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LITERATURE REVIEW ON MINE REHABILITATION BY FLOODING

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RESEARCH & TECHNOLOGY

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by
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Summary

This report presents the results of a literature survey on rehabilitation of disused open cut mines by flooding. The search has been restricted to issues concerning water quality in the flooded mine - engineering aspects and impacts of flooding on groundwater were not considered in detail. Overall the search has not produced much information about modelling the quality of water in lakes produced from the flooding of mines. To produce a model to do this for the brown coal mines in Victoria will require a sizeable level of independent development. On the other hand there is a substantial body of information available that would be of considerable general assistance (particularly investigations by the former SECV). A general summary of the literature relating to mine flooding and consequent water quality is as follows.

- Germany is the only country to practice mine rehabilitation by flooding on a wide scale and experience has been built up by the creation of small lakes over many years in the former GFR. Water quality is seen as important but no results from any studies (including modelling) has been reported although much has been written on the issues of geomechanical stability. However, they are only now starting to consider the creation of larger lakes of the size suggested for Victoria. 25 km^2) lakes are being planned and will be filled with water diverted up to 50 km from the Rhine. Artificial filling improves both water quality and geomechanical stability. Rheinbraun Engineering und Wasser have carried out a range of studies to predict water quality and nutrient development in such a lake but no detailed information has been obtained.
- Mine flooding is also being carried out for rehabilitation of the coal fields of the former east Germany but progress is slow because of limited technical knowhow and funds.
- In North America little has been reported on the deliberate flooding of mines in the United States but there are some accounts of abandoned mines that have flooded naturally. There are accounts of successful rehabilitation of small mines as sports fisheries in Canada.
- Modelling of the expected water quality in abandoned gold mines that have been allowed to flood naturally has been carried out in the United States. Compared with flooded mines in Victoria the lakes are much smaller, and the geology and climate are quite different.
- Numerous modelling studies of natural lakes have been reported relating to their biological and physical properties. Modelling of the chemical properties of the water has been restricted to studies of external pollution (industrial and agricultural runoff).
- An extensive range of studies has been carried out by the former SECV which provides valuable information about a range of factors that might affect water quality in a flooded mine. One study specifically on the effects of flooding the brown coal mines in Victoria concluded that there would be no problem with water quality in the resulting lakes if they were filled using river water. Surveys of the small (7 Ha area, 20 m deep) lake that has formed in the former Yallourn North Extension Open Cut Mine show the water to have a neutral pH, very little colour and low turbidity.

1. INTRODUCTION

All of the four main open cut brown coal mines in Victoria (Anglesea, Loy Yang, Morwell and Yallourn) will require rehabilitation at the end of their working lives. Requirements will be that the end result is aesthetically pleasing and perhaps more importantly that there are no adverse environmental consequences either in the short or long term. Existing concept master plans for the long term rehabilitation of these mines indicate that flooding is likely to be the cheapest and most satisfactory solution. This raises a number of engineering and environmental issues which will need to be addressed prior to any commitment or process of seeking approvals.

One important issue is the quality of the water body that will be formed in each of the mines and a project has been initiated within the Brown Coal Industry Research Program (BCIRP) to look at this aspect. The objectives of this project are as follows.

- Identify the major factors that are likely to influence the long term water quality of flooded open cut mines.
- Develop a predictive model for the final water quality
- Assess the impact of current and future operational practices upon the final water quality.

The initial activity has been to conduct a literature search on open cut mine rehabilitation by flooding, covering current practices/projects, mathematical modelling, environmental assessment and regulatory requirements. Results from the literature review are presented in this report.

2 LITERATURE REVIEW

2.1 General Approach to Search

Searches were carried out on electronic data bases and by manual searching of particular journals likely to contain relevant articles. Experience has shown that electronic searches using keywords can produce limited results for subjects where the choice of precise and limiting keywords is difficult. In general the search process did not produce a large number of relevant articles on the flooding of worked out mines and the manual searches were principally of value in locating information on topics generally related to but not directly to do with the flooding of mines. Details of the databases and journals searched are as follows.

- **Compendex** - a general engineering data base.
- **Dialog** - an engineering and science database.
- **Coal Abstracts on CD-ROM** - abstracts from IEA Coal Research, 1987-1997.
- **The EPRI database**
- **Braunkohle** - a German journal principally to do with brown coal mining in Germany.
- **Journal of Water and Soil Pollution** - journal
- **Water Environment Research** - journal

2.2 IEA Review of Rehabilitation Practices

2.2.1 Introduction

A review of the restoration and rehabilitation of surface coal mines has been produced by IEA Coal Research (Jackson, 1991). In the report the legislation governing surface mine restoration and rehabilitation in various coal-producing countries is described, followed by the necessary pre-mining site characterisation from which a reclamation plan can be drawn up. Chapters also consider soil reconstruction and remediation techniques which aim to achieve plant growth on the restored land at levels equal to or better than before mining. Other topics covered include the treatment of effluents produced by mining in order to prevent pollution of surface water, the rehabilitation of derelict land at mine sites and the creation of wildlife habitats. Good practices which contribute to successful restoration and rehabilitation of surface mined land are also identified. A topic of particular relevance to the present review is the practice and relevance of mine rehabilitation in various countries and these are summarised in the following sections.

2.2.2 Practice and Legislation in Australia

As in most countries surface coal mining operations are subject to stringent regulations and requirements concerning the restoration and rehabilitation of the affected land. Unlike some countries there have been few major mining operations on prime agricultural land so that most disturbed lands have been returned to pasture or forest. Significant research has been carried out in both New South Wales and Queensland into rehabilitation methods - these have all involved rehabilitation to land and no studies appear to have been done on the conversion of worked out open cut mines into lakes.

2.2.3 Practice and Legislation in Germany

In the Rhenish coal field (former west Germany or GFR) the brown coal mining area covers an area of 1500 km^2 and unconsolidated sands cover the coal and clays which are removed by bucket wheel excavators as is done in the Latrobe Valley. The overburden is used for filling worked out areas and for the creation of artificial hills in continuous process. After restoration the land is managed by the company for 3-5 years and is then returned to public ownership. About 40% of the land is restored to agriculture and steeper areas are forested while artificial lakes are created in areas deficient in overburden. The major issues discussed in the review relating to flooding are the creation and stocking of wildlife habitats - water quality is not discussed.

The former German Democratic Republic (former east Germany or GDR) has very extensive brown coal reserves but environmental management during the mining phase has been inadequate and almost non-existent for subsequent rehabilitation. For example overburden is extensively carried by conveyor bridges which while offering low operating costs also produce high, steep sided spoil heaps which require extensive and specialised levelling operations. Over the past 12 years legislation affecting surface mine reclamation has been progressively introduced but so far its impact has been minimal.

2.2.4 Practices and Legislation in the United States

Mandatory restoration and rehabilitation of former surface coal mining sites was first introduced in the 1930's by individual states and in 1977 federal legislation was passed and became law. The act contains over 100 specific performance standards and is a particularly detailed and technically complex statute. The legislation contains a number of contentious points - in particular wetlands and impoundments are not recognised as a legitimate post-mining land use. This is despite a positive policy towards them during the Bush administration.

2.3 Flooding of Coal Mines

2.3.1 Germany - Former GFR

Most articles on the flooding of coal mines relate to experiences in Germany where a number of defunct lignite mines have been rehabilitated (or are proposed to be rehabilitated) by flooding. The mines are normally flooded by surface water diverted from rivers and streams but in general little attention seems to have been paid to predicting what the final water quality is likely to be prior to flooding.

The hydrological boundary conditions for brown-coal mining of the Bayerische Braunkohlen-Industrie AG (Bavarian lignite mining region) together with the hydrological conditions in the mine have been discussed by Hoesslin (1980). Technical and legal problems associated with the proposed establishment of lakes in worked out open cut mines in the Bavarian coal mining region were also considered. These issues mostly related to the process of flooding the mines using river water - water was to be taken only during periods of high flow so that the overall flow conditions of the river would not be disturbed. As part of the same rehabilitation program Liebl (1980) has presented a detailed discussion of the design of stable slopes, dams and banks for the lakes. Although such engineering issues are important for the creation of lakes they will have a very limited (if any) impact on the water quality. Furthermore, this aspect of the rehabilitation is quite outside the scope of the present project and therefore these civil engineering aspects will not be described in this report.

An account of the geomechanical and hydrological aspects of residual lake construction in the Rhineland brown coal mining area has been given by Pierschke and Boehm (1996). In 1992 about 108 Mt of lignite was extracted from this field (Thole, 1994) which is 4 times the present annual production from the Loy Yang Mine. The geomechanical and hydrological aspects of the rehabilitation process are considered to be of particular significance. Much emphasis is placed on the design and contouring of the banks of the lake to prevent erosion and subsidence and also to create an adequate littoral zone. As a rule the residual pits are filled artificially with extraneous water which is plentifully available in the area. Artificial filling provides geomechanical advantages, shortens the filling time considerably and favourable influences the quality of the lake water. A brief account of the factors controlling the water balance in an artificial lake is presented particularly in relation to their impact on the geomechanical stability of the banks. It is emphasised that other aspects such as the ecology and water quality of the newly created lakes should also be taken into account but these matters are not discussed.

Several successful examples of the construction of artificial lakes from the flooding of disused coal mines are presented together with several colour photographs showing various features of the rehabilitation process. A major difference between these mines and those in Victoria is

their much lower ratio of coal to overburden which means that most of the overburden must be progressively be dumped back into the mine. Thus during the rehabilitation process large volumes of overburden must be spread and it is assumed that this covers most if not all of any remaining coal faces although this topic is not discussed. A colour photograph of one mine before flooding certainly suggests this is the case. Most lakes that have been formed so far are fairly small (up to about 1 km^2 in area) and clearly many lessons have been learned from these experiences. However, very much larger lakes (around 25 km^2 in area) are being planned to be filled with water diverted from the Rhine along canals up to 50 km long.

A general account of the long term planning for the reclamation of mined lands in the Rhineland brown coal mining area has been given by Calles (1997). The Calles Planning Bureau first began to draw up rehabilitation plans in the early 1960's based on the data from Rheinbraun AG (the mining company that operates nearly all of the mines in the region) working plans for their mines. Complete restoration of past conditions is generally not achievable but the nearest approach to this is a principal aim. Legal regulations and planning directives have recently been promulgated and the impact of these on the rehabilitation process is discussed. Overall this paper presents a general review of the planning being done for responsible environmental rehabilitation of the coal mining areas in the Rhine basin. There are no new ideas or concepts developed and in particular no details of any technical or engineering issues are given.

Further information has been obtained directly from Rheinbraun Engineering und Wasser GMBH (Schwarzenberg, 1997), a subsidiary of Rheinbraun AG. Major points covered are as follows.

- All fly ash from the power stations is dumped back into the mines but these areas are sealed with clay so that leaching will be negligible.
- Overburden material consists of about 80% sand with a pyrite content in the range 0.1-1.0% and as a result the groundwater from the dump can contain high levels of sulphate (up to 4,000 mg/L), iron (up to 1,500 mg/L) and heavy metals (10 mg/L) and can be quite acidic.
- The possible effect of exposed coal seams on water quality is considered to be negligible compared with the effects of overburden.
- Several investigations have been carried out help predict water quality in the dumps.
  * Variation of pyrite content in dumps.
  * Pyrite oxidation rate as a function of depth and contact time with oxygen.
  * Assessment of areas of pyrite weathering. Oxidation occurs only at the working faces (benches and slopes of mining and dumping) and to a depth of about 2 m so that about 14% of the pyrite will weather.
  * Laboratory studies on the effect of partly weathered pyritic sand on water quality.
  * Modelling studies of groundwater in future dumps using PHREEQW.
- Until now not many lakes have been filled and in most cases the water table has not yet re-stabilised. One lake requires liming each year to control acidity. For one future mine lake it will be necessary to mix calcium carbonate or a mixture of calcium carbonate and (alkaline) fly ash with the dumped overburden to neutralise the dump water and precipitate iron and heavy metals. The sulphate level in the lake water is expected to be 1,200-1,400 mg/L.
- Factors that affect the future lake water quality include,

* Whether or not the dump material is neutralised.
* Whether the lake boundaries are mainly situated in the overburden dump areas or unmined areas.
* The proportion of water originating outside the mine area (eg from rivers) that is used to flood the mine.
* In lakes deeper than 100 m stratification can occur so that acidic water which have a higher density will concentrate at the bottom of the lake. Conditions in these deep water zones may allow reduction processes to occur resulting in reforming and precipitation of pyrite.

- A proposal to construct a lake of about 25 km^2 with a maximum depth of 200 m which will be filled with water from the Rhine over a period of 100 years has been investigated. Issues considered include,
  * The neutralising ability of the river water resulting from its buffering capacity.
  * A study of the expected morphology of the lake and the impact of stratification on water quality in comparison to other lakes.
  * Estimation of nutrient development in the lake.

2.3.2 Germany - Former GDR

Articles have also been published on proposals for landscaping worked-out mines in the lignite mining areas within the provinces of the former German Democratic Republic (GDR or east Germany). Economic development has been much slower in the GDR over the past 50 years and historically the management of the mines has been to a rather lower standard than in the west. However, since re-unification the quality and quantity of work on rehabilitation has increased rapidly although published information is still rather limited. A description of the Geiseltal coalfield (near Leipzig in the province of Sanoy-Anhalt in cental Germany) has been given by Bilkenroth (1993) which contains details of a rehabilitation proposal. In 1992 the production of lignite from this field totalled 36 Mt (Thole, 1992). The intention is to form a lake shore with a total length of 41 km and then duct 400 GL of river water through a 14 km long tunnel into the pit. At the end of 15 years a lake 20 km^2 in area will have been formed which is to be used as a reservoir and for recreation. There is no information provided about expected water quality or of how the lake should be formed. It has been stated by Pietsch, (1996) that acidic mine water is less of a problem in this area compared with the Lusatian coal fields.

Current progress and future planning for the rehabilitation of mining areas in the Wetterau area of Lusatian lignite mining region (province of Brandenburg in former GDR) has been discussed by Lingemann (1993). This is a large field with an output of 93 Mt in 1992 (Thole, 1992). A total of 1250 Ha is to be reclaimed of which about two thirds will be recultivated for agriculture and the remaining 450 Ha will be turned into lakes. No details are given about how the lakes are to be formed or of any potential problems that are envisaged other than to say that progressive eutrophication is to be expected due to ingress of effluents from the surrounding agricultural areas. It is claimed that the quality of the water in the lakes already formed is good but no actual information is supplied. On the other hand it has been pointed out that the overburden from this region has a high acid potential which has caused major ecological problems in the past (Pietsch, 1996). It is suspected that much of what has been written about mine rehabilitation in the former east Germany should be treated with caution. This part of the

country has had a poor reputation for environmental management and while efforts are now being made to put things right, it will be some time before much real progress is made.

The control of water quality in geogenetically acidified lignite mining lakes in the eastern mining regions of Germany has been discussed by Klapper (1995). As a result of pyrite and marcasite oxidation the water in lakes that are allowed to fill naturally can have a pH as low as 2-3. As well the water can contain between 10 and 1,000 mg/L of Fe and between 1 and 100 mg/L of Al as well as increased levels of heavy metals - Mn, Zn, Ni, Cr, Pb and Cd. The Fe and Al provide strong buffering so that chemical neutralisation is inefficient because of the large quantities that would be required. The solution is to prevent groundwater and acidity outflow from the overburden dumps which can be achieved first of all by rapid filling from an external source so that the initial water flow is from the lake into the dump. In addition a closed vegetation cover must be quickly established on the surrounding overburden dumps to limit oxygen exchange between the soil and the atmosphere.

A detailed account of issues associated with the natural rehabilitation of mining areas in the Lusatia area has been presented by Pietsch, (1996) - typically limited environmental management has been practiced since mining first began during the Industrial Revolution. In particular the problems associated with the high acid potential of much of the dumped overburden from the mines in the region is discussed. As a consequence of the oxidation of the pyrite that is present, mobilisation of free mineral acid, sulphate and bivalent iron occurs which can lead to high acidity (pH 1.9 to 3.1) and iron levels in surface waters. An account is presented of the stages in the spontaneous regeneration of the post mining landscape both terrestrial and of lakes that were allowed to form in low lying areas.

This last article was one of a series of papers published in a special volume *of Water, Air and Soil Pollution* which were partly based on contributions to the symposium "Minesite Recultivation" which was held at the Brandenburg Technical University in Cottbus, Germany, in June 1994. Much of symposium focussed on the reclamation of post-mining landscapes in the Lusatian lignite mining district of the former GDR. Open cast mining over the past 70 years has had a devastating effect on an area of about 700 km^2 and research into recultivation has been going on since the 1930's. But because of the scientific isolation of the former GDR the results from this research have not been readily available to western audiences until very recently.

Another paper from the series discussed the environmental impact of mining in the lignite mining region of Central Germany where strip mining is extensively practiced (Hildmann and Wunsche, 1996). The formation of lakes from former pits is considered but there appears to be little information based on practical experience. Flooding is said be carried out using water from rivers and streams but it is not clear if this refers to past and present practice or whether it is a proposed strategy for the future - it is suspected that the latter is the case. Benefits of flooding in this way are said to be,

- The filling process is reduced to just a few years
- The stability of the side slopes as a result of the hydrostatic pressure of the rapidly forming body of water.
- The alkalinity of the river water helps to overcome the tendency towards acidification of the water in the mine.

Land rehabilitation after brown coal mining in the Schlabenddorf area of the Lusatian coalfield has been described by Jahn et al. (1997). The objective is to create a landscape with natural features that are on a par with those prior to mining activity as well as the formation of nature reserves including the creation of lakes. A problem with the formation of lakes is widespread depression of the water table that occurred as a result of pumping during mining operations. Special precautions must be taken to ensure bank stability and these are described. No account water quality in the lakes that have been formed is given.

2.3.3 United States and Canada

In the United States a survey of water chemistry information for 138 surface mine lakes in Pennsylvania has been compiled by Brenner *et al.* (1986). The size and physical characteristics of the lakes varied considerably - from 6 to 352 Ha in area and 6-8 m in depth. The majority of these lakes had good water chemistry and supported a variety of aquatic life. pH values were mostly in the range 7.0 to 7.4 and were linearly correlated with the pH of the surrounding spoil. Alkalinity varied from 9-100 ppm, the calcium-magnesium hardness from 40-440 ppm and the total dissolved solids from 100-200 ppm in most of the lakes. Extensive biological surveys of the lakes were also made However, there was little discussion of the factors controlling the chemistry of the water in the lakes or of any of the planning that may have gone on before the mines were flooded. It is not clear whether flooding was by diversion of rivers and streams or by run-off but it is suspected that the latter is the case.

There are numerous papers on the creation of wetland habitats on reclaimed mining lands in the United States. Samuel (1989) has described some of the measures to be taken when creating small lakes or ponds to provide good water quality for the creation of a fishery. The development of wetlands to create habitats for waterfowl feeding and resting has been discussed by Nawrot and Klimstra (1989). A general overview of the regulatory and technical issues associated with the creation of wetlands on mined lands in the United States has been presented by Cairns and Pratt (1985). There is little value in presenting the details of the developments discussed in these papers since they all refer to small, shallow lakes. They have no particular relevance to the large, deep lakes that would be created by the flooding of open cut mines in Victoria.

The creation of a mountain lake sportfishery from an abandoned black coal mine in Alberta, Canada has been described by Acott (1989). The project to produce the 1.2 km^2 and 100 m deep lake included shoreline recontouring, littoral zone construction, macrophyte/plankton innoculation and habitat enhancement techniques. During the filling process (using water from a nearby creek) the water clarity was poor because of sediment stirred up by methane gas released from the exposed coal. However, 6 months after the lake was full (at the time the paper was written) the water clarity was excellent and no further turbulence was observed - it is believed that the weight of water and the deposited sediment sealed the coal from further methane release. A continuous limnological study had been put in place to determine the rate of food chain development which would lead to recommendations for a sportfish stocking program.

2.4 Prediction of Water Quality in Flooded Mines

The major concern with water quality in abandoned coal mines and their associated disturbed lands is souring of the soil by acid mine drainage. Acidification results from the oxidation of

iron pyrites which is commonly associated with coal deposits to a significant extent. Much has been written on acid mine drainage but the emphasis is on ways of reducing its negative impact on rehabilitation of the mining areas to land. Almost nothing has been found relating to the prediction of water quality in a flooded coal mine.

Work has been carried out on predicting water quality of minesites other than coal. A method for estimating the rate of pit lake formation and the potential water quality in the resulting lake has been presented by Vandersluis *et al.* (1995). This article is specifically concerned with mines in arid regions of the United States and includes a case study for the formation of a lake in an abandoned open pit gold mine in Nevada. The major sources for water inflow are direct precipitation onto the lake surface, run-off from the watershed and horizontal or vertical inflow of groundwater from bedrock or alluvium. This latter source is the most important in arid regions. Outflow results from evaporation and seepage.

Equilibrium geochemical modelling of water-wallrock interactions were used to predict the chemistry of the lake water and evaluate the potential for acidification of the water. Depending on the type, quality and quantity of geochemical data available the expected water quality can be modelled using either a mass balance or kinetic approach. For the former acid-base accounting data are used to estimate the potential degradation of the water by pyrite oxidation. For the latter, laboratory leaching tests are used to simulated the quality of runoff and groundwater entering the pit. To model the chemical equilibria the programs PHREEQE (Parkhurst *et al.* 1983) and MINTEQA2 (USEPA, 1991) were used. Another factor to be considered is whether the water in the lake is stratified but this is difficult to predict. One approach is to calculate the Petersen Scaling Parameter (surface area in km^2/mean depth in km) and compare this value with other lakes of similar size in similar climates. For example the Blue Lake (Mt Gambier, South Australia) is well mixed and has a Petersen Scaling Parameter similar to that expected for flooded Latrobe Valley mines.

A case study on the formation of a lake in an abandoned open cut gold mine in the western United States is also presented. Details are given of the pit filling calculations and of the geochemical modelling.

A similar model has been described by Pillard *et al.* (1995) and once again an abandoned open pit gold mine was used as an example site. The approach used and the results obtained were very similar to that described in the previous paper. The concentrations of a range of toxic metals were also calculated for the lake water and the predicted levels compared with state and federal criteria for several species of wildlife likely to inhabit the area.

Only one article on the modelling of artificial lakes created from mine pits has been located (Schubert, 1988) but despite extensive enquires it has been only possible to obtain an abstract. 21 lakes in the eastern and central United States were extensively sampled, geochemical analyses of soil, spoil and lake bed material were carried out and a range of hydrological variables were measured. Multivariate statistical procedures were then used to determine which watershed characteristics, hydrologic variables, geochemical parameters or lake morphometric variables would have the most influential on the resulting water chemistry of the mine lakes.

2.5 Research Carried Out by the SECV

2.5.1 Rehabilitation Studies

An assessment of the likely acidification of water in abandoned and flooded open cut mines in the Latrobe Valley has been made by Deed (1975). This work included sampling and analysis of the quality of water that had collected in already abandoned brown coal mines in Victoria. Mines with static volumes of water developed acidity by oxidation of pyritic sulphur but where a natural stream flowed through the water body there was no acidification. Experimental studies of the reactions of coals in contact with water were carried out and estimates made of the level of pyritic sulphur in coal from the various Latrobe Valley mines. These data were used together with the chemical properties of river waters that would be used to flood the mines to predict the water quality in the resulting lake. The conclusion was that none of the mines would become acidic under dynamic flow through conditions.

Extensive land rehabilitation has been successfully carried out by the former SECV particularly in the management of overburden dumps placed outside of the mines and an account of some of the work carried out in the Yallourn area has been reported by Waghorne (1993). A description is given of a 40 year old overburden dump that had been allowed to regenerate naturally with decolonisation by native plants and the attraction of native wildlife to a series of ponds that had formed. Parts of the area had also been used for ash settling lagoons together with a system of overflow ponds and grass filters to clarify the spent ash water. At the time of the development (1982) little had been done formally to restore the area but the natural rehabilitation has been so successful that it was decided that subsequent managed rehabilitation would blend with the existing site. This experience suggests that overburden and ash pond sediments from the Yallourn area are unlikely to cause significant environmental problems (at the surface level) and require only minimal management. Analysis of sediment samples collected from the old ash lagoon showed that the level of toxic trace elements deposited in this area was minimal (Black, 1987a).

2.5.2 Flooding of Yallourn North Extension

Since the study by Deed the Yallourn North Extension open cut has been abandoned and inflow of water by seepage and runoff has resulted in the formation of a small water body with an area of 7 Ha and a maximum depth of about 20 m. Monitoring of the chemical properties of this water has been carried out by the SECV and by Yallourn Energy. The results of a detailed on-site survey of the pond (at 5 locations across its surface and at varying depths showed that the water quality was good (Marut, 1995). Measurements were carried out in winter (at the end of June) and the temperature was about 7 °C at all depths with no evidence of thermal stratification. There was also little variation in pH (about 7.1), electrical conductivity (930 Ms/m) or colour (15-20 Pt/Co units). A sample of pond water collected in April 1996 had a pH of 6.7, a colour of 10 Pt/Co units and a turbidity of 3.5 NTU (Ashton, 1996).

The objective of this last investigation was to establish the source of coloration of some of the drainage waters around this abandoned minesite - it had been suggested that high iron levels may have been a contributing cause. In fact most of the observed coloration was due to very fine colloidal material (>0.45 μm - > 0.10 μm) although there was some colour development from other sources that could not be positively identified. Also the suggestion that the colour might be extracted from coal was ruled out.

There are no longer term measurements of the water quality in the mine lake- the only data available are for the overall discharge from the site which is a mixture of overflow from the lake and run-off from overburden dumps (Brown, K, Yallourn Energy, unpublished data). These quality of this water has generally been good with a TDS averaging about 700 mg/L and a pH of about 6.5 although there has been some increase in the colour over the past two years (see above).

2.5.3 Leaching Studies on Ash and Overburden

Several studies have been carried out by Black (1987a, 1987b, 1987c, 1987d, 1988a, 1988b, 1989) on the chemical properties of a range of soils, overburden, ash and mixtures of overburden and ash taken from various sites around power station and mine sites in the Latrobe Valley. Overburden from the Yallourn mine was somewhat acidic (pH 4.9-5.4) compared with soil collected from around the Morwell River diversion channel (pH 5.4-6.4). Mixtures of soil and ash were alkaline (pH 8.1) although the conductivity of a soil/water mixture showed that they did not contain particularly high levels of leachable salts. Soil samples have been collected from No 7 firehole in the Morwell coal field. Samples from the bottom of were similar to those from the diversion channel but samples from the top and middle were substantially more acidic (pH 4.8) and had much higher levels of exchangeable cations (Black, 1987b).

Measurements of the edaphic properties of a number of soils in the Latrobe Valley have been reported by Lau and Mainwaring (1984) - pH results were in the range 4.9-6.5 which is considered to be slightly acidic. A general feature of the soils tested was their low cation exchange capacity (mostly < 10 meq/100g) which indicates that they would be rather sensitive to acidification.

An important factor to consider in the assessment of water quality in a flooded mine is the extent of leaching of salts from ash pond sediments that may have been dumped into the mine during its working life. Laboratory investigations have been carried out to investigate the leaching properties of ash pond sediments using batch and column extraction techniques taken from both Yallourn (Black, 1990) and Hazelwood (Black, 1992a) ash ponds. These studies also included leaching tests on dry precipitator ash and the experimental results for Yallourn ash were extrapolated to field conditions for a scenario where ash would be collected and dumped dry. A computer model was used to predict the attenuation of a leachate plume emigrating from such an ash dump. At down-gradient distances of 1 km from the dump the model predicted that the concentrations of major ions and the minor ions boron, fluoride, molybdenum, selenium and strontium would be above the criteria recommended by the Victorian EPA for potable and agricultural water supply Special precautions would be required if dry ash were to be dumped in to mines which were to be flooded.

Larger scale field studies of the leaching of ash/overburden mixtures (1:24 ratio contained in 13 m^3 cells sunk into the Morwell Overburden Dump) have been carried out by Tang (1987) using pelletised dry ash from Morwell Power Station. It was found that soluble salts were readily leached from the mixture (producing leachate with a TDS of around 1.5 g/L) but that the pH of leachate was only about 7.3. It is suspected that the cation exchange capacity of the overburden (although probably fairly low) was sufficient to produce a significant amount of H^+ ion (by exchange with the anions in the leachate) which neutralised most of the alkaline ions dissolved from the ash. For a control cell containing only overburden the leachate had a pH of

6.8 and a TDS averaging 500 mg/L and had a higher alkalinity than that from the cell containing the ash/overburden mixture. However, this work has limited applicability to assessing the water quality in a flooded mine - disposal of material from dry ashing into a mine is unlikely to be contemplated. There have been no corresponding field trials on the leaching of ash pond sediments when mixed with overburden.

From the analysis of samples from several bores sunk into the banks of the ash ponds at Hazelwood Deed (1981) found little evidence for the migration of soluble salts away from the ponds. This was attributed to the pozzolanic nature of the ash which caused it to cement with the overburden thereby forming an impervious sealing layer. From laboratory tests it was predicted that coal ash derived from the Yallourn and Loy Yang fields would produce similar cementing and sealing layers when mixed with overburden. However, it was concluded by Black (1992b) from an evaluation of a study on the ash pond in the Yallourn North Open Cut that seepage of ash water to the ground water was occurring. In general it is possible that contamination of the groundwater from dumps of ash pond sediment could occur in a flooded mine unless proper precautions (eg adequate sealing of the dumps) were taken. Further work will be required to enable reliable recommendations to be made.

2.5.4 Coloration of Water in Contact with Coal

Various studies have been carried out by the SECV on the extent to which contact of water with coal can lead to coloration. Laboratory tests on the extraction of colour from a coal slurry (1500 mg/L solids) showed that at pH 5.5 (the equilibrium pH of the slurry) very little colour was developed (Fitzgerald, 1991). When the pH was increased to 8 by adding sodium bicarbonate substantial colour development occurred reaching a maximum after about 21 days. This test involved increasing the pH in a way that would not occur naturally so that the practical significance of the result is unclear. Other tests indicated that coal particles cause little or no increase in the coloration of the water with which they are in contact.

The general experience with coal laden dirty waters from the open cut mines in the Latrobe Valley is that they have only a little dissolved colour - however, for the most part only limited routine sampling and analysis has been carried out. The exception is at Hazelwood Power Corporation where a comprehensive survey of a number of dirty wastewater streams has been in place for many years. Examination of these data indicates that there is no evidence that contact of these wastewaters with coal results in any significant increase in their coloration (Hazelwood Power Corporation, unpublished data). A more limited survey carried out at Yallourn Energy in 1992 as part of an investigation into wastewater management and treatment in the then SECV produced similar results (Fitzgerald, unpublished data). Specific studies have been carried out by the former SECV to establish if the colour of wastewater at licensed discharge points can be attributed to contact of the water with coal (Fitzgerald, 1993 and 1994). The conclusion was that this was not the case and the instances of higher colour that were sometimes observed could be adequately explained by natural phenomena unrelated to the presence of coal.

As part of an investigation in the coloration of water discharged from the site of the former Yallourn North Open Cut Mine, laboratory experiments were carried out on the extraction of colour from coal by water taken from lake that had formed in the abandoned mine (Ashton, 1996). A very limited extraction of colour (an increase from 10-30 Pt/Co units) occurred under

very vigorous mixing conditions (a 10% slurry subjected to ultrasound for 8h) and it was concluded that very little extraction of colour would occur under natural conditions.

2.6 Studies of Natural Lakes

Methods for the predictive modelling of lakes have been presented in a book by Hakanson and Peters (1995). Sub-models are presented for sedimentation, primary production, trophic relationships and drainage area. Other topics include basic principles for building and testing predictive lake models together with range of predictive models. A more general monograph on mathematical modelling of streams, lakes and reservoirs has been assembled by Orlob (1984). Another example is a monograph on the physics and chemistry of lakes edited by Lerman *et al.* (1995).

In addition to these books and monographs there have been numerous journal articles presenting the results of studies carried out on natural lakes - the results from some of these will have at least some relevance to artificial lakes. To carry out this part of the survey manual searches were carried out on the journal *Water Environment Research* which each year devotes one of its monthly issues to a literature review of some several hundred pages. Since 1989 there has normally been a chapter on lake and reservoir management and this source has been used to identify papers that might provide useful input to the development of a model for water quality in a flooded mine. It was beyond the scope of the limited literature review presented in this report to evaluate all papers of potential interest and only a few have been selected.

A dynamic one-dimensional unsteady water quality simulation model (MINLAKE) for lake eutrophication studies and control strategies has been described by Riley and Stefan (1988). The model which can be run on a PC attempts to simulate the continuous change of lake stratification and water quality in response to weather, inflow, outflow, exchange processes at the sediment interface and inlake processes. Gallerano *et al.* (1993) have also developed a model for the study of eutrophic trends. Aoki (1993) described a model that used macroscopic measures that characterise lake systems to predict eutrophication trends from and earlier oligotrophic state. Model calculation of these indices were made for the eutrophic Lake Mendota (Wisconsin) and Suwa (Japan) by adopting the oligotrophic portion of Lake Biwa as a reference system.

Groundwater exchange with lakes in Alberta, Canada has been studied by Shaw and Prepas (1990a and 1990b). They first studied the accuracy of estimates of lake seepage using seepage meters and found that the most sensitive parameter affecting these was the variability in the spatial distribution of seepage flux within a small area of the lake bed. Seepage patterns were determined in 10 lakes and seepage inflow to lakes was generally found to be highest near the lake shore and decreased with distance from the shore.

3 COMMENTS ON LITERATURE REVIEW

Remarkably little attention appears to be paid to establishing the likely environmental impact of creating a lake from an abandoned mine before it is flooded. Issues associated with rehabilitation to land are taken much more seriously, particularly the souring of the reclaimed land as a result of acid mine drainage. Most articles on the rehabilitation of mines by flooding relate to Germany and the majority of these are about mining areas in the former east Germany (GDR). Environmental management in this part of the country has been totally unsatisfactory

in the past and the process of rehabilitation and the repair of many years of neglect will take a long time. Plans for this process are understandably only very general at this stage and papers describing these provide little hard information that could be used for detailed planning elsewhere. Some of these plans propose the flooding of abandoned mines although in the Lusatian mining region (Brandenburg Province, SE of Berlin) acid mine drainage is significant and has already caused major environmental problems. It would be expected that artificial lakes in the mined areas would be acidic at least initially but no mention of this issue is made in any of the articles. Indeed there is no discussion at all of the likely water quality of the lakes.

In the Rhenish and Bavarian lignite mining regions in the former GFR rehabilitation of worked out areas is a continuing process and from all accounts is an organised and well managed process. An important difference between these coalfields and those in Victoria is that the former have a much higher ratio of overburden to coal which in turn affects the general shape of the mines and the rehabilitation process. The surface area of the mined regions and the amount of overburden handled is much greater than in Victoria. Most of the rehabilitation is to land but creation of artificial lakes which are often substantial also forms an important part of the process. It is quite possible (although none of the articles mention this specifically) that any remaining coal is covered before the lake is filled. This may not be a requirement but it probably necessarily comes about because of the large volumes of dumped overburden which must be spread during rehabilitation. The lakes that have been created so far are all fairly small and presumably much has been learned from these experiences so that lakes of 25 km^2 to be filled with water taken from the Rhine are now being planned with confidence. In Bavaria water is taken from smaller rivers and the filling process must be managed to ensure that an adequate flow of water in the rivers is maintained. Landscaping and construction of adequate littoral zones are considered to be of particular importance and described in detail. Water quality is regarded as important but there is little discussion of this - issues of covering exposed coal faces or of leaching from materials dumped in the mine (overburden and ash) are not discussed.

A particular feature of the reports on flooding of mines in Germany is that nothing has been said on the subject of stratification. It would be expected that most of the lakes that have been formed or which are planned would undergo seasonal stratification based on accounts by Hutchinson (1975) of the properties of other lakes of similar size and geographic location. This will almost certainly be the case for mine lakes that might be created in Victoria – these can be expected to stratify during the spring based on the properties of the Blue Lake at Mount Gambier. This lake is highly stratified from late spring to early autumn but de-stratifies and mixes during the winter (Tamuly, 1970). Periodic stratification can be significant because the reducing conditions that occur at the bottom of the lake under these conditions can generate substantial levels of reduced species. When the lake water overturns in the spring these move up into the oxygenated zone. The accumulated oxygen demand associated with rapidly oxidisable reduced species (methane, sulphides and ferrous ion in particular) can be sufficient to make the entire lake anoxic if the turnover occurs too rapidly to allow compensation by oxygen inputs by photosynthesis and aeration (Gelda *et al*, 1995). It will be necessary to establish the likely impact of temperature stratification on water quality and other properties of flooded open cut mines in Victoria.

The rehabilitation of coal mining areas in the United States and Canada appears to be mostly to land but there a few examples of the formation of lakes. Information on water quality is limited

and there has been no discussion on the factors controlling water chemistry in such a lake or of how the chemistry could be modified.

Modelling studies that have been reported have a limited scope. Work to predict the water quality in lakes which form in abandoned gold mines in the United States has been carried out but this work does not have much relevance to the mines to be flooded in Victoria. These mines were in arid regions with different geomorphology and mineralisation characteristics and filling was by natural processes (precipitation, seepage, run-off etc.) rather than by artificial diversion of a river. Extensive investigations have also been carried out into the modelling of natural lakes.

There is a significant amount of research that has been carried out by the former SECV that has relevance to predicting water quality in a flooded mine. Of particular interest is the water quality of the small lake that has formed in the Yallourn North Extension mine since it closure some years ago. This lake has filled naturally and possibly represents a less than ideal scenario – relatively acidic groundwater and low buffering capacity of the water that has flowed in to fill the lake. Nevertheless the results of sampling and analysis studies show that the water is of good quality. In addition an extensive range of reports dealing with studies on the leaching characteristics of ash, ash pond sediment and overburden has been identified. The data from these will be of substantial value for inputs into a model to predict the impact of dumped overburden and ash pond sediment on the water quality in a flooded mine.

4 CONCLUSIONS

The literature review has not produced much information that can be used directly to establish the likely quality of water in flooded pits from brown coal mining in Victoria. Reports on the deliberate flooding of disused mines using water diverted from rivers have been confined to Germany which is the only country to practice this kind of coal mine rehabilitation on a large scale. In other countries rehabilitation is to land and while there may be some formation of lakes, these tend to be small and of minor consequence.

In the Rhineland coalfield of Germany experience has been gained in the creation of numerous small lakes over many years although little has been published on water quality. However, Rheinbraun have indicated in personal communications that acidification by oxidation of the pyrite in the extensive and sandy (porous) overburden dumps can be a major factor. - there seems to have been no need to carry out modelling to predict the water quality in a flooded mine. Geomechanical stability is very important and to improve this, artificial flooding by diversion of rivers is favoured and is considered to be essential for some large (25 km^2) lakes that are planned. The use of river water rather than allowing the lake to fill naturally also results in a better quality of water in the lake itself – filling is much more rapid so that the chemistry of the lake water will resemble that of the river.

The only modelling studies of water quality in flooded mine that have been found refer to lakes that form in abandoned gold mines in arid parts of the United States. However, the conditions are very different from those for brown coal mines in Victoria so that these articles have little direct relevance.

Extensive modelling of natural lakes has been carried out – for the most part these relate to the biological and physical properties of the lakes rather than to the chemical properties of the

water. Nevertheless they provide general information that would be useful for the development of a model for a flooded mine. In particular there may be a need to model the extent of temperature stratification in the proposed mine lakes and the likely effects of this on their chemical and biological properties.

There is a substantial body of information contained in reports issued by the former SECV about local factors that might affect the quality of water in flooded mine in the Latrobe Valley. One study that has been carried out already suggests that there would be no problems with water quality in lakes formed in disused open cut mines in the Latrobe Valley. Measurements made on a small lake that has formed in an abandoned mine in the Latrobe Valley show that it has good water quality.

To produce a model to predict the quality of water in a flooded brown coal mine in Victoria will require a substantial level of independent development - nothing has been found in the literature that could be used directly even with modification. On the other hand there are the results of an extensive range of studies carried out by the former SECV that would generally be of considerable value as inputs to such a model.

One of the first considerations in the development of any model is to decide what are the important local issues. This is not part of the scope of this literature review but will be considered in another activity of the project.

5 REFERENCES

Acott, G B, (1989, "The Creation of a Mountain Lake Sportsfishery at Cardinal River Coals Ltd.", *Reclamation; A Global Pespectual*, Conference Proceedings, Walker D G, Powter, C B and Pole M W (eds), Calgary, AB, 27-31 August 1989, 151-156.

Aoki, I, (1992), "Inclusive Kullback index - a macroscopic measure in ecological systems", *Ecological Modelling*, **66**, 289-299.

Ashton, P, (1996), "Yallourn North Extension Open Cut - Colour Survey", Report No 9603242, Envirogen, Traralgon, Victoria.

Bilkenroth, K-D, (1993), "300 Years in the History of Geisetal and its Tertiary World - Brown Coal Winning and Subsequent Landscaping", *Braunkohle* (Ger.), **45(8)**, 4-9.

Black, C J, (1982), "Yallourn North Open Cut Seepage Study", Report No SO/82/50, Research and Development Department, State Electricity Commission of Victoria

Black, C J, (1987a), "Environmental Significance of Ashing Materials Deposited in the Blue Lagoon Area", Report No CT/87/22, Research and Development Department, State Electricity Commission of Victoria.

Black, C J, (1987b), "Peat Samples from Morwell Open Cut", Report No CT/87/34, Research and Development Department, State Electricity Commission of Victoria.

Black, C J, (1987c), "Soils from Morwell Overburden Rehabilitation", Report No CT/87/35, Research and Development Department, State Electricity Commission of Victoria.

Black, C J, (1987d), "Soils from the Morwell River Diversion Channel", Report No CT/87/49, Research and Development Department, State Electricity Commission of Victoria.

Black, C J, (1988a), "Soil Samples from Savages Track", Report No CT/88/10, Research and Development Department, State Electricity Commission of Victoria.

Black, C J, (1988b), "Characterisation of Samples to be Used in Batch and Column Leaching Tests", Report No LO/88/074, Research and Development Department, State Electricity Commission of Victoria.

Black, C J, (1989), "Batch Extraction Studies of Hazelwood and Morwell Precipitator Ash and Hazelwood No 3 Ash Pond Sediment", Report No LO/89/130, Research and Development Department, State Electricity Commission of Victoria.

Black, C J, (1990), "Yallourn W Ash Leaching", Report No SC/90/174, Research and Development Department, State Electricity Commission of Victoria

Black, C J, (1992a), "Leachability of Morwell Brown Coal Ash", M. App.Sc. Thesis, Department of Chemical Engineering, University of Melbourne.

Black, C J, (1992b), "Yallourn North Open Cut Seepage Study", Report No SO/82/50, Research and Development Department, State Electricity Commission of Victoria

Brenner, F J, (1974), "Ecology and Productivity of Strip-Mine Areas in Mercer County, Pennsylvania", Research Technical Completion Report No A-029-PA, Institute for Research in Land and Water Resources, The Pennsylvania State University.

Brenner, F J, Snyder, W Schalles, J F, Miller, J P, and Miller, C, (1985), "Primary Productivity of Deep-Water Habitats on Reclaimed Mine Lands", Proceedings of Conference on Wetlands & Water Management on Mined Lands, October 23-24 185, Pennsylvania State University.

Cairns, J and Pratt, J R, (1985), "Aquatic Environments on Mined Lands: Progress and Future Needs", Conference Proceedings *Wetlands and Water Management on Mined Lands*, Brooks, R P, Samuel, D E and Hill J B (eds), University Park, PA, 23 October 1985, 1-8.

Calles, H V, (1997), "Planning the Landscape of Tomorrow", *Braunkohle* (Ger.), **49(1)**, 33-42.

Deed, R G, (1975), "Expected Quality of Water in Flooded Latrobe Valley Open Cuts", Report No 314, Planning and Investigations Department, Scientific Division, State Electricity Commission of Victoria.

Deed, R G, (1981), "Behaviour of Some Latrobe Valley Brown Coal Ashes on Their Interment in Overburden Dumps", Report No LO/81/139, Research and Development Department, State Electricity Commission of Victoria.

Fitzgerald, W R, (1991), "Sources of Colour in SECV Wastewaters", Report No LO/91/496, Research and Development Department, State Electricity Commission of Victoria.

Fitzgerald, W R, (1993), "Development of Colour in the Hazelwood Cooling Pond", Report No LS/93/670, Research and Development Department, State Electricity Commission of Victoria.

Fitzgerald, W R, (1994), "Causes of Water Coloration in Eel Hole Creek Wetlands", Report No LS/94/784, Research and Development Department, State Electricity Commission of Victoria.

Gallerano, F, Ricci, R and Viotti, P, (1992), "Analysis of the eutrophication trend in a deep lake", *Ecological Modelling*, **66**, 157-179.

Gelda, R K, Auer, M T and Effler, S W, (1995), "Determination of Sediment Oxygen Demand by Direct Measurement and by Inference from Reduced Species Accumulation". *Mar Freshwater Res.*, **46**, 81-88.

Hakanson, L, (1995), *Predictive Limnology: Methods for Predictive Modelling*, SPB Academic Publishing, Amsterdam.

Hildmann, E, and Wunsche, M, (1996), "Lignite Mining and its After-Effects on the Central German Landscape", *Water, Air and Soil Pollution*, **91(1&2)**, 79-87.

Hosslin, W, (1980), "Technical and Legal Problems in Abandoned Open-cast Mines of Bayerische Braunkohlen-Industrie Ag at Schwandorf", *Braunkohle* (Ger.), **32(9)**, pp 273-277.

Hutchnison, G E, (1975), A Treatise on Limnology, Vol. 1, Part 1, Geography and Physics of Lakes, John Wiley & Sons.

Jackson, L J, (1991), "Surface coal mines - restoration and rehabilitation", Report No IEARC/32, IEA Coal Research, London.

Jahn, W, Tschirner, N and Seftenberg, H, "Brown Coal Mining and Land Rehabilitation in the Schlabendorf Area", *Braunkohle* (Ger.), **49(1)**, 25-32.

Klapper, H, (1995), "Water Quality in Geogenetically Acidified Lignite Mining Lakes of Germany", 6th International Conference on the Conservation and Manipulation of Lakes, Kasumigaura, Japan.

Lau, W M and Mainwaring, S J, (1983), "The Determination of Soil Sensitivity to Acid Deposition with Reference to the Latrobe Valley", Proceedings of Eighth International Clean Air Conference, Hartman, H F, O'Heare, J N, Chiodo, J and Gillis, R, (eds), 7-11 May 1984, Melbourne, 201-213.

Lerman, A, Imboden, D M and Gat, G R, (1995), *Physics and Chemistry of Lakes*, Springer-Verlag, Berlin & New York.

Liebl, E, (1980), "Dam and Bank Design of Artificial Lakes in Abandoned Open Cast Mines of Bayerische Braunkohlen-Industrie AG Schwandorf", *Braunkohle* (Ger.), **32(9)**, 267-272.

Lingemann, H, (1993), "The Mining Industry in Wolfersheim - The present Stage of Recultivation and Further Measures to be Adopted". *Braunkohle* (Ger.), **45(5)**, 9-13.

Marut, E, (1995), "Yallourn North Extension Open Cut Mine On Site Analysis of Rear Pond Conditions", Report No CSLV/95/146A, Scientific & Environmental Services, State Electricity Commission of Victoria

Nawrot, J R and Klimstra, W D, (1989), "Wetland Habitat Development on Mined Lands", *Animals in Primary Succession - the Role of Fauna in Reclaimed Lands*, Majer, J D (ed), CUP, Cambridge, 269-285.

Orlob, G T, (1984), *Mathematical Modelling of Water Quality: Streams, Lakes and Reservoirs*, No 12 Wiley IIASA International Series on Applied Systems Analysis, John Wiley & Sons

Parkhurst, D L, Thorstenson, D, C, and Plummer, L, N, (1983), "PHREEQE - A computer program for Geochemical Calculations,", U.S, Geological Survey, Water Resources Investigations Paper, 80-89.

Pierschke, K -J and Boehm, B, (1996), "Geomechanical and Hydrological Aspects of Residual Lake Construction in the Rhineland Brown Coal Mining Area", *Braunkohle* (Ger.), **48(6)**, 647-653.

Pietsch, W H O, (1996), "Recolonization and Development of Vegetation on Mine Spoils Following Brown Coal Mining in Lusatia", *Water, Air and Soil Pollution*, **91(1&2)**, 1-15.

Pillard, D A, Doyle, T A, Runnells, D D, and Young, J, (1995), "Post-mining Pit Lakes: Predicting Lake Chemistry and Assessing Ecological Risks", Colorado State Univ Tailings and Mine Waste '96 Conf Proc, Balkema, A A, (ed), Fort Collins, CO, 469-478.

Riley, M J and Stefan, H G, (1988), "Minlake: A Dynamic Lake Water Quality Simulation Model", *Ecological Modelling*, **43**, 155-182.

Samuel, D E, (1989), "The Reclamation of Lands for Outdoor Recreation", *Animals in Primary Succession - the Role of Fauna in Reclaimed Lands*, Majer, J D (ed), CUP, Cambridge, 287-302.

v. Schwarzenberg, (1997), Department of Geology and Hydrology, Rheinbraun Engineering und Wasser, GMBH, private communication.

Shaw, R D and Prepas, (1990a), "Groundwater-Lake Interactions: I. Accuracy of Seepage Meter Estimates of Lake Seepage", *Journal of Hydrology*, **119**, 105-120.

Shaw, R D and Prepas, (1990b), "Groundwater-Lake Interactions: II. Nearshore Seepage Patterns and the Contribution of Ground Water to Lakes in Central Alberta", *Journal of Hydrology*, **119**, 121-136.

Schubert, J P, (1988), "Hydrology and Geochemistry of Surface Coal Mine Lakes", in Monograph, *Mine Drainage and Surface Mine Reclamation. Volume 1 Mine Water and Mine Waste*, from Annual Meeting of the American Society for Surface Mining and Reclamation, Pittsburg, PA, 17 Apr 1988.

Tamuly, A, (1970), "Physical and Chemical Limnology of the Blue Lake of Mount Gambier South Australia", *Trans. R. Soc. S. Aust.*, **94**, 71-86.

Tang, D, (1987), "Environmental Effect of Ash Pellet Internment in Overburden Dumps: Preliminary Investigation", Report No LO/86/708, Research and Development Department, State Electricity Commission of Victoria.

Thole, B, (1994), "Lignite Mines in the Federal Republic of Germany: Extraction and Utilisation Concepts According to Environment Protection Criterion", *Mines et Carrieres, Les Techniques*, **76**, 103-107.

USEPA, (1993), MINTEQA2, "A geochemical Assessment Model for Environmental Systems, Version 3.11".

Vandersluis, G D, Straskraba, V and Effner, S A, (1995), "Hydrogeological and Geochemical Aspects of Lakes Forming in Abandoned Open Pit Mines", in Monograph *Water Resources at Risk; a Selection of Papers*, Hotchkiss, W R, Downey, J, S, Gutentag, E, D, and Moore, J, E, (eds), from Conference on Water Resources at Risk, Denver, CO, May 14-18 1995.

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