the number of operating coal pits in Britain had reached 90 with the average pit employing around 20 men (AUSIMM, 1993). With the development of steam powered machinery marking the beginning of the industrial revolution, this led to a rapid increase in the worldwide demand for coal.

By the time coal was discovered in Australia, in 1791 in NSW, and in 1793, in Tasmania, it was already one of the most important commodities in European countries. Simple engineering was already being introduced with pits approaching 100 m in depth (Martin *et al.*, 1993). With the problems of pumping and hoisting being overcome by the use of steam engines, mines were able to extend into more gassy environments, and into more complex workings.

The commencement of coal mining in the Sydney Basin, remote from innovative developments in the old world, was much more primitive than in England. In NSW and Tasmania, recalcitrant convicts made up most of the early mining work force (Martin *et al.*, 1993). These early convict-driven coal mining activities made a significant contribution to the progress of the Australian settlement.

Coal was the first commodity discovered in Australia, the first mined, and after two centuries of settlement, coal remains the most important commodity in terms of local use for energy and international trade (Martin *et al.*, 1993). The progressive spread of European settlement from Sydney to other locations, predominantly around the coast, led to other discoveries within the Sydney Basin. Aside from the coal mines in the Sydney Basin, only those in the Bowen Basin Queensland, approach the importance of
the Sydney Basin resources (Martin et al., 1993). The Bowen Basin, however, suffers from the logistical problems of remoteness from the seaboard, manufacturing centres and cities (Martin et al., 1993). As Sydney is virtually at the deepest point of the coal basin, exploration depended upon land and sea explorations to reveal outcrops. The deep erosion and dissection on the coast and mountains to the west aided discoveries. The search for fishing grounds along the coast, and agricultural land to the north and mountains to the west, and the harvesting of cedar timber in the Illawarra, resulted in the establishment of permanent bush tracks (Martin et al., 1993), which facilitated coal discovery.

Early discoveries in Queensland around 1825 were in the vicinity of Ipswich, along the Brisbane River, where a seam was cropping out. Two years later coal was also discovered on the Brisbane-Ipswich track (Martin et al., 1993). 1846 marked the discovery of coal in the Bowen Basin. Between 1805 and 1840 other relatively small discoveries of coal were made in Tasmania, Victoria, Western Australia and South Australia.

The general uniformity of the Australian coal seams lends them to mechanisation as faults, folds, washouts, and floor stone rolls are generally not common (Martin et al., 1993). By 1946, thirty seven percent of all coal mined in NSW was cut mechanically by continuous miners and pillar extraction. From 1960 to1990, the transition between pillar extractions to the current long wall mining greatly increased the production of many underground pits. Open cut mines were not a significant contributor to the total coal production in NSW until World War 2 when open cut mining was promoted to overcome wartime shortages. After the war, some open cut pits remained, but it was not until the 1960s that significant open cut mining was undertaken in the Hunter Valley (Martin et al., 1993).

Whilst the total production from Queensland has now eclipsed that of NSW, the rapid increase in production from Queensland has only occurred since 1960. The large production increases have been attributed to the opening up of the Central Bowen Basin and particularly from the application of large open cut mining operations there. The coal seams of the Bowen Basin are generally much shallower than the coal seams in New South Wales lending them to the open cut method of mining.
The introduction of large scale mechanisation for coal mining in the early 1970s enabled coal to be removed at a much faster rate than ever before. This increase in production also led to increases in water needs at mine sites, with substantially more water needed to wash larger amounts of coal, for dust suppression on the surface and underground, and for the cooling of longwall and continuous miners underground. This use of water has created certain environmental issues:

- Increased salinity in mine discharges and Water Management Systems;
- Uncontrolled dirty water discharges from mine sites;
- The creation of acid mine drainage (AMD) or alkaline waters on site;
- Contamination of site storage ponds from oil and grease derived from underground and aboveground hydraulic and machinery oil;
- High levels of heavy metals contained within the waste material (Ecoengineers Pty Ltd, pers comm).

These impacts of water use at mines have caused considerable legislative and community concerns, this in turn, has led to a demand for good water management practices at coal mines to minimise the negative effects of poorly managed water systems on site, and to reduce offsite detrimental environmental impacts.

1.2 WATER QUALITY AT WEST CLIFF COLLIER AND THE RESEARCH QUESTIONS ADDRESSED IN THIS STUDY

This project investigated the water quality at West Cliff Colliery in order to develop improved systems for managing water resources for minimal environmental impact. Details of West Cliff Collieries Water Management System (WMS) are given in Section 2.14. While West Cliff is totally self-sufficient and independent of any town water supply, issues have arisen with the quality of water being discharged into the receiving waterways, being Brennans Creek and the upper Georges River. A water management system has been established to try and maintain an adequate supply of clean recycled water and to prevent discharges to the environment outside West Cliff’s Environmental Protection Licence requirements. In doing this, a number of questions were addressed:
1. Is it possible to maintain a pH <8.5 for discharges out of the West Cliff mine water Reclaim Pond into Brennans Creek? Maintaining a pH of < 8.5 would ensure compliance with West Cliff's current EPL.

2. Can operating the Brennans Creek Dam in a manner involving water rerouting and new valve control systems proposed in Section 3.4 achieve a reduction in salinity of discharged waters? Although there is no upper limit in the current West Cliff Colliery EPL set for saline discharges, any reduction in salinity will have a positive effect on water quality in the Georges River, as well as improving water quality for on-site use.

3. Is it possible to achieve a target Brennans Creek Dam level of 11 m? At this level, hydrological modelling carried out by Water Solutions (2004) on the Brennans Creek Dam catchment has shown that 90% of rainfall events will be able to be captured equating to approximately 65 megaliters (ML) of fresh rain water.

4. Do the three new approaches described within this thesis, specifically the controlling of bottom water discharges through the reclaim pond, increasing freshwater harvesting, and automating the environmental management of discharged excess mine site water, have general application to the design and operation of water management systems elsewhere?
CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

This section of the thesis presents a brief history of coal mining in the Illawarra, its economic contribution to the region, and provides a general overview to the geology of the Sydney Basin of which the Southern Coalfield is a part. Water related environmental issues associated with mining, in particular coal mining in the Illawarra, are addressed and discussed. The general aspects of the current Water Management Systems (WMS) of the operating coal mines in the region are presented in Sections 2.12 to 2.18. A summary of the current water management systems of the operating coal mines in the Illawarra is presented in Section 2.19.

2.1 COAL MINING IN THE ILLAWARRA

The major expansions of coal mining in the Illawarra began in 1848 with the commissioning of the Mt Keira mine; a year later regular coal deliveries were made to Wollongong. By 1860, the Mt Keira tramway was completed, and the export of coal began (Martin et al, 1993). Following the successful mining at Mt Keira, other mines were developed along the Illawarra Escarpment and further inland towards Picton. In the period 1949 – 1970, many company mergers took place, the number of collieries almost halved, and production more than doubled (Martin et al, 1993). This was predominantly attributed to the industry changing mining methods from bord and pillar extraction to longwall mining. The associated higher capital requirements were justified by higher production and the prospect of improved productivity. Figure 2.1 shows the location of coal mines in the Illawarra region.

The direct economic input of Illawarra Coal to the Illawarra and Wollondilly local communities is easily recognised. In the 12 months to June 2005, Illawarra Coal produced 6.07 million tones of premium quality coal, spent $340 million on domestic goods and services, provided jobs for 998 employees and approximately 400 contractors, and directly contributed over half a million dollars to the local community through donations and sponsorships. In addition, the flow-on effects to the local economy were about 5900 jobs, $520 million in Gross Regional Product and $278 million in household income, with Illawarra Coal as a whole accounting for
Figure 2.1. Approximate location of coalmines in the Illawarra region. Berrima Colliery lies just outside the Illawarra area. Bellambi West is now known as NRE Colliery No 1.
approximately 4.4% of GRP and 3% of employment in the Illawarra/Wollondilly region (IRIS, 2005)

The above data recognise only the contribution of Illawarra Coal to the local economy. It can be assumed that the overall contribution of coal mining to the local economy would be much greater still, with the additional input provided by Gujarat NRE, Excel Coal, and Centenial Coal with the three additional mines that they operate (in addition to the four that Illawarra Coal is currently operating).

2.2 GEOLOGY OF THE SYDNEY BASIN AND ILLAWARRA COAL FIELD

The Southern Coalfield and the greater Sydney Water Catchment both lie within the Sydney Basin. The Sydney Basin is the southern extent of the much larger Sydney-Bowen Basin, which extends from Batemans Bay in southern NSW to Collinsville in QLD (Reynolds, 1977). It contains relatively undeformed gently folded sedimentary rocks of Permian (270 Mya) and Triassic (225 Mya) ages. The Sydney Basin extends from Batemans Bay in the south to Muswellbrook in the north and Rylstone to the west.

The economic coal seams in the Illawarra area occur in the terrestrial and paralic sediment of the Late Permian Illawarra Coal Measures. The coal measures overlie marine sediments of the Shoalhaven Group and are in turn overlain by the fluvial sediments of the Narrabeen Group and the Hawkesbury Sandstone (Ward et al., 1995). The Illawarra Coal Measures rest conformably on the Shoalhaven Group, with the boundary generally being gradational. In the Dapto area, the boundary between the two groups is well defined by the presence of latite members of the Gerringong volcanic facies (Ward et al., 1995). The Narrabeen Group conformably overlies the coal measure sequence over most of the field, but in the extreme southern and southwestern areas, the Hawkesbury Sandstone overlaps the Narrabeen Group. The Illawarra Coal Measures have a general thickness of 200 m, but attain a thickness of over 400 m in the northeastern part of the field (Ward et al., 1995).

The Illawarra Coal Measures accumulated on a stable shelf margin of the Sydney Basin. The inertinite content of the coal is high (>55%) and increases towards the top of the seams; this reflects the emergence of the peat above the water table during regional subsidence (Ward et al., 1995).
Within the Illawarra Coal Measures, there have been up to 11 coal seams named, of which two, the Bulli and Wongawilli seams are still currently mined. The Bulli seam is the uppermost seam of the coal measures, and, where it is mined, it is up some 1.8 to 2.1 m in thickness (Reynolds, 1977). Its coking properties and low ash content make the Bulli seam highly sought after in the steel manufacturing industry, consequently making it the most valuable of the seams in the Illawarra Coal Measures (Reynolds, 1977).

2.3 WATER ISSUES AT MINE SITES

The provision of water supply, its usage and discharge, are major concerns for all mines, both underground and opencut, often accounting for a significant portion of the daily running cost of mining, particularly if purchased town or raw water is needed to supply mine demand. To reduce these costs, mines will often collect as much site runoff as possible, and recycle the water whenever economically feasible.

The constant recycling of on-site waters can mean that, over time, the levels of salinity, acidity or alkalinity, or other contaminants may build up within the internal water management system to a point which may lead to problems with licensed discharges. If discharges of waters with certain concentrations of contaminants that, for example, exceed default guideline levels set out in the national water quality guidelines, were to occur, they may well have adverse ecological impacts on the receiving waters.

Mine site waters that are unsuitable for discharge into natural waterways typically carry high concentrations of:

- Suspended solids; and/or,
- Salts, and/or strongly acidic materials; or,
- Alkaline materials; and/or,
- Trace metals; and/or
- Organic compounds.

Acidic waters reflect the formation of sulfuric acid from accessory pyrite in the coal and associated shales (Black and Craw, 2000). Saline waters are a product of the leaching of soluble salts from coal seams, associated shales, igneous dykes and intrusions, and reject emplacements. Coal seams may intersect aquifers and the groundwater in them.
may contain salts at concentrations in the order of many thousands of mg/L and excessive levels of trace heavy metals. Drainage from waste rock and reject emplacements with dispersive fine coal and clay components is the typical cause of high levels of suspended solids (Hounslow, 1995).

2.4 ACID MINE DRAINAGE (AMD)

Though not a major problem for coal mines in the Southern Coalfield, acid mine drainage is of considerable concern to many coal mines worldwide, whether still in operation or abandoned (Black and Craw, 2000). The principal driving factor for the creation of acid mine waters is an abundance of the mineral pyrite (FeS$_2$) in the coal seams. Oxidation of pyrite, occasionally catalysed by micro-organisms, is responsible for the production of AMD. This process of oxidation is greatly enhanced by mining activities due to the increased exposure of potentially reactive surfaces to the atmosphere (O$_2$) and certain bacterial species. Pyrite is abundant as an accessory mineral in many coal deposits and often contains metallic elements such as As, Cd, Co, Cu, Pb and Zn (Monterroso and Macias, 1998; Black and Craw, 2000). It is generally accepted that metal distribution is chiefly controlled by pH, with an increase in pH resulting in the co-precipitation and/or adsorption of metals primarily with secondary Fe oxyhydroxide minerals (Boult, 1996; Banks et al., 1997). Co-precipitation and/or adsorption may alter the metal load and potentially allow storage in an insoluble form, within the receiving streams and wetlands (Boult, 1996; Black and Craw, 2000).

The oxidation of pyrite is relatively complex and involves a number of reactants and products under differing conditions. The oxidation of pyrite from the exposure to atmospheric conditions is well documented and can be summarised by the reactions (1 to 4) below (Black and Craw, 2000). Reactions 1 and 2 take place under acidic conditions with O$_2$ as the primary oxidant, reaction 3 occurs in basic conditions with O$_2$ as the primary oxidant and reaction 4 in acidic conditions with Fe$^{3+}$ as the primary oxidant (Mosses, 1991; Webb, 1994; Gray, 1997; Schuring et al., 1997; and Kirby, 1999):
\[
2\text{FeS}_2 + 7\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{Fe}^{2+} + 4\text{SO}_4^{2-} + 4\text{H}^+ \quad (1)
\]
\[
2\text{Fe}^{2+} + \frac{1}{2}\text{O}_2 + 2\text{H}^+ \rightarrow 2\text{Fe}^{3+} + \text{H}_2\text{O} \quad (2)
\]
\[
2\text{FeS}_2 + 15/2\text{O}_2 + 7\text{H}_2\text{O} \rightarrow 2\text{Fe(OH)}_3(s) + 4\text{SO}_4^{2-} + 8\text{H}^+ \quad (3)
\]
\[
\text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+. \quad (4)
\]

A study carried out in the Witbank Coalfield, South Africa (Bullock and Bell, 1997) highlighted some of the detrimental effects of AMD. AMD seepages typically have pH values <2 and contain relatively high TDS concentrations (in a range between 2500 – 5000 mg/L) (Bullock and Bell, 1997). In an area approximately 3 ha in size, almost all plant life had been killed, as most plants cannot tolerate low pH waters since the high concentrations of hydrogen ions cause inactivity of enzyme systems, restricting respiration and root uptake of mineral salts and water. High levels of dissolved ions, particularly aluminium, also contributed to the destruction of vegetation in this area. Within this affected area, almost no aquatic life exists with the exception of some species of red and green algae in sedimentation ponds.

### 2.5 SALINITY

It is commonly recognised throughout Australia that salinity provides probably the best basis for environmental regulation of flows in freshwater coastal streams and rivers (Bluhdorn and Arthington, 1995; Dept of Water Resources, 1994; Hart, 1992.).

The ANZECC National Water Quality Guidelines state a default guideline value for EC for NSW upland rivers of 30 – 350 μS/cm and a default guideline value for EC for NSW lowland rivers of 125 – 2200 μS/cm. These guidelines also note that NSW coastal rivers typically have a normal EC in the 200 – 300 μS/cm range (ANZECC and ARMCANZ, 2000). For all of the creeks flowing from the mines in the Illawarra area, it is unclear as to whether they should be regarded as upland or lowland river systems. This is of concern, as often EC values, which are recorded immediately downstream of the discharge confluences, are above the national default guideline values for a NSW upland river, but may possibly lie within the national default guideline values for a NSW...
lowland rivers. Constantly exceeding these guidelines in the majority of circumstances would result in a Pollution Reduction Program (PRP) being negotiated between the offending company and the EPA, or in more severe cases, the EPA may impose a PRP. Uncontained spills or one-off offences may result in prosecution by the NSW DEC (formerly NSW EPA).

It is also recognized, and stated in the national water quality guidelines, that default trigger values (such as the 300 – 350 μS/cm for NSW upland or coastal rivers) may be increased or reduced for some ecosystems (ANZECC and ARMCANZ, 2000). This scenario could apply, for example, when it could be shown that there is negligible ecotoxicity at some higher salinity than 300 – 350 μS/cm or, if the ecotoxicity of a less saline water had been compounded some way by other known chemical factors, e.g., excessively low or high pH values, major concentrations of inorganic species such as the bicarbonate ion (HCO₃⁻) (Cowgill and Malazzo, 1991; Hoke et al., 1992), potentially ecotoxic trace elements (Tessier and Turner, 1996), or anthropogenic organic compounds like polymer flocculants used in water treatment (Lamberton, 1995).

In terms of salinity, an important principal to operate under, as specified in ANZECC and ARMCANZ (2000a), is whenever possible, to make reference to site specific factors. This means the guidelines would be different in terms of salinity and its effects based upon the classification of whether a river was “upland” or “lowland”.

With respect to the major ions which are found in regional mine waters of the Illawarra, a comprehensive study of the effects of common salt types on ecotoxicity by Mount et al. (1997), noted that their toxicity could be ranked in order K⁺ > HCO₃⁻ ~ Mg²⁺ > Cl⁻ > SO₄²⁻. Sodium (Na⁺) and calcium (Ca²⁺) cations were found not to be particularly toxic. Although these major ions are essential and naturally occurring in many water ways, above certain concentrations they become ecotoxic. It is at these ecotoxic levels that Mount et al. (1997) ranked them in order of their toxicity. With regard to the waters discharged from coalmines around the region, there is much evidence to suggest that the most ecotoxic major anion is bicarbonate (HCO₃⁻) (Cowgill and Malazzo, 1991; Hoke et al., 1992; and Mount et al., 1997). Hence, it is clear that of all the major ions present in all the Illawarra regional mine waters, bicarbonate (HCO₃⁻) is the principal driver of any major ion (i.e. salinity) induced ecotoxicity (Ecoengineers Pty Ltd, 2003).
Despite the fact that mine discharge waters around the Illawarra are saline, there is little literature available which reports the effects of saline waters on freshwater aquatic biota in the Illawarra area. From data presented by Mount et al (1997), it can be shown that if local mine waters were diluted to the point where the concentration of NaHCO₃ was essentially in the range of 600 – 650 mg/L, then ecotoxic effects on the water flea *Ceriodaphnia dubia* should disappear, i.e., a No Observable Effect Concentration (NOEC). This is important as *Ceriodaphnia dubia* is considered one of the most sensitive indicators of aquatic ecotoxicity (Williams et al., 1993; USEPA., 1994) and is the preferred organism of the NSW EPA for the direct toxicity assessment (DTA) of industrial discharges for that reason.

A similar NOEC level of salinity for Illawarra regional mine waters (i.e., at ~1000 μS/cm) was also verified by NSW EPA Ecotoxicology Section who could not detect toxicity (either acute or chronic) to the water flea by Elouera Colliery mine water which has an EC of around 1000 μS/cm (reported in Ecoengineers Pty Ltd, 2003).

Jarvis (1997) found minor reductions in the abundance and diversity of macro invertebrates, possibly also indicative of borderline chronic ecotoxicity effects, in the upper Georges River at his denoted site pool 4a over the period of July 1995 – May 1996. This pool was located approximately 0.6 km downstream of the Bulli to Appin Road Bridge, just below the confluence of Brennans Creek and upper Georges River, which is directly within the influence of any discharges from the Brennans Creek Dam, which discharges treated waste waters from West Cliff Colliery. Jarvis recorded EC values in the range of 309 – 1210 μS/cm (which were undoubtedly moderated by weather effects) and upstream sites above the Georges River/ Brennans Creek confluence in the range of 174 – 325 μS/cm. The mean EC of the water at the Jarvis downstream site was 593 μS/cm with an 80th percentile value of 775 μS/cm.

In the Hunter Valley (another large coal mining area within NSW), under conditions of the Hunter River Salinity Trading Scheme, discharges of saline mine waters to the Hunter River are permitted during periods of flow in the river that are deemed sufficient to limit the salinity of the river downstream of any discharges to 900 μS/cm (Ecoengineers Pty Ltd, 2003). The main purpose of setting a limit, as in the Hunter Valley trading scheme, was to ensure that no ecotoxic effects on aquatic biota in the Hunter River would be induced by discharged saline mine waters.
2.6 CARBONATE SYSTEMS

All of the underground coal mines in the Illawarra have moderately saline waters, which can be attributed to the influence of a carbonate system. This system greatly affects the buffer intensity and neutralizing capacity of the waters (Brownlow, 1996; Langmuir, 1997; and Lottermoser, 2003). The system comprises a series of reactions involving carbon dioxide (CO$_2$), bicarbonate (HCO$_3^-$), carbonate (CO$_3^{2-}$) and carbonic acid (H$_2$CO$_3$) (reaction 5).

$$
H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2 H^+ + CO_3^{2-} \quad (5)
$$

The reactions affecting these different species are important in ground and surface waters and involve the transfer of carbon among the solid, liquid and gas phases (Lottermoser, 2003). The transfer of carbon also results in the production of carbonic acid (H$_2$CO$_3$). Bicarbonate is the dominant species found in natural waters with a pH greater than 6.3 and less than 10.3; carbonate is dominant at pHs greater than 10.3; and carbonic acid dominates at pHs below 6.3 (Sherlock et al., 1995).

Being able to distinguish between these species is important for the evaluation of mine water chemistry. This is because bicarbonate is a charged species whereas carbonic acid is not charged and therefore does not contribute any electrical conductivity (EC) to the water. In addition, dissolved bicarbonate ions consume hydrogen ions providing a neutralizing capacity to the water. Bicarbonate has the capacity remove free H$^+$ from the water, lowering the acidity of the water (reaction 6). Therefore the greater the total concentration of bicarbonate species the greater the buffering capacity and alkalinity of the water (Lottermoser, 2003).

$$
HCO_3^- \text{(aq)} + H^+ \text{(aq)} \leftrightarrow H_2CO_3 \text{(aq)} \quad (6)
$$

The alkalinity is a measure of the bicarbonate and carbonate concentration in the water indicating its buffering capacity; the higher the alkalinity the higher the acid-neutralising capacity (Deutsch, 1997).
2.7 TRACE METALS

Many trace elements (e.g., Fe, Mn, Cu, Co, Zn and Se) are essential for all life within certain concentration limits, but above the required concentrations, many of these elements (e.g., Zn, Cu and Se) can have adverse effects (Allen et al., 1998). Trace metals can be grouped according to their fundamental chemical properties; for example, some trace metals (Fe, Mn, Co, and Cr) tend to form cations which react with negatively charged ions and suspended particles, thus becoming enriched in soils or sediments (Allen et al., 1998). Trace metals, such as, Cu, Ni and Zn, tend to form stronger complexes or compounds with organic matter making them more stable for transport though aquatic environments (Allen et al., 1998).

Trace elements, which are found in coal mine water discharges, can pose a potential risk to aquatic ecosystems. The trace elements associated with coalmine discharge wastewaters in the Illawarra are generally Cu, Ni, and Zn. Arsenic (As) is also present in low concentrations (White, 2001).

It is important to realize, however, that trace elements are present in water in a large number of chemical forms (Stumm and Morgan., 1996) and that not all of these forms are bioavailable or cause ecotoxic effects (Hoffmann et al., 1995). Due to the bioavailability of trace metals, the national water quality guidelines explicitly provide for a risk assessment decision tree approach to allow for the consideration of the nature of the chemical speciation of such metals to determine what proportion may be present in the ecotoxic forms (ANZECC & ARMCANZ, 2000).

With respect to As, essentially all of the aqueous species of As are toxic to some degree, and the overall ecotoxicity of As is only modified by the degree to which As exists in the two different redox states – the reduced As (III) and the oxidized As (V). In a well oxygenated water, such as, the receiving waters for mine water discharges, the majority of As would be in the less toxic As (V) state (Ecoengineers Pty Ltd, 2003).

For the three major trace metals found in Illawarra mine discharge waters, the ecotoxic species are principally of the divalent cationic M$^{2+}$ form (where M= Cu, Ni or Zn) but also include the less toxic monovalent cationic forms MOH$^+$, MHCO$_3^+$, MCl$^+$, MF$^+$ (Tessier and Turner, 1995; Ecoengineers Pty Ltd, 2003).
Speciation modeling of discharged mine water chemistry carried out by Ecoengineers Pty Ltd (2003) using a geochemical model PHREEQC-2 (Parkhurst and Appelo., 1999) showed that the downstream aqueous speciation of Cu, Ni and Zn was noticeably modified by the relatively high salt concentrations in the water with EC in the 1000 – 10,000 μS/cm range. At these concentrations, carbonate, chloride and sulfate were found to complex dissolved Cu, Ni and Zn, so that most of the total concentration was converted into non-toxic neutral and anionic species (see Equations 7-18). Through modeling, it was also found that at higher pHs, total alkalinites and ECs, (ironically in the direction that increases ecotoxic effects due to increased salinity and bicarbonate concentrations) there is a greater complexation of the trace metals reducing their ecotoxicity.

The modeling also showed that the concentrations of ecotoxic Zn species present could possibly be increased at pHs below 8.0 and lower bicarbonate concentrations (Ecoengineers Pty Ltd, 2003). This suggests that the monitoring of Total Alkalinity in mine discharges would be worthwhile as this parameter is important for assessing total bicarbonate concentrations and hence assessing whether Zn is sufficiently complexed by the bicarbonate to significantly reduce its ecotoxic effects. From this modeling, it was also found that the trace elements posing the greatest risk of in-river ecotoxic effects in the Illawarra region were As and Zn.
\[ \text{Cu}^{2+} + 2\text{CO}_3^- \leftrightarrow \text{Cu(CO}_3)_2^{2-} \quad \text{Anionic Species (non ecotoxic)} \quad (7) \]

\[ \text{Cu}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CuCO}_3^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (8) \]

\[ \text{Cu}^{2+} + \text{SO}_4^{2-} \leftrightarrow \text{CuSO}_4^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (9) \]

\[ \text{Cu}^{2+} + 2\text{Cl}^- \leftrightarrow \text{CuCl}_2^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (10) \]

\[ \text{Ni}^{2+} + 2\text{CO}_3^- \leftrightarrow \text{Ni(CO}_3)_2^{2-} \quad \text{Anionic Species (non ecotoxic)} \quad (11) \]

\[ \text{Ni}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{NiCO}_3^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (12) \]

\[ \text{Ni}^{2+} + \text{SO}_4^{2-} \leftrightarrow \text{NiSO}_4^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (13) \]

\[ \text{Ni}^{2+} + 2\text{Cl}^- \leftrightarrow \text{NiCl}_2^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (14) \]

\[ \text{Zn}^{2+} + 2\text{CO}_3^- \leftrightarrow \text{Zn(CO}_3)_2^{2-} \quad \text{Anionic Species (non ecotoxic)} \quad (15) \]

\[ \text{Zn}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{ZnCO}_3^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (16) \]

\[ \text{Zn}^{2+} + \text{SO}_4^{2-} \leftrightarrow \text{ZnSO}_4^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (17) \]

\[ \text{Zn}^{2+} + 2\text{Cl}^- \leftrightarrow \text{ZnCl}_2^0 \quad \text{Neutral ion pair (non ecotoxic)} \quad (18) \]
2.8 ENVIRONMENTAL BEHAVIOUR OF ARSENIC

The element arsenic (As) is a metalloid, meaning that it exhibits both metallic and non-metallic properties. It can exist in the metallic As (0), trivalent As (III), and pentavalent As (V) oxidations states in a variety of minerals. Arsenic co-occurs as arsenide minerals with sulfidic ores with minor or trace sulfides in a variety of rock types, including coals and carbonaceous shales. As (III) & (V) occur in a number of arsenite and arsenate minerals. It is generally believed that the bulk of arsenic in coal and shales occurs in sulfide minerals, primarily iron sulfides. Low levels of arsenic in coal (<5 mg/kg) may be associated with the organic fraction of the coal (Coleman and Bragg, 1990).

During weathering, arsenic is released primarily as soluble arsenates under neutral or alkaline conditions; it is then generally immobilized by co-precipitation with iron, manganese or aluminum oxyhydroxides (Tessier and Turner, 1995).

As (0) will not normally be found in natural waters. As (V) is thermodynamically favoured over As (III) in well – oxygenated fresh waters and occurs mainly as the arsenate anions $\text{H}_2\text{AsO}_4^-$ and $\text{HAsO}_4^{2-}$ (Tessier and Turner, 1995). Studies generally show that the common oxidation state in fresh water is As (V) but improvements in analytical capabilities over the last decade have shown that As (III) can be detected as a significant proportion of the total As in many surficial situations (Tessier and Turner, 1995). This is because, under mildly reducing conditions, As (III) species such as arsenious acid ($\text{H}_2\text{AsO}_4$), and arsenite anions ($\text{H}_3\text{AsO}_3^-$ and $\text{HAsO}_3^{2-}$) are formed (Tessier and Turner, 1995).

Arsenic is a well known ecotoxic element with its ecotoxicity resulting from its propensity for bioaccumulation, particularly in algae, aquatic plants, and fish which feed on them. It also accumulates in sediments due to its adsorption to settling particles followed by reduction to As (0) within the sediment (Reimer et al, 1988). Much of the knowledge on the ecotoxic effects of arsenic was obtained because sodium arsenite and similar arsenic compounds were long used in the USA as aquatic herbicides in the 1940s through to the 1970s (Ecoengineers Pty Ltd, 2001). For fresh waters, the trigger values for the different levels of protection of 99%, 95%, 90%, and 80% of all aquatic species are set out in Table 2.1 (ANZECC and ARMCANZ, 2000). Note that the concentrations of arsenic are expressed in $\mu$g/L (parts per billion; ppb) and need to be divided by a
2.9 ENVIRONMENTAL BEHAVIOUR AND ESSENTIALITY OF COPPER

Copper is a relatively common trace element in nature and the twenty eighth most abundant in the Earths crust (Landner and Reuther, 2004). Copper concentrations are often elevated in surface waters around agricultural areas due to its use as both as an anti algal and anti fungal control (Landner and Reuther, 2004). In sediments, Cu is efficiently retained from uptake by organisms due to the formation of stable complexes with negatively charged organic compounds (Landner and Reuther, 2004). Copper adsorption to Fe and Mn oxyhydroxides and organic matter can be an efficient retention process in oxidic sediments, where as precipitation of Cu sulphide may constitute a major sink in anoxic sediments.

The fate of elemental copper in water is complex and influenced by pH, dissolved oxygen and the presence of oxidising agents and chelating compounds or ions (USEPA, 1995). Surface oxidation of copper produces copper(I) oxide or hydroxide. In most instances, the copper (I) ion is subsequently oxidized to the copper (II) ion (WHO, 2004). In pure water, Cu$^{2+}$ ion is the more common oxidation state (USEPA, 1995) and
forms strong complexes with hydroxide and carbonate ions and organic ligands, e.g., humic and fulvic acids, and is readily adsorbed by clay particles (Landner and Reuther, 2004). The formation of insoluble malachite [Cu$_2$(OH)$_2$CO$_3$] is a major factor in controlling the level of free Cu$^{2+}$ ion in aqueous solution. Cu$^{2+}$ ion is the major species in water up to pH 6; at pH 6–9.3, aqueous CuCO$_3$ is prevalent; and at pH 9.3–10.7, the aqueous [Cu(CO$_3$)$_2$]$^{2-}$ ion predominates (Stumm & Morgan, 1996). Elemental copper (Cu$^0$) is chemically relatively inert and dissolves very slowly in oxic and slightly acidic environments.

The reason for copper being a necessity for living organisms is its specific incorporation into a large number of enzymatic and structural proteins. Copper plays an important role in oxidation/reduction enzyme activities, because of its ability to function as an electron transfer intermediate. Copper is a constituent of enzymes involved in cellular respiration, free radical defence, neurotransmitter function, connective tissue biosynthesis, and cellular iron metabolism. Copper is also essential for the utilisation of iron in the formation of haemoglobin as well as playing an essential role in the activation and repression of gene transcription (IPCS, 1998). For fresh water, the trigger values for the different levels of protection (99%, 95%, 90%, and 80%) of all aquatic species are set out in Table 2.2 Note that the concentrations of copper are expressed in μg/L (parts per billion; ppb) and need to be divided by a factor of 1000 to be expressed in the units mg/L (parts per million; ppm) which they are commonly listed in regulatory limits.
Table 2.2: National guideline trigger concentrations for Copper, Nickel, and Zinc in freshwaters for the protection against ecotoxicity of 99%, 95%, 90% and 80% of species (ANZECC and ARMCANZ, 2000).

<table>
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<th>Trigger Values for Freshwater (μg/L)</th>
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Please see print copy for Table 2.2

2.10 ENVIRONMENTAL BEHAVIOUR AND ESSENTIALITY OF NICKEL

Nickel is widely distributed in nature, forming about 0.008% of the Earth’s crust. The core of the Earth contains 8.5% nickel and deep sea nodules 1.5% (World Health Organisation (WHO, 2000). In uncontaminated river sediments, Ni concentrations vary between 1 – 150 mg/kg dw, but can reach up to 1000 mg/kg dw in the vicinity of nickeliferous deposits (Landner and Reuther, 2004). Nickel can be enriched in coal and crude oil with a range in coal of up to 300 mg/kg, but most samples contain less than 100 mg/kg (WHO, 2000).

There is evidence that nickel is an essential trace element in several animal species, plants, and prokaryotic organisms. Nickel appears to be essential for humans, although there is very limited data available concerning nickel deficiency (WHO, 2000). Certain Ni compounds and metallic Ni at higher concentrations are toxic to most plants and fungi, moderately toxic to mammals, and known human carcinogens (Landner and Reuther, 2004). Similarly to Cu, Ni also shows elevated surface water concentrations around agricultural areas. As cited by Landner and Reuther (2004), Scandinavian field surveys indicate that both acidity and humic substances influence the distribution of Ni in surface waters.
Ni occurs predominantly in the divalent $\text{Ni}^{2+}$ form in the environment and forms strong complexes with organic ligands, like carboxylates, fulvates and humates. Ni forms soluble chloride, sulfate and nitrate salts, whereas Ni oxide is only soluble under acidic conditions, in contrast to Ni hydroxides, sulfides, arsenides, arsenates, and silicates, which are relatively insoluble (Landner and Reuther, 2004). For fresh waters, the trigger values for the different levels of protection of 99%, 95%, 90%, and 80% of all aquatic species are set out in Table 2.2 Note that the levels of nickel are expressed in $\mu\text{g/L}$ (parts per billion; ppb) and need to be divided by a factor of 1000 to be expressed in the units mg/L (parts per million; ppm) which they are commonly listed in regulatory limits.

2.11 ENVIRONMENTAL BEHAVIOUR AND ESSENTIALITY OF ZINC

Zinc is an ubiquitous element in nature, though it is believed that approximately 96% of its release into the global environment is a result of anthropogenic activities, like electroplating, smelting and ore processing, corrosion from alloys and galvanised surfaces as well as erosion from agricultural land (Landner and Reuther, 2004). In natural surface waters, the concentration of zinc is generally below 10 $\mu\text{g/L}$, and in ground waters, 10 – 40 $\mu\text{g/L}$ (WHO, 1996). It is believed that dissolved Zn in Canadian and Scandinavian freshwater rarely exceeds 40 $\mu\text{g/L}$. Most Zn entering the surface waters precipitates into the sediments (Landner and Reuther, 2004). Sediment bound Zn in relatively unpolluted lakes in southern, central, and northern Sweden varied between 130–140, 130–380, 59–330 mg/kg dw, respectively. Background concentrations for zinc in the fresh waters or sediments of other European countries generally range between 12 and 150 mg/kg dw (Landner and Reuther, 2004).

With regard to the aqueous speciation of Zn, the free Zn ion coordinates with water molecules to form octahedral $\text{Zn(H}_2\text{O)}_6^{2+}$ in the absence of inorganic and organic ligands. At pH 4 –7, Zn exists in freshwaters almost completely as the aqueous ion, while at pH 6 the free ion and $\text{ZnSO}_4^{0+}$ are the dominant forms. It is supposed that about 90% of dissolved inorganic Zn occurs as the free ion in addition to $\text{ZnHCO}_3^{+}$, $\text{ZnCO}_3^{0}$, and $\text{ZnSO}_4^{0}$. In general, Zn is increasingly released from sediments under high dissolved oxygen, low salinity and pH (Landner and Reuther, 2004).
Zinc is an essential element in all living organisms (WHO, 1996). Zinc is important in membrane stability in over 300 enzymes, including many dehydrogenases, aldolases, peptidases, polymerases, and phosphatases (WHO, 1996). Zinc is also essential in the metabolism of proteins and nucleic acids (Landner and Reuther, 2004). Zinc deficiency has been reported in a wide variety of cultivated plants and animals, with severe effects on all stages of reproduction, growth and tissue proliferation (Landner and Reuther, 2004). For fresh waters the trigger values for the different levels of protection of 99%, 95%, 90%, and 80% of all aquatic species are set out in Table 2.2. Note that the levels of zinc are expressed in μg/L (parts per billion; ppb) and need to be divided by a factor of 1000 to be expressed in the units mg/L (parts per million; ppm) which they are commonly listed in regulatory limits.

WATER MANAGEMENT SYSTEMS AT ILLAWARRA COAL MINES

This section reviews the current water management systems of the operating coal mines in the Illawarra in terms of the number of settling ponds and dams, as well as coal washing facilities and water usage. Information regarding the surrounding water catchments and the run of mine production is also presented for each mine. The information provides a more detailed background from which to assess West Cliff Colliery’s WMS practices within a regional framework.

2.12 TAHMOOR COLLIERY

Tahmoor Colliery is located within the catchment of Teatree Hollow Creek, which flows north towards the Bargo River (see Figure 2.1). Open sclerophyll woodland predominantly covers the mines catchment area. The mine site is located east of Remembrance Drive, is divided by a main southern rail line, and has a production of 1.5 million tonnes per year. The washery, raw coal stockpile and pit top are enclosed within the colliery’s rail loop. South of the rail loop are the product stockpiles. Washery waste material is transferred using a conveyor across the main southern rail line to the reject disposal area. The waste material is then stored in an approved landfill site. When finished, the landfill area will cover an area of 73 ha.
The Water Management System (WMS) at Tahmoor consists of a number of dams, drains, pipelines, sumps and pump stations. Mine waters pumped from underground pass through four mine water treatment dams, which are located in the pit top area. The capacity of these dams is approximately 20 ML. Mine water is pumped from underground at an average rate of 3.5 to 5.0 ML/day. Supply of the coal washery water is pumped from storage dams with excess washery water returned to a settling dam (No 2). The last of these dams (No 4) releases water via a licensed discharge point into Teatree Hollow Creek.

Surface runoff from the pit top and raw coal stockpile currently flows to dams 1 and 2. Water from dam 2 is pumped to the product stockpile dams S2 and S3 that provide the water for the stockpile dust suppression system. The product stockpiles are located south of the pit top areas in a depression that acts as a retention basin for approximately 14 ML and is denoted as Dam S1. Runoff from the washed coal product stockpiles is directed to dams S2 and S3. Dam S3 discharges to dam S4 (capacity 36 ML) located on the western side of the main southern railway (Ecoengineers Pty Ltd, 2003)

2.13 DOUGLAS PARK PROJECT/APPIN COLLIERIES

The immediate receiving point for the discharge from this colliery site is Clements Creek, an upper tributary of Allens Creek, into which the licensed discharge from the colliery occurs. The secondary receiving water is the Nepean River, at any point downstream of the confluence of with Allens Creek. The main colliery site is located beside Sandy Gully within the catchment of Allens Creek (see Figure 2.1). Sandy Gully generally only flows during and following rain events and lies just north of Clements Creek. The main colliery site is situated on Douglas Park Drive and lies 3 km south of the Nepean River and Hume Highway.

The surrounding catchment area of Allens Creek is covered largely by farmland, including dairy farms, cattle grazing and hobby farming. A dry sclerophyll (Eucalypt/Casuarina) transition forest generally covers the slopes and the valleys of the catchment of Allens Creek and its tributaries. The catchment also contains the small towns of Wilton and East Douglas Park.
The WMS consists of a number of dams, drains, pipelines, sumps and pump stations. Mine water is typically pumped aboveground where it accumulates in finished underground mine workings known as goafs. The water is extracted in order to manage water levels underground for both safety and operational reasons. At present, Tower Colliery is not in operation, but is under care and maintenance. When in operation this mine was producing ~ 1 million tonnes per year. The mine water that is being pumped from underground currently derives from a horizontal borehole connection between Tower Colliery and underground workings from the adjacent Appin Colliery to the northeast (Figure 2.2).

![Figure 2.2: Aerial view of Appin Colliery looking south; at present Appin colliery is currently mining what used to be the Tower lease. The relative lack of above ground infrastructure is due to the absence of a coal washery. Raw coal from Appin Colliery is transported by truck to West Cliff Colliery for washing.](image)

Tower Colliery mine water, like the mine waters of all the other underground coalmines in the Illawarra, is moderately saline with an EC in the order of 1000 – 10,000 μS/cm range (Ecoengineers Pty Ltd, pers comm). The salinity of these waters is strongly associated with the sodium bicarbonate/carbonate (NaHCO$_3$ / Na$_2$CO$_3$) salts. At the source, the mine water invariably contains a significant concentration of dissolved CO$_2$ due to the higher partial pressure of CO$_2$ than atmospheric (Ecoengineers Pty Ltd, 2003)
When these waters are pumped to the surface, they slowly lose CO₂ with a simultaneous rise in pH until the dissolved CO₂ is in equilibrium with the atmospheric partial pressure of CO₂. At this point, the pH of the water is around 9.5 with a reduced carbonate alkalinity. Agitation or aeration of the water will increase the rate of CO₂ loss and therefore the rate of pH rise (Ecoengineers Pty Ltd., 2003).

The mine water is pumped via a borehole to the aboveground site and then directed through an acid dosing plant where it is dosed “substoichiometrically” with sulfuric acid to between pH 6.5 – 8.5. The substoichiometric addition of acid means that a temporary drop in pH is achieved without the immediate loss of dissolved CO₂. This shifts the water into the optimal pH range (values) for a subsequent coagulation/flocculation treatment to remove suspended solids (Ecoengineers Pty Ltd, 2003).

The water then passes through two settling basins, which provide sufficient hydraulic residence time to enable most flocculated fine coal and clay solids to settle out. This water then passes to two sand filter lagoons where further filtration occurs to lower the level of residual suspended solids. Dirty site water runoff from car parks, buildings, hard surfaces, open air equipment stores, workshops (after oil separation) and the Methane Drainage Plant are also directed to these filter lagoons for treatment before discharge.

Ultimately the filtered underflow from the lagoons is passed through a granular activated charcoal (GAC) filter unit to remove any remaining oils and other organic contaminants, prior to discharge into Sandy Gully, a short tributary of Clements Creek.

2.14 WEST CLIFF COLLIERY

Of the coalmines in the Illawarra, West Cliff Colliery is the only mine which is totally self-sufficient with regard to its water management system, with little or no reliance on town water. The entire West Cliff Colliery site is located within a 4.813 km² catchment of Brennans Creek, located at 34°14' S and 150°49'E (see Figure 2.1). The catchment is predominantly covered by a mixture of open sclerophyll woodlands, active and rehabilitated surfaces of coal washery discard, coal and coalwash stockpiles, roadways and aboveground mine site buildings and related infrastructure (Figures 2.3 and 2.4).
Figure 2.3: The West Cliff colliery Mine site and the surrounding catchment of Brennans Creek Dam, which supplies the colliery with water. The catchment is covered by open sclerophyll woodlands.

Figure 2.4: Aerial view of West Cliff Colliery south site in 2004.
The main purpose of the colliery Water Management System (WMS) at West Cliff is to:

- Recycle contained site waters by catching clean and dirty waters on site;
- Store and clean dirty water runoff in dirty water ponds and tanks, then store as clean water in Brennans Creek Dam (BCD), approximate capacity 320 ML;
- Use recycled water from BCD to directly supply the water needs of the entire site including underground requirements, coal preparation plant (CPP), and bathhouse facilities with a serviceable clean water supply;
- Collect rainfall and groundwater to supply the closed loop system;
- Pump mine water out of the mine workings for cleaning and then recycling via BCD.

The WMS includes a number of drains and ponds, denoted as Ponds P1 to P7 (see Figure 2.5), with a total capacity of approximately 100 ML. The ponds are used to store and retain site dirty water, largely coal stockpile and haul road runoff (Ponds P1, P2, P5, P6 and P7), site stormwater runoff (Pond P3), and coalwash emplacement seepage (Pond P4).

The coalwash emplacement now occupies much of the upper, southern end of Brennans Creek Valley. Coalwash emplacement (valley filling) in stages 1 and 2 has proceeded over a 28-year period in a northerly direction down the Brennans Creek Valley. Stage 1 has undergone rehabilitation with local soils and revegetation with native plant species.

Immediately downstream of the BCD lies the Reclaim Pond. The Reclaim Pond was built at the foot of the BCD wall in Brennans Creek to catch seepages through the BCD wall and other natural ferruginous groundwater springs. The Reclaim Pond was installed after agreement with the NSW EPA in 1994. The water from the Reclaim Pond is pumped back over the BCD wall, recycling it back into BCD. Below the Reclaim Pond, Brennans Creek runs approximately 520 metres before discharging into the Upper Georges River at a point approximately 1 km to the northeast of Appin.
Figure 2.5: Schematic diagram of the West Cliff Colliery WMS (Water Solutions Pty Ltd, 2004)

Please see print copy for Figure 2.5
2.15 METROPOLITAN COLLiERY

Metropolitan Colliery is located at lat. 34°12’, long. 150°58’ approximately 43 km southwest of Sydney and around 41 km north of Port Kembla. It is adjacent to the Darkes Forest, Coalcliff and West Cliff Collierys (see Figure 2.1). The mine site lies within the catchment area of Camp Creek surrounded by the Royal National Park and the township of Helensburgh. The production of the mine is approximately 1.2 million tonnes per year.

At Metropolitan there is a regional dip of 1 in 50 to the northwest, with minor faulting. The average seam thickness varies between 2.3 and 3.6 metres.

The Water Management System (WMS) at Metropolitan consists of a number of dams, drains, pipelines, sumps and pump stations. Mine waters pumped from underground pass through a water treatment plant, a primary separation tank and are then piped to the primary separation lagoon (Bill Huuskes, Manager Technical Services, Metropolitan Colliery, pers comm). Dirty water diversion channels direct surface runoff water to the two Turkey Nest Dams with a combined capacity of approximately 12 ML. The dirty water then passes through the Taj Mahal pump station where it is pumped underground at a rate of 50 L/sec for underground usages like dust suppression and cooling. Excess water is piped back to a water treatment plant where it then passes through the primary separation tank to the settling ponds. Clean water from the ponds flows along diversion channels to licensed discharge points into Camp Creek.

Runoff from product and refuse stockpiles is directed into settling ponds located towards the middle of the site.

2.16 ELOUERA COLLiERY

Elouera Colliery is an underground coal mine owned by Endeavour Coal (a subsidiary company of Illawarra Coal Holdings P/L), BHP Billiton (BHPB), and is currently leased to, and mined by, Delta Mining. It is located in AMG Zone 56 – Easting 296.044 – Northing 6180.096, approximately 14 kilometres South West of Wollongong on the Illawarra escarpment at West Dapto (Wongawilli village see Figure 2.1). Elouera Colliery was established in February 1993 with the merger of the Wongawilli and Nebo
Collieries. Prior to the merger, the two mines operated independently in adjoining reserves.

There are two main transport entries into the mine, namely a roadway for rubber tyred vehicles and the other for rail mounted equipment. The mine is primarily serviced by the rubber tyred transport system following the Stage 2 development upgrade of the mine. Coal is transported to the surface of the mine via an inclined conveyor approximately 2.5 km in length.

There are three separate supplies of water for Elouera mine, town water (treated and untreated) and groundwater. Untreated fresh water direct from the upper Cordeaux No.1 reservoir also enters the mine via the No.3 air-shaft. This supply is also retained as a backup to the underground water recycling system. Total fresh water (town water) consumption for the period July 03 to June 04 was 119 ML. This quantity has increased significantly when compared to previous periods because water produced from mining had diminished due to an extended dry period in the region thus requiring increased use of raw water to supplement the demand. Total fresh water consumption for the previous period July 02 – June 03 was 29.9 ML.

Elouera is generally considered to be a “wet” mine, as it needs to be routinely de-watered. Ground water is collected from the underground workings and is reticulated throughout the mine to provide water for mining operations (dust suppression) and for charging of fire fighting services. The mine water is moderately alkaline and the dissolved solids content is predominantly in the form of sodium bicarbonate (Ecoengineers Pty Ltd, pers comm). This is characteristic of the groundwater quality seeping into the underground mines in the Illawarra. Excess ground water is discharged from the mine at licensed discharge points.

Surface mine water from the main mine water discharge point for the mine (EPA licensed discharge point No.2) and general surface drainage is captured in a settling and sediment retention pond prior to being discharged via an unnamed stream into Robins Creek. Water from this pond is also used for dust suppression at both the coal stockpile area and the nearby Wongawilli emplacement area. Waste water from the main bathroom at Elouera is passed through maturation (septic tank system) and filter ponds (primary and secondary stabilisation lagoons) prior to discharge at EPA licensed
discharge point No.1 into Robins Creek. Mine water from underground released at the Nebo Portal (now a Dendrobium Mine responsibility) is discharged at an EPA licensed discharge point and is directed to American Creek.

Groundwater is collected in pits/sumps underground and is recycled underground as much as possible. The recycled water is primarily used for dust suppression at the operating coal face, transport roadways and conveyor systems. Elouera receives inflows of groundwater. The routine inflow is approximately 50 to 60 L/s during normal conditions with increases to approximately 120 L/s during prolonged periods of substantial regional rainfall. Excess water is pumped to the surface via a pipeline up the main drift and into the main dam. Elouera dewateres the mine at an average rate of approximately 7 ML/day. Water is pumped from the main dam for dust control on the coal stockpile and loading facility as previously mentioned.

2.17 DENDROBIUM COLLIERY

Dendrobium is located approximately seven kilometres from the heart of Wollongong City in the village of Mt Kembla. Dendrobium employs approximately 170 mine employees and has approval to produce up to 5.2 million tonnes of coal per year.

The mine is separated into two main sections; the mine portal and the Kemira Valley coal loading area. At the time of opening, Dendrobium was the first new mine investment in New South Wales Southern Coalfield in more than 20 years, with construction and development works beginning in early 2002.

A significant permanent creek, Upper American Creek, passes around the portal site on its south western, southern and eastern sides and then flows down through Mt. Kembla to join Brandy and Water Creek just west of Govett Crescent, Figtree. Above the confluence with Brandy and Water Creek, Upper American Creek has a catchment area of about 887 ha. The area around the mine site is extensively wooded with rainforest species, often with a strong understorey of lantana. The catchment of Upper American Creek above the Nebo site is about 243 ha (Ecoengineers Pty Ltd, 2000).

The Creek exhibits a distinct geomorphological form characterised by steep bed gradient, highly turbulent flow and well-defined channels in a generally erosive but
heavily wooded environment. It is strongly incised around the mine site with the bed being comprised of bedrock and boulder-size alluvium, which is indicative of high peak flow rates (Ecoengineers Pty Ltd, 2000).

American Creek is generally non-turbid in low flow conditions but turbid in high flow conditions. A 1987 study by Wollongong City Council highlighted the turbid nature of Upper American Creek under high flow conditions (Hales, R., referenced in Rennex, 1994).

The site has been in the past, and is still, serviced by a Smith and Loveless type extended aeration ‘package’ sewage treatment plant designed (STP) with an aeration chamber, clarifier and sludge return line. It is designed to treat flows of up to 7.04 m$^3$/hour (170 kL/day) and to handle 5-day biochemical oxygen demand (BOD) loads of up to 16.8 kg/day (Ecoengineers Pty Ltd, 2000). At present, dirty surface water runoff from the workshop area and all of the remainder of the site is treated together with bath house water, black water from toilets and oily water from the workshops in the STP.

Treated effluent from the STP is not chlorinated, but is presently pumped to purpose-built primary and secondary stabilisation lagoons ( facultative ponds) further up Cordeaux Road in the Windy Gully area adjacent to American Creek, about 1.5 km southwest of the Nebo site. These ponds have a combined surface area of 2800 m$^2$ and are nominally 0.9 m deep when filled. The lagoons provided a minimum 17 days retention time when the STP was operating at full load. The so-treated waste water is discharged by trickle irrigation from the second of the two stabilisation lagoons (Ecoengineers Pty Ltd, 2000).

Mine water is pumped from the underground workings and piped to a location immediately downstream of the mine site access road bridge over American Creek, where it is discharged.

The Kemira Valley Coal Loading Terminal is located approximately 2.0 km northeast of the (Mt. Kembla) Nebo Entry Portal site, near the junction of the headwater tributaries of Brandy and Water Creek. The facility comprises of one main coal stockpiles fed by conveyor from the mine workings. Coal is loaded out via a specialised rail loading facility from underneath the stockpile and then it is transported to the Port Kembla Steel Works. Around the north eastern perimeter of the coal stockpile are three
sedimentation ponds designed to capture runoff water from the stockpile and surrounding area. Overflow and seepages from the first pond are directed around the stockpile where they are treated by flocculation to remove a large proportion of the TSS load before entering sedimentation ponds A and B.

The existing coal loading facility has a NSW DEC licensed discharge through a single drain to Brandy and Water Creek which requires regular monitoring for Total Suspended Solids (TSS), 5 day Biochemical Oxygen Demand (BOD$_5$ – sometimes denoted as BOD), and Oil and Grease (O&G).

2.18 GUJARAT NRE No1 COLLIERY

Gujarat NRE No 1 Colliery is located west of Russell Vale, to the north of Wollongong. The site and catchment area cover an area of approximately 66 ha. The main surface workings of the site are bordered by the Princes Highway to the east, residential areas to the south and north, and backed by the steeply sloping Illawarra Escarpment to the west. The washery, which is currently not in operation but used as a treatment facility for dirty site water, and raw coal stockpile are located on the northern side of the site. Raw coal is transported via conveyor from a portal located in the south western corner of the site. The main offices and car parks are located the western end of the site backing onto the escarpment.

The current WMS consists of a series of dams and tanks (Figure 2.6). Clean water for the bathhouse is bought from Sydney Water and accounts for 100,000 L per week. There are two dams located up the escarpment with a combined capacity of 20 ML. These dams catch surface runoff and rainwater and are required to meet statutory regulations for fire fighting purposes underground. Water from these dams is gravity fed to the underground workings. Overflow from these dams flows back down the escarpment towards the main coal stockpiles. Located near the raw coal conveyor are two holding dams approximately 10 ML each; these dams catch runoff from the escarpment and the raw coal stockpile as well as rainwater, mine water is also stored in these dams. Gujarat NRE Colliery No 1 is considered a wet mine with approximately 1ML per day being pumped out from the mine workings. Runoff from the main stockpile area and the two smaller dams is captured in the main storage dam on site. This dam has a capacity of 62 ML. Water from this dam is pumped back to the washery where it is
treated by coagulants and flocculants for reuse on site and discharge into Bellambi Creek. Two small dams on the main access road to the pit top area capture runoff from the road way and from the truck wash down area (Don Jephcott, Manager Technical Services, Metropolitan Colliery, pers comm).

At present 300,000 tonnes of coal are mined each year with the production planning to be ramped up to 1,000,000 tonnes per year. Raw coal from the mine is transported via truck to Port Kembla; from there it is shipped to India where it is washed and then coked for use in the steel making industry.

Figure 2.6: Aerial photo of the Gujarat NRE No 1 Colliery site at Russelvale in 1996.
2.19 SUMMARY OF WATER MANAGEMENT ISSUES FOR COAL MINES

This chapter has shown that all of the coalmines in the Illawarra region have extensive Water Management Systems. Management of water is a key colliery process and represents a significant cost in mine operations. There is also a significant issue of control of water quality discharged into the environment through licensed discharge points, which are monitored by the NSW DEC. For these reasons, there is a major interest in new approaches to the management of mine water resources, especially the quality, in order to increase the efficiency of water use (reducing the dependence on town water supplies) and to improve the quality of water on site for the benefit of workers, the environment, and to avoid non-compliance discharges. Improving water quality can also dramatically reduce the cost of operations, particularly in underground workings where saline waters reduce the effectiveness of hydraulic chocks, and increase the corrosion of equipment both on the surface and underground. During the processing of raw coal in a coal preparation plant, poor water quality can lead to increased running costs as more chemicals, particularly flocculants and reagents, are required to dose coal feeds as the process water may lie outside the optimum range for these chemicals.

In this thesis water quality at only one mine was studied, but it is hoped that the information derived from this study can be applied to other locations, leading to improved water quality management.
CHAPTER 3. MATERIALS AND METHODS

This section of the thesis describes water sampling, testing and daily monitoring regimes used in this study. As all of the work was carried out at West Cliff Colliery, readers are referred to a description of the colliery in Section 2.14 and the schematic diagram of the West Cliff WMS figure 2.5. The data were collected in an attempt to answer the research questions presented in Section 1.2.

3.1 STUDY AREA AND SAMPLING SITES

The daily testing and monthly sampling sites for the day-to-day monitoring and operation of the study trial were chosen as they represent key areas of West Cliff Colliery’s current Water Management System. A site located approximately 50 m upstream of the confluence of Brennans Creek with the Georges River was chosen as a control area, as there is no influence from the West Cliff Colliery mine water discharges (POINT 11).

Specific sampling locations on the West Cliff Colliery site were chosen for the following reasons (to be read in association with Figure 3.1)

POINT (0) is the surface water of the BCD. This area was monitored to give a day-to-day indication of the quality of water at the surface of the BCD. This also allowed for the influences of any freshwater inputs, i.e., rainfall, or dirty water overflows from other settling ponds on site, to be measured as they mixed with the BCD water. The daily temperature and EC readings were used to calculate the density of the surface water.

POINT (1) is the BCD Spillway and EPL# 2504 Licensed Discharge POINT (1) (LDP 1). The spillway was monitored whenever it was flowing as a statutory requirement of the trial and current EPL. When flowing, the spillway also represents an uncontrolled discharge from the West Cliff Colliery Mine Site directly into Brennans Creek.

POINT (9) is the bottom water of the BCD before it enters the Reclaim Pond (see Figure 3.2). This area was monitored to give a day-to-day indication of the quality of water at the bottom of the BCD (12.5 m deep when at the spillway). Depending on the quality of the bottom water, releases out of POINT 9 are controlled by the opening or closing of the scour valve. The daily temperature and EC measurements of this water were also
used to calculate its density. Redox measurements were also taken here daily. A flow meter located on the pipe allows the daily discharge volume to be monitored.

POINT (10) is the new LDP into Brennans Creek. Point 10 is located approximately 50 m to the North West of POINT (9). Water coming out of POINT (10) is released from the end of the reclaim pond and is controlled by an on/off butterfly valve. Being released from the end of the reclaim pond means that water from POINT (9), seepages from the dam wall, any rainfall, and a ground water spring can mix together to improve the quality of the water before release into Brennans Creek. A flow meter located at POINT (10) indicates the volume of water that has been directly discharged into Brennans Creek. The difference between the reading on the flow meters at Point (10) and POINT (9) also gives an indication of the amount of ground water and dam seepages into the reclaim pond.

POINT (11) is the sampling area approximately 50 m up stream of the confluence of Brennans Creek and the Georges River. This area is beyond the influence of any water discharges from West Cliff Colliery. It may, however, be influenced by discharges from Appin Colliery, located approximately 700 m up river.

POINT (12) is at the confluence of Brennans Creek and the Georges River.

POINT (13) is where the returning mine water from the underground workings is checked. Water at this site is sampled daily when it is flowing, as it is controlled by a floating offtake valve underground. A flow meter located on this outlet enables a determination of the amount of excess mine water returning to the surface. This is done by subtracting the cumulative flow being pumped underground from the cumulative return flow from underground.

POINT (14) is the clean return water into BCD from the washery after treatment in settling tanks to remove oil and grease as well as fine sediments. EC, pH, redox and temperature readings are taken at this site. The EC and temperature readings are used to determine the density of the water to facilitate prediction of how this water will mix with the water in BCD when it enters the dam.
Figure 3.1: Schematic diagram of the West Cliff Colliery Washery area with relative locations of sample POINTS 0, 1, 9, 10, 11, 12, 13, and 14 shown.
3.2 WATER SAMPLING METHODS AND QUALITY CONTROL

The key water quality parameters pH, EC, temperature and Oxidation Reduction Potential (ORP) were measured at the designated sites with probes and meters that had been freshly calibrated each day. In the case of pH this was done with 2 buffers bracketing the expected pH range of the mine water and in the case of EC with a conductivity standard close to the typical values expected. Probes were used with a temperature probe to ensure pH and EC were corrected to the standard temperature of 25°C for comparative purposes.

Sampling and analysis of water samples collected were conducted using appropriate sample bottles supplied and previously decontaminated by a National Association of Testing Laboratories (NATA) accredited laboratory and supplied with appropriate additives and labelling as prescribed by NATA protocols.

Sampling protocols, including the use of field blanks and replicates and analysis methods employed were strictly in accord with New South Wales State guidelines for the sampling and analysis of water pollutants (i.e., ANZECC&ARMCANZ, 2000; DEC NSW, 2004), and with best practice generally in water management in the Australian mining industry (Environment Australia, 1999).

In all cases, analysis methods employed were those providing adequate Limits of Resolution (LOR) (e.g., Inductively Coupled Plasma Mass Spectrometry for trace metals) and were those principal methods listed in DEC (NSW) (2004), namely the chemical methods described in ‘Standard Methods for the Examination of Water and Wastewater’ 20th Edition (APHA, 1998).

The following comments summarize the most important points of those procedures;

1. Samples were collected with or without filtration, into appropriate NATA-accredited laboratory-supplied bottles containing, where necessary, appropriate preservatives. Filtration equipment was stored in dilute acetic acid between sampling locations, being rinsed well with demineralized water just before use at each location. Storage in dilute acetic acid has been shown to control the leaching of trace elements, particularly iron, manganese and aluminium, which often precipitate from these waters and may coat
plastic filtration equipment and also zinc which is found in zinc stearate, a blow molding release agent commonly leached from plastic equipment.

2. Samples for filtered trace elements were filtered at the sampling site using appropriate plastic syringes and syringe filter apparatus that had been decontaminated as described above.

3. Field blanks, both filtered and unfiltered, and replicate samples, particularly for trace elements, were prepared at a rate of at least 10% of all samples collected. Field blanks were prepared from ‘rinsate blank’ water supplied by the testing laboratory that has been guaranteed to have all trace elements present at levels less than the Limit of Resolution (LOR).

### 3.3 WATER TESTING TECHNIQUES AND METHODOLOGY

Water quality in designated sections of the WMS was monitored daily as follows:

1. Temperature was measured using a solid-state sensor (TPS k=10/ATC/Temp Conductivity Sensor, 5m. model number 122218) calibrated at the beginning of each month.

2. pH was monitored with a probe and meter (TPS submersible pH sensor, gel filled, 5m. model number 111224) that had been freshly calibrated with a two point calibration using pH 7.00 and 9.22 buffers at the start of each day of monitoring.

3. Salinity was monitored with a probe and meter (TPS k=10/ATC/Temp Conductivity Sensor, 5m. model number 122218) that had been freshly calibrated with a single point calibration using an EC = 2760 uS/cm standard KCl electrolyte at the start of each day of monitoring.

4. BCD water level was recorded at 8 am each day from a measuring pole in the dam.

5. Cumulative flow out of the BCD and the Reclaim Pond was recorded at approximately 8 am daily from a 15 cm (6 inch) pipe fitted with a mechanical turbine driven flow meter.
6. pH, temp, and salinity were measured daily at approximately 8:00 am – at the BCD surface (POINT 0), BCD bottom drain valve (POINT 9), the discharge from the Reclalm Pond (POINT 10) and from the spillway when it was flowing (POINT 1).

7. The previous 24 hour rainfall at West Cliff Colliery was noted daily at 9 am.

8. pH, temp, and salinity of the upcoming mine water (POINT 13) and clean return water from the coal prep plant into the BCD (POINT 14) were measured daily at approximately 10 am.

9. pH, temp, and salinity were measured daily at approximately 12 pm at two sites in the Georges River, one being 50 m upstream of the confluence of the Georges River and Brennans Creek (POINT 11), and the other being 50 m downstream (POINT 12).

10. Cumulative daily flow, pH, temp, and salinity were measured at approximately 4 pm for discharge out of the Reclalm Pond and from the bottom drain of the BCD. Similar readings will also be recorded for the surface of the BCD.

11. The density of the water (expressed in units of g/cm³) was calculated using a standard algorithm that relates the density of pure water to temperature (T) (indicated in italics below), but adds a further contribution to the density from the dissolved salt load (i.e., TDS) in the water, the latter (TDS) being computed from a previously-established mean relationship between the TDS of West Cliff WMS waters and their EC (shown in bold below) (Ecoengineers Pty Ltd, 2004). The algorithm is as follows:

\[
\text{Density} = 0.99997 + 2.80602678 \times 10^{-5} \times T - 5.75758928 \times 10^{-6} \times T^2 + EC \times 0.568 \times 10^{-6}
\]

12. Around the middle of each month, no greater than 5 weeks apart, grab samples at key sites were taken for laboratory analysis. Table 3.1 indicates the parameters for which samples at POINTS 0,9, and 13 were analysed while, Table 3.2 indicates what parameters were measured for the samples at POINTS 1 and 10.
Table 3.1: Parameters measured, sampling method, and detection limit for POINTS 9, 0, and 13.

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<th>DETECTION LIMIT</th>
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Table 3.2: Parameters measured, sampling method, and detection limit for POINTS 1 and 10.

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<td>Total Alkalinity as CaCO3</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>1</td>
</tr>
<tr>
<td>Sulphate as SO4 2-</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>1</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>1</td>
</tr>
<tr>
<td>Calcium</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>1</td>
</tr>
<tr>
<td>Magnesium</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>1</td>
</tr>
<tr>
<td>Sodium</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>1</td>
</tr>
<tr>
<td>Potassium</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>1</td>
</tr>
<tr>
<td>Total Metals by ICP-MS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.001</td>
</tr>
<tr>
<td>Arsenic</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.001</td>
</tr>
<tr>
<td>Copper</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.001</td>
</tr>
<tr>
<td>Manganese</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.001</td>
</tr>
<tr>
<td>------------------</td>
<td>------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>Nickel</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.001</td>
</tr>
<tr>
<td>Zinc</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.005</td>
</tr>
<tr>
<td>Iron</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.05</td>
</tr>
<tr>
<td>Fluoride by PC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titrator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluoride</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.1</td>
</tr>
<tr>
<td>Sulphide as S2-</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>0.1</td>
</tr>
<tr>
<td>Total Anions</td>
<td>meq/L</td>
<td>Grab sample</td>
<td>0.01</td>
</tr>
<tr>
<td>Total Cations</td>
<td>meq/L</td>
<td>Grab sample</td>
<td>0.01</td>
</tr>
<tr>
<td>Ionic Balance</td>
<td>%</td>
<td>Grab sample</td>
<td>N/A</td>
</tr>
<tr>
<td>Oil &amp; Grease</td>
<td>mg/L</td>
<td>Grab sample</td>
<td>5</td>
</tr>
</tbody>
</table>

### 3.4 OPERATION OF THE WATER MANAGEMENT SYSTEM

In accordance with the water testing techniques and methodology in the previous sections (3.2 and 3.3), the WMS was managed by way of manual control of two valves, a scour valve at POINT 9, which could be adjusted to vary the flow coming out of the bottom of BCD and an on/off butterfly valve controlling the discharge through POINT 10 (see Figure 3.2). The flow out of POINT 9 was controlled such that water being discharged through POINT 10 was below the limits set in West Cliff’s EPL # 2504. In the event that the water quality being discharged through POINT 10 was above its specified limit, the discharges through POINT 9 and 10 were shut off and the reclaim pump initiated. Water from the Reclaim Pond was then pumped over the dam wall back into BCD. Discharges would also be cut back to a minimal flow of 0.2 to 0.3 ML/day if the water level in BCD fell to 11 m. A small discharge of 0.2 to 0.3 ML/day would maintain a small environmental flow in the Upper Georges River.
Cross Sectional diagram of the BCD Wall, Spillway
POINT 9, Reclaim pond, and POINT 10

BCD Wall
- Constructed of compacted coal wash
- Internal atmosphere high in CO2
due to natural oxidative diagenesis of compacted coal wash in dam wall

Seepage rate through BCD wall approx 100 kL/day

Degassing of CO2 from dam surface

Spillway height to overflow 12.5 m LDP No 1.

Reclaim Pond where mixing of BCD bottom water via POINT 9 discharge, dam wall seepages and groundwater takes place. Groundwater inflow approx. 30 - 50 kL/day.

V-notch weir to measure flow rate of dam wall seepage.

Figure 3.2: Cross sectional diagram of the BCD dam wall and the manual operation POINTS 9 and 10 (diagram not to scale).
3.5 DATA HANDLING

All field data (i.e., pH, EC, and temp) was logged on the TPS90 FLMV - Field lab analyser. Logged data were then transferred as a text file to a PC at the end of each week. The data were then converted from a text file into a Microsoft Excel workbook format, and entered into the appropriate spreadsheet. The graphs and statistical analysis (i.e., linear trendlines, r-squared values, and moving average trendlines) in this thesis were generated in Excel through the Excel Statistical analysis extension pack. Results from the monthly water samples were also added into a separate Excel spreadsheet.
4. RESULTS AND DISCUSSION

This section of the thesis reports on investigations into the effects on water quality when operating West Cliffs WMS in the manner prescribed earlier in Sections 3.2 and 3.3. The results of daily readings and monthly sampling of water quality are presented, and discussion of these results in terms of the system operation is provided. The order of presentation of results is:

1. BCD Spillway (POINT 1) and BCD surface (POINT 0) water quality measurements and data in Section 4.1,

2. The new licensed discharge point (POINT 10) water quality measurements and data in Section 4.2,

3. The BCD discharge (POINT 9) water quality measurements and data in Section 4.3,

4. The upcoming mine water (POINT 13), monthly water quality measurements and data in Section 4.4

The continuous pH and salinity of POINT 10 is presented in Section 4.5. The behaviour of Brennans Creek Dam in terms of pH, salinity, density and redox is presented in Section 4.6. The continuous pH and salinity of POINTS 11 and 12 are presented in Section 4.7. The daily and total flows through POINTS 10 and 1 are presented in Sections 4.8 and 4.9 respectively. The Brennans Creek Dam water level management and recorded rainfall during the trial are presented in Section 4.10. Automatic monitoring and control is discussed in Section 4.11. In Section 4.12 there are complementary studies presented relating to the effects of water quality in the upper Georges River on macro-invertebrates.
4.1 BCD SPILLWAY (POINT 1) AND BCD SURFACE (POINT 0) MONTHLY WATER QUALITY MEASUREMENTS

Tables 4.1 and 4.2 list the measured values of the prescribed parameters for the trial (Oil and Grease (O&G), pH, Total Suspended Solids (TSS) and also the additional parameters of interest EC, (total) arsenic, (total) copper, (total) nickel, and (total) zinc, for POINTS 0 and 1 for the 18 months of August 2004 to Feb 2006.

**TABLE 4.1: Monthly BCD Spillway (POINT 1) water quality monitoring data obtained from August 2004 through to December 2005.**

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>O&amp;G mg/L</th>
<th>pH</th>
<th>TSS mg/L</th>
<th>EC µS/cm</th>
<th>As mg/L</th>
<th>Cu mg/L</th>
<th>Ni mg/L</th>
<th>Zn mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/08/04</td>
<td>&lt;5</td>
<td>8.84</td>
<td>7</td>
<td>2880</td>
<td>0.012</td>
<td>0.021</td>
<td>0.182</td>
<td>0.121</td>
</tr>
<tr>
<td>16/11/04</td>
<td>&lt;5</td>
<td>9.01</td>
<td>13</td>
<td>2660</td>
<td>0.012</td>
<td>0.021</td>
<td>0.171</td>
<td>0.109</td>
</tr>
<tr>
<td>13/12/04</td>
<td>6</td>
<td>9.08</td>
<td>14</td>
<td>2580</td>
<td>0.011</td>
<td>0.023</td>
<td>0.176</td>
<td>0.107</td>
</tr>
<tr>
<td>17/07/05</td>
<td>&lt;5</td>
<td>8.90</td>
<td>192</td>
<td>1370</td>
<td>0.007</td>
<td>0.014</td>
<td>0.098</td>
<td>0.060</td>
</tr>
<tr>
<td>2/12/05</td>
<td>&lt;5</td>
<td>9.14</td>
<td>50</td>
<td>2190</td>
<td>0.007</td>
<td>0.014</td>
<td>0.109</td>
<td>0.049</td>
</tr>
<tr>
<td>EPL Limits</td>
<td>10</td>
<td>6.5 – 8.5</td>
<td>No limit</td>
<td>No limit</td>
<td>No limit</td>
<td>No limit</td>
<td>No limit</td>
<td>No limit</td>
</tr>
</tbody>
</table>

It can be seen in Table 4.1 that on all five occasions when POINT 1 was sampled concurrently with POINT 10 (see Table 4.3), the pH of the active POINT 1 (BCD Spillway) discharge exceeded the EPL upper pH limit of 8.5. The TSS value in July 05 also exceeded the EPL upper limit of 50 mg/L and in December 2005, when POINT 1 was last flowing, it was on the EPL upper limit. In addition, the salinity (EC) of the BCD surface water-derived POINT 1 discharge has ranged from closely similar to the bottom water derived POINT 10 (see Table 4.3) discharge at the beginning of the trial (when BCD had just turned over) to much lower values by December 2004. Salinity at POINT 1 was much lower on 17 July 2005, when the BCD spillway was strongly flowing following a brief but intense period of rainfall between 24 June 2005 and 2 July 2005 (see Figure 4.21).
TABLE 4.2: Monthly BCD Surface (POINT 0) water quality monitoring data obtained from March 2005 through to February 2006.

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>O&amp;G mg/L</th>
<th>pH</th>
<th>TSS mg/L</th>
<th>EC µS/cm</th>
<th>As mg/L</th>
<th>Cu mg/L</th>
<th>Ni mg/L</th>
<th>Zn mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/03/05</td>
<td>&lt;5</td>
<td>9.08</td>
<td>12</td>
<td>2930</td>
<td>0.01</td>
<td>0.02</td>
<td>0.152</td>
<td>0.069</td>
</tr>
<tr>
<td>19/04/05</td>
<td>&lt;5</td>
<td>9.05</td>
<td>5</td>
<td>2870</td>
<td>0.013</td>
<td>0.018</td>
<td>0.164</td>
<td>0.080</td>
</tr>
<tr>
<td>17/05/05</td>
<td>&lt;5</td>
<td>9.13</td>
<td>4</td>
<td>2980</td>
<td>0.015</td>
<td>0.018</td>
<td>0.173</td>
<td>0.070</td>
</tr>
<tr>
<td>10/06/05</td>
<td>&lt;5</td>
<td>8.95</td>
<td>6</td>
<td>2840</td>
<td>0.012</td>
<td>0.017</td>
<td>0.165</td>
<td>0.068</td>
</tr>
<tr>
<td>15/07/05</td>
<td>173</td>
<td>8.91</td>
<td>88</td>
<td>1790</td>
<td>0.007</td>
<td>0.012</td>
<td>0.101</td>
<td>0.041</td>
</tr>
<tr>
<td>17/08/05</td>
<td>&lt;5</td>
<td>9.01</td>
<td>9</td>
<td>2280</td>
<td>0.009</td>
<td>0.013</td>
<td>0.153</td>
<td>0.056</td>
</tr>
<tr>
<td>15/09/05</td>
<td>&lt;5</td>
<td>9.05</td>
<td>10</td>
<td>2620</td>
<td>0.009</td>
<td>0.013</td>
<td>0.162</td>
<td>0.059</td>
</tr>
<tr>
<td>18/10/05</td>
<td>&lt;5</td>
<td>9.12</td>
<td>10</td>
<td>2730</td>
<td>0.009</td>
<td>0.013</td>
<td>0.157</td>
<td>0.062</td>
</tr>
<tr>
<td>19/11/05</td>
<td>&lt;5</td>
<td>9.15</td>
<td>12</td>
<td>2910</td>
<td>0.012</td>
<td>0.021</td>
<td>0.167</td>
<td>0.079</td>
</tr>
<tr>
<td>2/12/05</td>
<td>&lt;5</td>
<td>9.10</td>
<td>19</td>
<td>2650</td>
<td>0.012</td>
<td>0.018</td>
<td>0.132</td>
<td>0.062</td>
</tr>
<tr>
<td>10/01/06</td>
<td>&lt;5</td>
<td>9.18</td>
<td>18</td>
<td>2630</td>
<td>0.012</td>
<td>0.021</td>
<td>0.149</td>
<td>0.074</td>
</tr>
<tr>
<td>9/02/06</td>
<td>&lt;5</td>
<td>9.10</td>
<td>10</td>
<td>2740</td>
<td>0.015</td>
<td>0.024</td>
<td>0.166</td>
<td>0.076</td>
</tr>
</tbody>
</table>

EPL Limits: No limit

To understand the influence of operating the trial in the manner prescribed in Sections 3.2, 3.3, and 3.4, by means of controlled bottom water discharges on the chemistry of surface water in BCD, samples of BCD surface water POINT 0 were taken at monthly intervals. From the values listed in Table 4.2, it can be seen that, in all instances, pH was higher than the upper 8.5 EPL limit; in some instances, it was nearly 0.7 pH units above the upper limit. Both TSS and O&G were also exceeded their respective EPL limits in July 2005. This is of significance as this surface water would, more than likely, be overflowing from the BCD spillway if controlled bottom discharges were not implemented to provide a freeboard level in the dam. The preceding three months before July 05 was one of the driest periods of the trial.
### 4.2 LICENCED DISCHARGE (POINT 10) MONTHLY WATER QUALITY MEASUREMENTS

Table 4.3 lists the measured values at POINT 10 of the prescribed parameters for the trial O&G, pH, TSS, and also the additional parameters of interest EC, (total) arsenic, (total) copper, (total) nickel, and (total) zinc, for the 19 months from August 2004 to Feb 2006.

**TABLE 4.3:** Monthly licensed discharge (POINT 10) water quality monitoring data obtained from August 2004 through to February 2006.

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>O&amp;G mg/L</th>
<th>pH</th>
<th>TSS mg/L</th>
<th>EC µS/cm</th>
<th>As mg/L</th>
<th>Cu mg/L</th>
<th>Ni mg/L</th>
<th>Zn mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/08/04</td>
<td>&lt;5</td>
<td>8.52</td>
<td>14</td>
<td>2820</td>
<td>0.011</td>
<td>0.018</td>
<td>0.187</td>
<td>0.108</td>
</tr>
<tr>
<td>22/09/04</td>
<td>&lt;5</td>
<td>8.25</td>
<td>8</td>
<td>2480</td>
<td>0.010</td>
<td>0.010</td>
<td>0.230</td>
<td>0.150</td>
</tr>
<tr>
<td>20/10/04</td>
<td>14</td>
<td>8.43</td>
<td>12</td>
<td>2770</td>
<td>0.011</td>
<td>0.011</td>
<td>0.187</td>
<td>0.100</td>
</tr>
<tr>
<td>16/11/04</td>
<td>&lt;5</td>
<td>8.44</td>
<td>6</td>
<td>2930</td>
<td>0.013</td>
<td>0.010</td>
<td>0.217</td>
<td>0.096</td>
</tr>
<tr>
<td>13/12/04</td>
<td>&lt;5</td>
<td>8.30</td>
<td>6</td>
<td>2770</td>
<td>0.010</td>
<td>0.006</td>
<td>0.208</td>
<td>0.071</td>
</tr>
<tr>
<td>14/01/05</td>
<td>&lt;5</td>
<td>8.24</td>
<td>7</td>
<td>2640</td>
<td>0.008</td>
<td>0.004</td>
<td>0.165</td>
<td>0.064</td>
</tr>
<tr>
<td>18/02/05</td>
<td>&lt;5</td>
<td>7.87</td>
<td>6</td>
<td>2500</td>
<td>0.008</td>
<td>0.003</td>
<td>0.174</td>
<td>0.042</td>
</tr>
<tr>
<td>16/03/05</td>
<td>&lt;5</td>
<td>8.07</td>
<td>3</td>
<td>2650</td>
<td>0.008</td>
<td>0.004</td>
<td>0.155</td>
<td>0.033</td>
</tr>
<tr>
<td>19/04/05</td>
<td>&lt;5</td>
<td>8.40</td>
<td>9</td>
<td>2640</td>
<td>0.010</td>
<td>0.011</td>
<td>0.159</td>
<td>0.066</td>
</tr>
<tr>
<td>17/05/05</td>
<td>&lt;5</td>
<td>8.42</td>
<td>280</td>
<td>2650</td>
<td>0.008</td>
<td>0.010</td>
<td>0.141</td>
<td>0.046</td>
</tr>
<tr>
<td>10/06/05</td>
<td>&lt;5</td>
<td>8.31</td>
<td>12</td>
<td>2550</td>
<td>0.007</td>
<td>0.011</td>
<td>0.153</td>
<td>0.042</td>
</tr>
<tr>
<td>15/07/05</td>
<td>&lt;5</td>
<td>8.32</td>
<td>17</td>
<td>2310</td>
<td>0.005</td>
<td>0.010</td>
<td>0.154</td>
<td>0.045</td>
</tr>
<tr>
<td>17/08/05</td>
<td>&lt;5</td>
<td>8.64</td>
<td>14</td>
<td>2550</td>
<td>0.006</td>
<td>0.009</td>
<td>0.142</td>
<td>0.041</td>
</tr>
<tr>
<td>15/09/05</td>
<td>&lt;5</td>
<td>8.50</td>
<td>12</td>
<td>2560</td>
<td>0.008</td>
<td>0.011</td>
<td>0.165</td>
<td>0.053</td>
</tr>
<tr>
<td>18/10/05</td>
<td>&lt;5</td>
<td>8.40</td>
<td>10</td>
<td>2540</td>
<td>0.007</td>
<td>0.008</td>
<td>0.16</td>
<td>0.048</td>
</tr>
<tr>
<td>19/11/05</td>
<td>&lt;5</td>
<td>8.67</td>
<td>12</td>
<td>2750</td>
<td>0.008</td>
<td>0.008</td>
<td>0.158</td>
<td>0.049</td>
</tr>
<tr>
<td>19/12/05</td>
<td>&lt;5</td>
<td>8.48</td>
<td>44</td>
<td>3410</td>
<td>0.009</td>
<td>0.008</td>
<td>0.159</td>
<td>0.045</td>
</tr>
<tr>
<td>10/01/06</td>
<td>&lt;5</td>
<td>8.60</td>
<td>7</td>
<td>2580</td>
<td>0.010</td>
<td>0.009</td>
<td>0.159</td>
<td>0.058</td>
</tr>
<tr>
<td>9/02/06</td>
<td>&lt;5</td>
<td>8.69</td>
<td>7</td>
<td>2310</td>
<td>0.008</td>
<td>0.007</td>
<td>0.152</td>
<td>0.047</td>
</tr>
<tr>
<td><strong>EPL Limits</strong></td>
<td><strong>10</strong></td>
<td><strong>6.5 – 8.5</strong></td>
<td><strong>50</strong></td>
<td><strong>No limit</strong></td>
<td><strong>No limit</strong></td>
<td><strong>No limit</strong></td>
<td><strong>No limit</strong></td>
<td><strong>No limit</strong></td>
</tr>
</tbody>
</table>
All EPL limits on the prescribed parameters for water samples from the new licensed discharge POINT 10 were met with the exception of: O&G on 20 October 2004; TSS on 17 May 2005; and pH on 19 August 2004, 17 August 2005, 19 November 2005, 10 January 2006, and 9 February 2006.

Explanations for the EPL limit exceedances identified above are as follows:

It is believed that the minor O&G exceedance on 20 October 2004 arose because the outlet box in the dam wall of the Reclaim Pond had just been replaced and the flow meter checked. The design was found to be limiting the flow rate out of POINT 10. Possibly during the incorporation of the new outlet box, small amounts of grease used on the new outlet metalwork may have been bleeding into the discharged water around the time the sample was collected.

It is believed that the laboratory-reported TSS of 280 mg/L for the POINT10 sample collected on 17 May 2005 is completely spurious and more than likely arose due to a laboratory transcription error. When collected, the sample was not noticeably turbid and the laboratory reported only 2.83 mg/L total iron (Fe) for the sample – quite typical of all previous and following monthly samples when Total Fe lay in the range 0.3 – 2.9 mg/L and TSS lay in the range 3 – 17 mg/L. As the suspended solids in water passing though this point are known to be largely comprised of precipitated Fe oxyhydroxides (Ecoengineers Pty Ltd, 2004), the laboratory-reported total Fe of 2.8 mg/L for the 17 May sample also suggests there was nothing out of ordinary with the TSS.

The reported high pH value on 19 August 2004 is attributed to the start of the trial and initial set-up of the monitoring regime. The trial started on 2 August 2004 and during the initial stages, adjustment of flows out of the control valve at POINT 9 and its effects on the quality of water in the Reclaim Pond were difficult to predict. The high pH value on 17 August 2005 was probably due to a delay in analysis at the laboratory, leading to degassing of CO2 from the sample after opening, raising the pH of the sample. The high pH values recorded on 19 November 2005, 10 January 2006, and 9 February 2006 coincided with Georges River grouting remediation work. During this time the flows in the river were stopped completely for the grouting work to be carried out. After grouting, water is generally released from the BCD at a faster rate, to return a steady flow back to
the river as fast as possible. Increasing the flow out of POINT 10 means that pH is harder to control.

It can also be seen that there was a slow decline in the concentrations of As, Cu, Ni and Zn in the licensed POINT 10 discharge over the course of the 18 months of the trial from August 2004 to February 2006 (Figures 4.1 and 4.2).

**Figure 4.1: The concentrations of As and Cu out of the licensed discharge POINT 10 over time from August 2004 to February 2006**
The arsenic concentration has been reduced by a factor of about 2 from around 10 – 13 µg/L to around 7 µg/L. The default trigger value for As(V) for protection of 95% of all aquatic species in the national water quality guidelines is 13 µg/L (ANZECC&ARMCANZ, 2000). Cu has been reduced by a factor of approximately 2.5 from approximately 18 µg/L to approximately 7 µg/L, well above the default trigger value for Cu for protection of 95% of all aquatic species in the national water quality guidelines which is 1.4 µg/L (ANZECC&ARMCANZ, 2000). Ni has been reduced by a factor of approximately 1.3 from approximately 200 µg/L to around 150 µg/L, again above the default trigger value for Ni for protection of 95% of all aquatic species in the national water quality guidelines of 11 µg/L (ANZECC&ARMCANZ, 2000). Zn has been reduced by a factor of approximately 2.4 from approximately 120 µg/L to approximately 50 µg/L, well above the default trigger value for Zn for protection of 95% of all aquatic species in the national water quality guidelines of 8 µg/L (ANZECC&ARMCANZ, 2000).
Although Cu, Ni and Zn concentrations are above the national water quality guidelines, aqueous geochemical speciation modelling using the United States Geological Survey geochemical model PHREEQC (Parkhurst and Appelo, 1999) showed the concentrations of the ecotoxic cationic species to be 0.0027 µg/L for Cu$^{2+}$, 0.06 µg/L for Ni$^{2+}$, and 0.09 for µg/L Zn$^{2+}$. With pH being in the 8.0 – 8.5 range, all of these ecotoxic cationic species are below the default trigger values for protection of 95%, and in some cases 99%, of all aquatic species in the ANZECC water quality guidelines (see Appendix 1 for model output).

These reductions are believed to be a direct result of:

- The BCD beginning to progressively capture a higher proportion of the runoff from its catchment area due to the BCD bottom water discharge strategy; and

- Adsorption of As, Cu, Ni and Zn on precipitated iron (Fe) and manganese (M) oxyhydroxides, both within the BCD, due to increases in the oxidation reduction potential (ORP; Eh) of bottom waters within the dam (due to improved discharge of reduced bottom waters) and within the Reclaim Pond itself, the Fe and Mn in the latter being sourced from the BCD dam wall and groundwater seepage components.
Table 4.4 lists the measured values of the prescribed parameters for the trial (O&G, pH, TSS) and also the additional parameters of interest EC, (dissolved) arsenic, (dissolved) copper, (dissolved) nickel, and (dissolved) zinc for POINT 9 for the 18 months from September 2004 to February 2006.

**TABLE 4.4: Monthly BCD discharge (POINT 9) water quality monitoring data obtained from September 2004 through to February 2006.**

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>O&amp;G mg/L</th>
<th>pH</th>
<th>TSS mg/L</th>
<th>EC µS/cm</th>
<th>As mg/L</th>
<th>Cu mg/L</th>
<th>Ni mg/L</th>
<th>Zn mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>22/09/04</td>
<td>&lt;5</td>
<td>8.68</td>
<td>3</td>
<td>2700</td>
<td>0.010</td>
<td>0.010</td>
<td>0.230</td>
<td>0.150</td>
</tr>
<tr>
<td>20/10/04</td>
<td>&lt;5</td>
<td>8.75</td>
<td>3</td>
<td>3000</td>
<td>0.015</td>
<td>0.013</td>
<td>0.199</td>
<td>0.129</td>
</tr>
<tr>
<td>16/11/04</td>
<td>&lt;5</td>
<td>8.78</td>
<td>2</td>
<td>3140</td>
<td>0.016</td>
<td>0.009</td>
<td>0.236</td>
<td>0.124</td>
</tr>
<tr>
<td>13/12/04</td>
<td>&lt;5</td>
<td>8.82</td>
<td>2</td>
<td>3110</td>
<td>0.015</td>
<td>0.009</td>
<td>0.223</td>
<td>0.107</td>
</tr>
<tr>
<td>14/01/05</td>
<td>&lt;5</td>
<td>8.98</td>
<td>5</td>
<td>2870</td>
<td>0.012</td>
<td>0.017</td>
<td>0.164</td>
<td>0.065</td>
</tr>
<tr>
<td>18/02/05</td>
<td>&lt;5</td>
<td>8.70</td>
<td>4</td>
<td>2800</td>
<td>0.009</td>
<td>0.002</td>
<td>0.159</td>
<td>0.052</td>
</tr>
<tr>
<td>9/03/05</td>
<td>&lt;5</td>
<td>8.77</td>
<td>3</td>
<td>2880</td>
<td>0.012</td>
<td>0.007</td>
<td>0.157</td>
<td>0.051</td>
</tr>
<tr>
<td>19/04/05</td>
<td>&lt;5</td>
<td>8.93</td>
<td>4</td>
<td>2840</td>
<td>0.014</td>
<td>0.012</td>
<td>0.159</td>
<td>0.079</td>
</tr>
<tr>
<td>17/05/05</td>
<td>&lt;5</td>
<td>9.12</td>
<td>4</td>
<td>2990</td>
<td>0.015</td>
<td>0.015</td>
<td>0.167</td>
<td>0.067</td>
</tr>
<tr>
<td>10/06/05</td>
<td>&lt;5</td>
<td>8.98</td>
<td>5</td>
<td>2870</td>
<td>0.012</td>
<td>0.017</td>
<td>0.164</td>
<td>0.065</td>
</tr>
<tr>
<td>15/07/05</td>
<td>&lt;5</td>
<td>8.99</td>
<td>12</td>
<td>2410</td>
<td>0.012</td>
<td>0.018</td>
<td>0.189</td>
<td>0.082</td>
</tr>
<tr>
<td>17/08/05</td>
<td>&lt;5</td>
<td>8.95</td>
<td>8</td>
<td>2940</td>
<td>0.009</td>
<td>0.013</td>
<td>0.161</td>
<td>0.062</td>
</tr>
<tr>
<td>15/09/05</td>
<td>&lt;5</td>
<td>8.93</td>
<td>6</td>
<td>2740</td>
<td>0.010</td>
<td>0.012</td>
<td>0.162</td>
<td>0.065</td>
</tr>
<tr>
<td>18/10/05</td>
<td>&lt;5</td>
<td>9.21</td>
<td>4</td>
<td>2720</td>
<td>0.010</td>
<td>0.010</td>
<td>0.160</td>
<td>0.065</td>
</tr>
<tr>
<td>19/11/05</td>
<td>&lt;5</td>
<td>8.98</td>
<td>5</td>
<td>2940</td>
<td>0.010</td>
<td>0.009</td>
<td>0.157</td>
<td>0.057</td>
</tr>
<tr>
<td>19/12/05</td>
<td>&lt;5</td>
<td>8.93</td>
<td>14</td>
<td>3010</td>
<td>0.013</td>
<td>0.008</td>
<td>0.160</td>
<td>0.064</td>
</tr>
<tr>
<td>10/01/06</td>
<td>&lt;5</td>
<td>8.92</td>
<td>8</td>
<td>2730</td>
<td>0.013</td>
<td>0.007</td>
<td>0.156</td>
<td>0.066</td>
</tr>
<tr>
<td>9/02/06</td>
<td>&lt;5</td>
<td>8.90</td>
<td>8</td>
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<td>0.014</td>
<td>0.007</td>
<td>0.164</td>
<td>0.067</td>
</tr>
<tr>
<td>Mean ± 1 S.d.</td>
<td>&lt;5</td>
<td>8.91</td>
<td>5.56</td>
<td>2855</td>
<td>0.012</td>
<td>0.011</td>
<td>0.176</td>
<td>0.079</td>
</tr>
</tbody>
</table>

- **Additional Parameters of Interest:**
  - EC (µS/cm)
  - (Dissolved) Arsenic (As mg/L)
  - (Dissolved) Copper (Cu mg/L)
  - (Dissolved) Nickel (Ni mg/L)
  - (Dissolved) Zinc (Zn mg/L)
During the study period there was a noticeable decline in the filterable zinc and nickel from the BCD bottom drain valve water, but there was no noticeable decline for arsenic and copper (Figures 4.3 and 4.4). The decline in zinc is attributed to the concurrent decline in the filterable zinc levels in the upcoming mine water over this period refer Section 4.4. The decline in nickel is attributed to improved flocculation and settling within the BCD, due to the modified way in which the WMS was operated. It is noted that a likely mode of removal of trace metals in the BCD would be adsorption on to settling sediment, which seems to have applied for nickel.

**Figure 4.3:** The concentrations of As and Cu out of the BCD discharge POINT 9 over time from September 2004 to February 2006.
Figure 4.4: The concentrations of Ni and Zn out of the BCD discharge POINT 9 over time from September 2004 to February 2006.
4.4 UPCOMMING MINE WATER (POINT 13) MONTHLY WATER QUALITY MEASUREMENTS

Table 4.5 lists the measured values of the prescribed parameters for the trial (O&G, pH, TSS) and also the additional parameters of interest EC, (dissolved) arsenic, (dissolved) copper, (dissolved) nickel, and (dissolved) zinc of POINT 13 for the 19 months from September 2004 to Feb 2006.

TABLE 4.5: Monthly upcoming mine water POINT 13 water quality monitoring data obtained from August 2004 through to February.

<table>
<thead>
<tr>
<th>Sampling Date</th>
<th>O&amp;G mg/L</th>
<th>pH</th>
<th>TSS mg/L</th>
<th>EC µS/cm</th>
<th>As mg/L</th>
<th>Cu mg/L</th>
<th>Ni mg/L</th>
<th>Zn mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/08/04</td>
<td>&lt;5</td>
<td>8.62</td>
<td>248</td>
<td>4030</td>
<td>0.025</td>
<td>0.002</td>
<td>0.219</td>
<td>0.200</td>
</tr>
<tr>
<td>22/09/04</td>
<td>&lt;5</td>
<td>8.69</td>
<td>446</td>
<td>3500</td>
<td>N/A</td>
<td>N/A</td>
<td>0.216</td>
<td>N/A</td>
</tr>
<tr>
<td>20/10/04</td>
<td>&lt;5</td>
<td>8.78</td>
<td>442</td>
<td>3850</td>
<td>0.023</td>
<td>0.007</td>
<td>0.220</td>
<td>0.230</td>
</tr>
<tr>
<td>16/11/04</td>
<td>22</td>
<td>8.78</td>
<td>447</td>
<td>4160</td>
<td>0.033</td>
<td>0.005</td>
<td>0.194</td>
<td>0.182</td>
</tr>
<tr>
<td>13/12/04</td>
<td>&lt;5</td>
<td>8.81</td>
<td>310</td>
<td>3970</td>
<td>0.043</td>
<td>0.006</td>
<td>0.176</td>
<td>0.123</td>
</tr>
<tr>
<td>14/01/05</td>
<td>&lt;5</td>
<td>8.77</td>
<td>84</td>
<td>4080</td>
<td>0.033</td>
<td>0.011</td>
<td>0.182</td>
<td>0.100</td>
</tr>
<tr>
<td>18/02/05</td>
<td>&lt;5</td>
<td>8.53</td>
<td>48</td>
<td>3860</td>
<td>0.027</td>
<td>0.014</td>
<td>0.180</td>
<td>0.102</td>
</tr>
<tr>
<td>9/03/05</td>
<td>5</td>
<td>8.65</td>
<td>570</td>
<td>3910</td>
<td>0.024</td>
<td>0.008</td>
<td>0.173</td>
<td>0.131</td>
</tr>
<tr>
<td>19/04/05</td>
<td>&lt;5</td>
<td>8.68</td>
<td>164</td>
<td>4060</td>
<td>0.029</td>
<td>0.011</td>
<td>0.188</td>
<td>0.169</td>
</tr>
<tr>
<td>17/05/05</td>
<td>&lt;5</td>
<td>8.36</td>
<td>8</td>
<td>4200</td>
<td>0.030</td>
<td>0.010</td>
<td>0.180</td>
<td>0.098</td>
</tr>
<tr>
<td>10/06/05</td>
<td>&lt;5</td>
<td>8.59</td>
<td>339</td>
<td>3650</td>
<td>0.024</td>
<td>0.009</td>
<td>0.177</td>
<td>0.076</td>
</tr>
<tr>
<td>15/07/05</td>
<td>10</td>
<td>8.55</td>
<td>771</td>
<td>3170</td>
<td>0.027</td>
<td>0.016</td>
<td>0.177</td>
<td>0.121</td>
</tr>
<tr>
<td>17/08/05</td>
<td>6</td>
<td>8.78</td>
<td>1180</td>
<td>3770</td>
<td>0.022</td>
<td>0.011</td>
<td>0.172</td>
<td>0.089</td>
</tr>
<tr>
<td>15/09/05</td>
<td>&lt;5</td>
<td>8.80</td>
<td>470</td>
<td>3660</td>
<td>0.025</td>
<td>0.013</td>
<td>0.175</td>
<td>0.107</td>
</tr>
<tr>
<td>18/10/05</td>
<td>12</td>
<td>8.72</td>
<td>968</td>
<td>3500</td>
<td>0.025</td>
<td>0.009</td>
<td>0.188</td>
<td>0.097</td>
</tr>
<tr>
<td>19/11/05</td>
<td>&lt;5</td>
<td>8.68</td>
<td>320</td>
<td>3950</td>
<td>0.031</td>
<td>0.010</td>
<td>0.201</td>
<td>0.072</td>
</tr>
<tr>
<td>2/12/05</td>
<td>7</td>
<td>8.65</td>
<td>1070</td>
<td>3890</td>
<td>0.041</td>
<td>0.010</td>
<td>0.214</td>
<td>0.100</td>
</tr>
<tr>
<td>10/01/06</td>
<td>&lt;5</td>
<td>8.70</td>
<td>206</td>
<td>3620</td>
<td>0.034</td>
<td>0.009</td>
<td>0.222</td>
<td>0.102</td>
</tr>
<tr>
<td>9/02/06</td>
<td>&lt;5</td>
<td>8.61</td>
<td>508</td>
<td>3590</td>
<td>0.031</td>
<td>0.007</td>
<td>0.214</td>
<td>0.089</td>
</tr>
<tr>
<td>Mean ± 1 S.d.</td>
<td>5.11 ±</td>
<td>8.65</td>
<td>452.94 ±</td>
<td>3828.89 ±</td>
<td>0.029 ±</td>
<td>0.009 ±</td>
<td>0.192 ±</td>
<td>0.122 ±</td>
</tr>
<tr>
<td></td>
<td>5.10</td>
<td>0.12</td>
<td>345.44</td>
<td>260.95</td>
<td>0.006</td>
<td>0.003</td>
<td>0.018</td>
<td>0.044</td>
</tr>
</tbody>
</table>
Figures 4.5 and 4.6 show that there was no significant difference in the As, Cu, and Zn concentrations over the trial period. There was, however, a significant downwards trend in the Zn concentration of the upcoming mine water. At this stage it is not known why the levels in Zn concentrations have declined in the mine water over the study period. It is, however, known that the principal source of Zn in the mine water is derived from the galvanised pipes conducting it. As there are no noticeable trends in the change of pH or salinity in the mine water, changes in chloride concentrations are likely to be the driving factor for the downward trend observed in the dissolved Zn concentrations due to increased complexation of the Zn (Ecoengineers Pty Ltd, pers comm)

**Figure 4.5: The concentrations of As and Cu out of the upcoming mine water POINT 13 over time from August 2004 to February 2006.**
Figure 4.6: The concentrations of Ni and Zn out of the upcoming mine water POINT 13 over time from August 2004 to February 2006.

4.5 CONTINUOUS pH AND SALINITY BEHAVIOUR OF THE LICENCED DISCHARGE (POINT 10)

Figure 4.7 shows the average weekly pH of the POINT 10 licensed discharge monitoring point computed as the average of (usually 10) twice daily readings. It also shows the pH of the occasional spills over the BCD spillway past POINT 1 (in red).
At the beginning of the trial there were some initial minor problems in manually matching the flow through the BCD bottom drain (POINT 9) and the un-metered seepages from the Dam wall and surrounding sandstone strata (POINT 10).

Following resolution of these issues, a balanced regular flow was routinely maintained. By combining the inflow of natural groundwater and dam wall seepages into the reclaim pond with the BCD bottom water discharge via POINT 9, the pH of the licensed POINT 10 discharge was then able to be maintained consistently below the EPL limit of 8.5. This was maintained for close to the entire 18 months from August 04 to February 06.

Gaps in the pH data for POINT 10 in mid July 2005 and late October 2005 were due to river rehabilitation work being carried out in the Georges River downstream of its confluence with Brennans Creek. During these two periods, which lasted for 2 weeks each, there was no water released from West Cliff Colliery via the POINT 10 discharge.

From 4 July until 5 August 2005 water was released from POINT 10 at such a rate that the pH was marginally above 8.5 (range 8.5 - 8.9). This was done in order to maximize
the rate of fall in the level of BCD and to minimize the pH of water running out of Brennans Creek because over that period:

- the BCD was full and spilling strongly over the spillway past POINT 1 with a much higher pH (range 8.8 - 9.05) than in the bottom water-derived POINT 10 discharge as indicated in Figure 4.7; and,

- there had been very heavy rain on 1 July 2005 and hence there was substantial runoff in the Upper Georges River catchment to dilute the outflow from the Creek (see Figures 4.17 and 4.21 in later discussion).

Analysis and geochemical modeling conducted on the Reclaim Pond water revealed that the water within the Reclaim Pond comprised about 75 – 80% of BCD bottom water seepages through or around the dam wall, and about 20 – 25% of the water was a low salinity groundwater with chemistry similar to local rain water (Ecoengineers Pty Ltd, pers comm). The modeling showed that most of the Reclaim Pond water that is derived from the BCD became equilibrated along its travel path with an atmosphere containing 0.5 – 5% by volume carbon dioxide. As the BCD dam wall is constructed largely of compacted coalwash, the atmosphere within the dam wall is enriched with carbon dioxide, due to oxidative diagenesis – a process that occurs continually within coal and coalwash stockpiles (Ecoengineers Pty Ltd, 2004). Modeling also showed that the water had become saturated with respect to siderite (ferrous carbonate) and rhodocrosite (manganese carbonate). As these minerals occur together in local coalwash about 7 – 9% by weight total, this also suggests that most of the Reclaim Pond water is derived from seepages through the dam wall (Ecoengineers Pty Ltd, 2004).

Consequently, the lower pH values that have been maintained within the Reclaim Pond during this trial, were largely a result of the dissolution of carbon dioxide into seepages from the dam wall that mix with groundwater and BCD bottom water in the Reclaim Pond. The coalwash dam wall material which contains siderite and rhodocrosite also contributes most of the dissolved iron and manganese which is leached out as water from the BCD seeps through the dam wall.
There was considerable catchment runoff captured in BCD during the extended wet period between early October 2004 and early January 2005 as indicated in Figures 4.9 and 4.21. It can be clearly seen from Figure 4.8 that over the first eight months of operation (i.e., until March 2005) the system being trialled had a noticeable effect on reducing the overall salinity (EC) of the BCD (and hence of the WMS as a whole), which is particularly noticeable at POINTS 9 and 10. There was a progressive decline in average BCD EC from around 2875 μS/cm at the beginning of the trial in August 2004 to about 2650 μS/cm by March 2005 equivalent to a reduction in the load of salts circulating within the WMS by about 1% per month. The 8% decline in salinity of POINT 10 over the first eight months of the trial is attributed to the improved capture of rainfall/runoff in the BCD.

However, after March 2005, there was a slow but progressive increase in the average salinity of the BCD. Initially, this was most likely because of a significant fall off in rainfall, with very much lower than average rainfalls through the months of April, May and June (Figure 4.9). This had the effect of minimizing the diluting effects of runoff entering the BCD and maximizing the concentrating effects of evaporation from both BCD and other water bodies in the catchment as well as maximizing evapotranspiration generally from the vegetated areas of the catchment.
This dry period was punctuated by a short, intense period of rainfall between 24 June and 2 July 2005 when some 139 mm was recorded, including 94 mm on 1 July. This produced a sharp reduction in the salinity of BCD waters in July/August 2005 (Figure 4.8), but by the end of the trial the average salinity in the BCD had unexpectedly continued to rise, attaining a level around 2975 μS/cm and around 2750 μS/cm at POINT 10. Following further investigation, and noting that rainfall in August continued to be unusually low (maintaining the concentrating effects) the continuing rise in salinity in BCD was attributed to an as-yet unexplained rise in mine water salinity (Figure 4.10).
From early June 2005 there was a substantial increasing trend in the salinity of the pumped-out mine water from an earlier level averaging about 3750 μS/cm from August 2004 to July 2005 to a new level, averaging around 4000 - 4200 μS/cm (Figure 4.10). At this point in time no obvious reasons for this change can be identified. The 5-point average moving trend line in Figure 4.10 calculated by taking the average value over five consecutive points and plotting a smooth running average trend line clearly shows the rising trend in mine water salinity during 2005.

The three dry months of April, May and June 2005 coupled with a 12% increase in mine water salinity in the last three months of the 18 month trial were sufficient to negate the 8% improvement (reduction) in WMS salinity levels (as seen in the WMS’s major storage, the BCD) achieved over the first eight months of the trial.

The mine water is a mixture of BCD water pumped underground for mining uses and groundwater inflows to underground workings. The recent increase in mine water salinity cannot be attributed to the recent dry spell, as the salinity of water pumped underground from BCD never exceeded about 2900 μS/cm during this study period.
4.6 BEHAVIOUR OF BRENNANS CREEK DAM, IN RELATION TO pH AND SALINITY AT BCD SURFACE (POINT 0), SPILLWAY (POINT 1), AND BCD DISCHARGE (POINT 9)

Figures 4.11, 4.12, 4.13, 4.14 and 4.15 show the average weekly density of surface and bottom waters of BCD, the density difference between the bottom POINT 9 water and the surface POINT 0 water, the average weekly temperature POINT 9 and 0, as well as the average weekly pH values AT POINTS 9 and 0. The redox value for POINT 9 is also presented in Figure 4.15. Together these data show that:

1. At the beginning of the trial, in early August 2004, the BCD had recently turned over as both temperatures and densities at the top and bottom of the dam were very similar;

2. From December 04 – May 05 salinity in the BCD was falling, the Dam remained fully stratified, principally on the basis of temperature; and

3. The average salinity of BCD has been increasing over the entire trial period.

However, the data in Figure 4.11, showing best estimates of the density difference between BCD top and bottom waters, indicate that the BCD turned over again in mid-June 2005. Following this, there was a slow re-establishment of temperature-based density stratification occurring until the end of the trial period in February 2006. Continued monitoring beyond 3 August 2005 has also shown that BCD remained stratified from mid June, although it temporarily approached close to another turnover in mid August 2005 with recovery of stratification from then to the end of the monitoring period.

The close approach to a third turnover in mid-August 2005 was probably due to the effects of the unexplained increase in mine water salinity. This is because, following pumping from underground, the mine water passes directly to the Coal Preparation Plant (CPP) where it is employed in the washing of coal. During that process, its salinity may change a little as its water chemistry equilibrates with the shale fraction of the Run Of Mine (ROM) coal which is discarded as coal washery material (CWM), but more importantly it becomes warmer from the energy imparted to it in the CPP. This in turn means that the water, after coagulation and flocculation, still flows to the BCD with a temperature that is higher than the other water sources entering the BCD.
This water is lighter and tends to ‘float’ on the colder waters of BCD, even though it is of higher salinity than that of the colder waters, until such time as it cools and sinks. This means that any significant increase in salinity of water exiting the CPP could, at least initially, tend to encourage a BCD turnover, as such waters would initially mix with the top layers of the Dam.

**Figure 4.11:** Average weekly density in the BCD bottom (POINT 9) and surface (POINT 0) waters from August 2004 through to February 2006.
Figure 4.12: Brennans Creek Dam density difference, bottom minus top (g/cm^3) from August 2004 through to February 2006.

Figure 4.13: Average weekly temperatures of the BCD bottom and surface waters from August 2004 through to February 2006.
Figure 4.14: Average weekly pH values of the BCD bottom water (POINT 9) and the surface water (POINT 0) from August 2004 through to February 2006.

Figure 4.15: Redox values in the BCD (POINT 9) water between February 2005 and February 2006.
4.7 CONTINUOUS pH AND SALINITY BEHAVIOUR OF THE UPSTREAM AND DOWNSTREAM GEORGES RIVER (POINTS 11 and 12)

Figure 4.16 shows the daily recorded EC and pH of POINT 11 in the upper Georges River, 50 m upstream of the confluence with Brennans Creek, over the period from August 2004 to January 2006. Although Figure 4.16 does not show flow rates past POINT 11, measurements for pH and EC were only taken when there was a visible flow at this location. This means that the gaps in the data of figure 4.16 represent intervals of no observable flow in the upstream Georges River.

Figure 4.16: Daily EC and pH for POINT 11 from August 2004 through to January 2006.
At the commencement of the trial in August 2004 there were observable flows in the Georges River at POINT 11 for a considerable time (after the commencement of the trial) largely due to a higher than average rainfall in October 2004 and good rainfalls in November 2004. Flows in the river at POINT 11 ceased for an extended of time from 24 December until the 25 of May 2005, due to lower than average rainfall in January and February 2005 (see rainfall data Figure 4.9). Within this period there are, however, 3 consecutive days of flow recorded on the 10, 11, and 12 March 2005, due to water discharges from the Appin Mine. Following this, from late June, flow at the upstream Georges River POINT 11 remained sporadic due to intermittent river mitigation work until January 2006. After this time, there was no flow recorded past POINT 11 due to a combination of lower than average rainfalls, and a lack of controlled mine water discharges from Appin Colliery because of river mitigation works being carried out by BHP Billiton further down river, which required no water being present in the river bed.

For the majority of the time that there was flow at POINT 11, the EC was below its EPL limit of 800 μS/cm, with the exception of three short periods from May 2005 to September 2005. During this time the flow was erratic, which caused the EC to rise slightly above its 800 μS/cm limit. The pH recorded at POINT 11 was also found to be in compliance with its upper limit of 8.5 for the entire time there was flow.

Figure 4.17 shows the daily recorded pH and EC values for POINT 12 located 50 m down stream of the confluence of Brennans Creek and the Georges River over the course of the trial from August 2004 to February 2006.
For the first three months of the trial, from August 2004 until late October 2004, the new operational system was relatively successful in keeping the pH at POINT 12 below 8.5. The EC at POINT 12 was, after some early commissioning difficulties of the control valve at POINT 9, held within the 900 – 1650 μS/cm range. For this period, Appin Colliery was discharging up to 1.1 ML/day of a low salinity environmental discharge, to compensate for natural flow losses downstream of the Brennans Creek confluence, caused by mine subsidence related effects. These licensed discharges from Appin Colliery were intended to be temporary, and only used when pool levels within the Georges River needed to be supplemented. This environmental flow from Appin Colliery ceased near the end of November 2004 after successful river mitigation activities in some sections of the river, coupled with a degree of natural sealing within the river bed fractures over time.
After 24 December 2004, the pH of the flow at POINT 12 rose to lie within the 8.5 to 9 range for the majority of the remainder of the trial period until February 2006. Over this same period, the EC also rose to higher values of between 2400 – 2700 μS/cm. After 1 February 2005, the gradual reduction in both salinity and alkalinity of the BCD waters (see Figure 4.8), achieved by the continued operation of the trial utilizing the bottom water discharge strategy began, to have a positive effect in reducing both pH and EC in the Georges River at POINT 12.

Due to the dry conditions from April 2005 to August 2005, and the absence of any consistent flows from Appin Colliery, the flows in the Georges River at POINT 12 were essentially due to the POINT 10 discharge from the Reclaim Pond and hence the pH and the EC in the river at POINT 12 reflected this. After this period until the end of the trial, the POINT 10 discharge remained the predominant source of flow in the Georges River downstream of the confluence. Upstream the river remained dry as a result of low rainfall and inconsistent Appin Colliery water discharges.
Figure 4.18 shows the daily and cumulative discharge volumes from the reclaim pond discharge POINT 10 over the period 2 August 2004 – 23 February 2006. The total volume discharged through POINT 10 between 2 August 2004 and 23 February 2006 is estimated to be 485 ML. This is equivalent to about 150% of the estimated total capacity of the BCD to the spillway level at 12.5 m maximum depth (on the dams level gauge) – estimated to be about 320 ML. In other words, one and a half full volumes of the BCD were discharged through POINT 10 during this period. This volume of water, if not discharged through POINT 10, would have resulted in a continuous uncontrolled discharge via POINT 1.

Figure 4.18: Daily and cumulative discharges for the licensed discharge POINT 10 from August 2004 through to February 2006.
4.9 DAILY AND TOTAL FLOWS OVER THE SPILLWAY (POINT 1) DURING THE STUDY PERIOD

Figure 4.19 shows the daily and cumulative discharge volumes from the BCD spillway through POINT 1 over the period 2 August 2004 – 23 February 2006. The total volume discharged through POINT 1 in this time period was estimated to be about 72 ML, equivalent to about 23% of the estimated total capacity of the BCD when filled to the spillway level.

By combining the controlled discharge through POINT 10 (485 ML) with the uncontrolled discharge via the BCD spillway POINT 1 (72 ML), it may be inferred that if the practice of discharging through a new POINT 10, based on controlled releases from the bottom of BCD, had not been instituted and trialled, some 557 ML (174% of the volume of BCD) would have spilled over the spillway past POINT 1 over the 18 month period. Therefore, for the duration of the study trial, the degree of uncontrolled spillage from BCD was reduced by a factor of 7, indicating that 85% of all fresh water runoff which would previously have discharged from BCD was successfully captured.

Figure 4.19: Daily and cumulative discharges over the BCD spillway (POINT 1) from August 2004 through to January 2006.
4.10 BRENNANS CREEK DAM WATER LEVEL MANAGEMENT AND RAINFALL DURING THE TRIAL

Figure 4.20 shows the water levels in the BCD and the concurrent rainfall record from September 1999 to 28 February 2006. The trial period began on the 2 August 2004. Figure 4.21 shows the BCD water level and rainfall exclusively for the trial period while Figure 4.22 shows the monthly recorded rainfall at the West Cliff Colliery rain gauge from September 1999 to January 2006. Figure 4.23 highlights the reductions in uncontrolled discharges from the year 2000 to 2005 for the spillway.

Figure 4.20: BCD level and rainfall from January 1999 through to February 2006.
Figure 4.21: BCD level and rainfall over the study period from August 2004 through to February 2006.

Figure 4.22: Total monthly rainfall from September 1999 through to January 2006.
It may be assumed from Figures 4.20 and 4.21 that overtopping would occur when the dam level was at the height of the spillway (12.5 m). The BCD generally overflows following large storm events and immediately after the maximum intensity phase (peak of the storm hydrograph) the rate of spill declines. This spillway decline occurred more rapidly during the establishment of the controlled POINT 10 discharge.

The BCD was full when the trial started and although there was significant rain following commencement of the trial, especially in October and December 2004, over the entire period of the trial the two lowest levels achieved in the BCD by controlled discharge through POINT 10 were 11.8 m and 11.5 m. The 11.8 m level was obtained and maintained for two brief periods only, namely:

1. 22 September 2004 – 1 October 2004; and
2. 6 May 2005 – 8 May 2005

The minimum level of 11.8 m reached on 22 September 2004, was sustained for eight days, and was terminated by significant rainfall over the catchment of 66 mm on 2 October 2004 and a further 93 mm over 15 – 23 October. By this time, the BCD water level had reached 12.5 m and was spilling past licensed discharge POINT 1.

A minimum level of 11.8 m was again reached on 6 May 2005 and sustained for only two days as it was terminated not by rainfall, but by a management decision to empty most of the water stored in other dams within the West Cliff WMS to conduct clean outs and integrity checks.

Dry weather conditions during January and February 2006 were the main driving factor behind achieving the low level of 11.5 m in BCD in February 2006. It is believed that if discharges were to have continued through all of February, a target level of 11 m would have most likely been achieved. Discharges had been ceased from the beginning of the second week of February so that river rehabilitation grouting work could be carried out in the Georges River.

Therefore, over the full period of the trial, the target level of 11.0 m recommended by Water Solutions on the basis of their West Cliff OPSIM model (Water Solutions Pty Ltd, 2004) was not attained. The target level of 11.0 m was determined through a detailed hydrological study of the BCD catchment area. This study found that with a free board of 1.5 m in the BCD that 95% of all rainfall events could be captured and retained within
the West Cliff WMS. This was also deemed a critical level at which the water needs for
the mine operation could still be met.

Although the target level of 11.0 m was not achieved during the trial, it is now the view
of the author that provided there are no further increases in mine water salinity, and pH
through POINT 9 does not increase much past 9.1 for extended periods which both
hamper discharge rates through POINT 10, continued operation of BCD in this mode
will achieve the 11.0 m level target.

Once that target is achieved, capture of high daily rainfalls up to at least 80 mm and
collection of 95% of all storm volumes within BCD is predicted and a much more
pronounced decline in WMS salt load is expected (Water Solutions Pty Ltd, 2004).

**Figure 4.23: Percentage of the time the BCD Spillway was overflowing (yearly
average).**
4.11 COMPLEMENTARY STUDIES

The Ecology Lab (2002) conducted a baseline survey of macro-invertebrates in the upper Georges River in March 2002, well prior to commencement of the Trial.

They reported that the greatest number of individuals and number of taxa over six sites ranging from just upstream of the confluence of Brennans Creek and the Georges River for a distance down river of about 3 km were recorded at Pool 7 which is immediately down river of the confluence with Brennans Creek and the Georges River. This probably reflects the frequent replenishment of water levels in Pool 7 due to discharges from BCD.

The Ecology Lab also reported that SIGNAL indexes calculated for both edge and pool rock habitats at all six sites studied were less than five, this suggests that the macro-invertebrate communities in this stretch of the of the river were dominated by taxa tolerant to levels of moderate to high water pollution.

At the time of The Ecology Lab (2002) study, water quality just below the confluence of Brennans Creek and Georges River would undoubtedly have been dominated by uncontrolled discharges via the BCD spillway POINT 1. It can be inferred from this that water quality at that time would have been inferior to that which has applied since the inception of the trial with levels of pH and EC in Pool 7 being generally higher that the limits of about pH 8.75 and 2750 µS/cm maintained throughout this trial (refer Figure 4.17).

The Ecology Lab (2006) conducted a second survey on the ecological effects of mine water discharges from West Cliff Colliery into Brennans Creek by comparing water quality and macro-invertebrates in the Upper Georges River, and Brennans Creek against two control sites, in Punchbowl and O’Hares Creeks, based an initial survey conducted in Autumn 2004 and two subsequent surveys conducted in Autumn and Spring 2005.

This more recent report found that although elevated EC and pH levels applied at the confluence of Brennans Creek and the Georges River throughout the study period, there was no indication that macro-invertebrate faunas in the vicinity of the West Cliff Colliery discharge were impoverished, or that taxon richness and abundances were small relative to those at the control locations.
The Ecology Lab (2006) also found that the temporal variability in macro-invertebrates between the two control locations and the study locations was not directly related to the variability in water quality indicators. It was more likely to be related to temporal differences in the quality of the edge habitats available to macro-invertebrates at individual sites brought about by changes in the volume and frequency of discharges from West Cliff Colliery (e.g. since inception of the trial operations).

During the time that the Ecology Lab conducted this second study it is important to recognise that the major source of flow in the upper Georges River was from the West Cliff Colliery POINT 10 discharge and to a very minor extent sporadic discharges from Appin Colliery.

5. CONCLUSIONS AND RECOMMENDATIONS

A trial operation of a modified West Cliff Colliery WMS, based on a novel approach of employing semi-continuous, controlled discharge of bottom waters from BCD has proved relatively successful in meeting its objectives over the 18 months of the trial period from August 2004 through to February 2006 considered in this thesis. The trial has continued beyond the period assessed in this document.

Firstly, this approach ensured that a primary objective of the trial, namely maintaining a pH of <8.5 for discharges out of the Reclalm Pond via (DEC-licensed discharge) POINT 10 into Brennans Creek, was met for almost the entire period considered here without having to resort to the more costly and complex measure of acid dosing. The POINT 10 EPL limit for pH was exceeded only slightly towards the end of the trial from late August 05 to mid September 05. This period of high pHs was due to a deliberate high rate of discharge via POINT 10 to terminate, as a rapidly as possible, an uncontrolled higher pH discharge over the BCD spillway POINT 1, following a large storm event. This same storm event also produced a concurrent diluting environmental flow in the upper Georges River, which would have ensured that pH in the river, both above and below the Brennans Creek confluence did not exceed 8.5 in any case (refer Figure 4.17).

Secondly, the net salinity load of the salts circulating within the WMS over the first 8 months of the trial was reduced by 8% as a result of improved capture of rainfall/runoff
into the BCD (refer Figure 4.8). Towards the later part of the trial period, in early September 2005, the reduction in net WMS salinity was unable to be sustained due to:

- prolonged dry weather increasing salt concentration around the West Cliff WMS through evapotranspiration (refer Section 4.10); and
- an unexpected and unexplained increase in salinity of the mine water being pumped out of the pit to the surface (refer Section 4.5).

While the reductions in salinity were not able to be sustained due to an unexplained increase in mine water salinity and extended dry weather conditions, the trial did show that this was possible given the right conditions and continued operation of the West Cliff WMS in this manner.

Thirdly, the controlled discharge of BCD bottom water through the scour valve at POINT 9 and then through the Reclaim Pond via POINT 10 into Brennans Creek resulted in an estimated reduction of 7 times the total volume of uncontrolled discharges over the BCD spillway for the 18 month trial period (refer Section 4.9 and Figure 4.23). Although the target BCD target level of 11 m was not achieved, it is probable that continual operation of the WMS in the new manner will lead to attainment of the target level. Operating the WMS in the new manner has ultimately ensured that over the trial period from August 2004 through to February 2006, 557 ML of water with the potential of a relatively high pH, high turbidity, and oil and grease contamination, has not been released in an uncontrolled manner directly into the environment. Rather, cleaner water has been released via controlled bottom water discharges through POINT 9 at the bottom of the BCD wall into the reclaim pond where it has been able to mix with BCD wall seepages and natural ground water having the effect of reducing its pH, and salinity to a condition where it is able to be confidently discharged into Brennans Creek in a controlled manner via the new licensed discharge POINT 10.

It is concluded that the trial has demonstrated that the new strategy of controlled BCD bottom water releases via the new licensed POINT 10 discharge is currently the best practicable means to ensure that over 85% of discharges from the Brennans Creek Catchment are:

1. fully controlled with respect to duration and flow rate; and
2. having minimal impact on the Upper Georges River, with respect to pH and salinity.

The new operation of the WMS is also the most cost effective way of managing water discharges into the environment, as it has not been necessary to resort to much more costly and complicated water treatment systems such as acid dosing for pH correction, and reverse osmosis or distillation processes to achieve reductions in the net salinity load of the system.

In addition to the aforementioned outcomes, the new operation of the WMS for the period considered here has had the added unexpected bonus of producing reductions in the concentrations of the ecotoxic element As, and potentially ecotoxic elements Cu, Ni, and Zn in the water discharged through POINT 10 (refer Section 4.2). These reductions that have been shown are most likely due to adsorption of these elements onto precipitated iron (Fe) and manganese (Mn) oxyhydroxides, both within the BCD, due to an increase in the oxidation reduction potential of bottom waters within the dam (through regular discharge of reduced bottom waters) and within the Reclaim Pond itself (the Fe and Mn in the latter being sourced from BCD wall seepages and groundwater spring components). These reductions were sustained for the entire period of the trial despite the increased salinity of the discharge waters over the latter part of the period.

This alternate approach of operating the West Cliff Colliery WMS has produced a positive outcome with respect to managing uncontrolled discharges from the BCD, reducing it by a factor of 7. At most monitoring POINTS, the potentially ecotoxic elements As, Cu, Ni, and Zn showed reductions which, although not all statistically significant, were noticeable.

Furthermore, the studies carried out by The Ecology Lab on macro invertebrates (refer Section 4.12) in the Georges River have shown that operating the West Cliff Colliery WMS in the manner prescribed has actually improved the aquatic habitat of the Georges River through the process of providing to a more regular flow regime via the POINT 10 discharge.

It has also been demonstrated that the compacted coal wash from the Bulli seam which is mined at West Cliff Colliery, and from which the dam wall is constructed, is an excellent natural filter. It provides a concentrated source of carbon dioxide (helping to
reduce the pH of alkaline mine water towards a more neutral pH range) the carbon
dioxide being supplied through the natural oxidative digenesis of the coal wash, and it is
a source of iron and manganese which contributed to the reductions of As, Cu, Ni, and
Zn via adsorption and complexation into non-ecotoxic species. Utilising the
physiochemical dynamics within the BCD itself, for example, the lower pH in the bottom
of the dam, and its higher oxidation reduction potential, has further assisted the
reduction in As, Cu, Ni, and Zn.

It can be practical and economically viable to manage water quality and discharge rates
on a large scale at an active mine site by utilising the surrounding environments both
natural (physiochemical dynamics in the BCD, and rainwater harvesting) and man
made (Brennan’s Creek Dam Wall) in unison. This study has also shown that given the
right conditions, there is potential to improve the water quality within the mines WMS,
reducing the need to access town water supplies, having the added benefit of relieving
some of the running costs of numerous water consuming aspects of the mining
operations onsite, which include dust suppression, coal washing, and water supply to
amenities. Given the current drought conditions Australia is experiencing, any reduction
of the use of potable town water will be of benefit to industry both economically, and in
demonstrating its social responsibility to the community.

5.2 Recommendations

After manually controlling water discharges from West Cliff Colliery via the POINT 10
discharge for the 18-month period, it has been shown that this method is a viable
alternative to the previous regime of uncontrolled spillway discharges. Continued
operation by this new method is also the most practicable way of controlling water
discharges from site while also minimising the environmental impacts of poor quality
discharged water. There is now scope for the system to become fully automated and
controlled by means of a Programmable Logic Controller (PLC). It is envisaged that
automation will require one analogue control valve on the POINT 9 discharge. This will
allow the rate of flow to be controlled to varying degrees depending on water quality.
There will also be two sensors located in the pipe at POINT 9 connected to the PLC
control. These sensors will essentially monitor the water quality coming out of the bottom of BCD for pH, temp, and EC.

At POINT 10, there will also be an automatically controlled digital valve. This will allow for complete shut off of flow through POINT 10 in the event of unacceptable water quality. Water quality through POINT 10 will also be constantly monitored through installed pH, temp, and EC probes in the pipe.

A pressure sensor will also be calibrated connected to the PLC and placed in BCD to measure the water level. This will enable the system to be shut off when the water level in the BCD reaches its target operating water level of 11.0 m.

The PLC control system will then be integrated into the West Cliff Colliery internal mine Supervisory Control and Data Acquisition system. This essentially means that the BCD discharge system can be monitored in real time from any networked computer on site. It will also ensure that safe back up and storage of the data is made in compliance with ISO 14001 and the EPL. In addition, this will enable the system to be manually overridden in circumstances such as equipment malfunctions, e.g., probe failures.

Given that the majority of the mines in the Illawarra have similar water needs, and that several of these mines are actively mining the Bulli seam, there is potential for other mine sites to adopt a similar model for treating waste water onsite, by using the otherwise wasted coal wash in a similar manner to that at West Cliff Colliery. This may be through:

- Incorporating the waste coal wash into the design and construction of new sedimentation ponds onsite;
- Adopting a similar dam wall construction to that of West Cliff Colliery; and
- Constructing onsite filtration systems along dirty water flow paths using the coal wash.

The benefits of using PHREEQC geochemical speciation modelling software have also been shown here to be an effective tool in modelling the processes and changes that occur within the water management system. The modelling has also been invaluable in determining the concentrations of the cationic ecotoxic species from the non-ecotoxic
neutral and anionic species of the trace heavy metals As, Cu, Ni, and Zn in the waste water discharge from site. By using this readily available modelling software ideally in the design phase of a new water management system or the upgrade of an existing water management system, it is possible to greatly increase the likelihood of a positive environmental outcome relating to the concentrations of potentially ecotoxic heavy metals in water discharge streams to the environment. The availability of this software also lends itself to uses on other mine sites in Australia or abroad where heavy metals may pose potential environmental issues.
6. REFERENCES


Sherlock, E.J; Lawrence, R.W; Poulin, R. (1995); On the neutralization of acid rock drainage by carbonate and silicate minerals. Environ Geol **25**: 43 – 54.


Webb, J.A. and Sasowsky, I.D., 1994. The interaction of acid mine drainage with a


7. **APPENDIX 1**

PHREEQC Speciation Model output for POINT 10 water.
Input file: C:\DOCUME~1\ECOENG-1\LOCALS-1\Temp\phreeqc.tmp
Output file: C:\Documents and Settings\ECOENGINEERS\My Documents\West Cliff\POINT 10 April 06.out
Database file: c:\Program Files\Phreeqc\Wateq4f.dat

Reading data base.

SOLUTION_MASTER_SPECIES
SOLUTION_SPECIES
PHASES
EXCHANGE_MASTER_SPECIES
EXCHANGE_SPECIES
SURFACE_MASTER_SPECIES
SURFACE_SPECIES
RATES
END

Reading input data for simulation 1.

DATABASE c:\Program Files\Phreeqc\Wateq4f.dat
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SOLUTION 1
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  pH  8.57
  units mg/l
  density 1
  Alkalinity 1260 as Ca.5(CO3).5
  Ca 4
  Cl 253
  Fe(+2) 0.09
  K 4
  Mg 3
  Na 770
  S(6)  51 as SO4
  As 0.008
  Mn(+2) 0.062
  Cu 0.008
  Ni 0.145
  Zn 0.043
PRINT
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END

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TITLE

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POINT 10 April 06

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Beginning-of-initial-solution-calculations.
Initial solution 1.

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\text{pe} &= 4.000 \\
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\text{Ionic strength} &= 3.444e-02 \\
\text{Mass of water (kg)} &= 1.000e+00 \\
\text{Total carbon (mol/kg)} &= 2.458e-02 \\
\text{Total CO2 (mol/kg)} &= 2.458e-02 \\
\text{Temperature (deg C)} &= 20.000 \\
\text{Electrical balance (eq)} &= 6.802e-04 \\
\text{Percent error, 100*(Cat-|An|)/(Cat+|An|)} &= 1.02 \\
\text{Iterations} &= 13 \\
\text{Total H} &= 1.110361e+02 \\
\text{Total O} &= 5.558196e+01
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-------------------Distribution of species-------------------

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**End of simulation.**

**Reading input data for simulation 2.**

**End of run.**
No memory leaks