Mine Pit Lakes: Closure and Management

Editor

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The Mine Water and Environment Research (MiWER) Centre is a formal research centre based at the Edith Cowan University Centre for Ecosystem Management (Joondalup Campus) in Western Australia.

MiWER is an international team of highly qualified professional scientists with skills spanning ecology and environmental chemistry to microbial ecology and sustainability: all with an interest in mine water.

Within the MiWER Centre, staff apply their scientific knowledge and skills to researching both applied and fundamental water quality issues of the mining industry and mining legacies, in particular pit lakes. We often have opportunities for research collaborations with other research providers.

We also provide a high quality consultancy service to industry and government on environment management issues in the area of freshwater ecosystems in addition to water in mining issues.

Technical Reviewers

The dedicated efforts of the peer reviewers have resulted in the high quality chapters compiled for this publication. The editor thanks the following people who contributed their time and expertise as reviewers of chapters for the Mine Pit Lakes: Closure and Management book. A technical and critical review of each chapter was undertaken by a minimum of two reviewers for the production.

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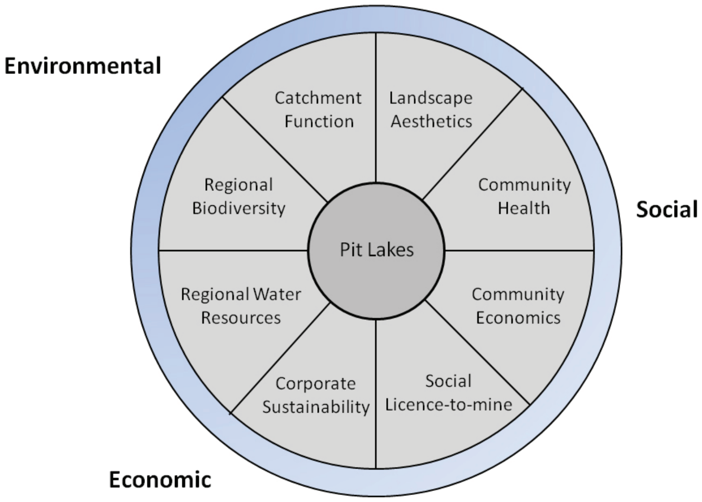
Preface

Mine closure guidance increasingly considers pit lakes explicitly, even in the initial planning and feasibility stages. Sustainability is also at the heart of most closure guidelines, with environmental sustainability already a key outcome, and social sustainability becoming increasingly important. It follows that closure guidelines are also expecting sustainable practice for what is often the greatest social and environmental risk of open-cut mining: pit lakes.

The role of pit lakes in assimilating a number of catchment values and processes is key here; a dysfunctional lake will contribute to a dysfunctional catchment and vice versa. Rather than separating and segregating pit lakes from the mine closure process, this book encourages integration of pit lakes into both broader mine closure planning and also into post mining landscape functions and goals as the below diagram shows.



This book was developed to meet a growing need to better manage the many pit lakes and pit lake districts current and future that challenge communities, regulators and miners. Covering historic abandoned pits that have now flooded, through to new mining proposals that envisage pit voids below groundwater level at end of life-of-mine. Although much still needs to be understood in terms of final outcomes and goals for pit lake development and closure, this book comprehensively covers many considerations that operators should contemplate when developing a mine that will result in a pit lake. It will also assist when stakeholders are approached by operators seeking to close their operations leaving a water-filled final void.

We start our journey of considerations with the option of not having a pit lake at all with the "Management of mine wastes using pit void backfilling methods – current issues and approaches". The history of pit lakes then advises us how to develop a sustainable pit lake with "Lessons learned from pit lake planning and development" which reviews successes and failures from pit lakes across a number of mining industries. Stakeholder consultation and goal setting for pit lakes is discussed in "What Type of Lake Do We Want? Stakeholder Engagement in Planning for Beneficial End Uses of Pit Lakes" and the development of planning guidance materials are covered by "Generating regional guidance for best practice pit lake closure and reclamation".

The fundamental consideration of hydrology in filling and maintaining pit lake volumes and hydraulic connectivity is covered by "Hydrologic and geomorphic design of pit lakes for long-term sustainability", whilst predicting final water quality and its drivers is covered by "Use of water quality models for design and evaluation of pit lakes".

“Meeting environmental goals for pit lake restoration – factoring in the biology” and “The role and value of riparian vegetation for mine pit lakes” provide advice on how to develop aquatic and surrounding terrestrial ecosystems in pit lakes and their catchments where restoration opportunities often currently either fail to succeed or are ignored altogether.

The management technique of rapidly filling pit lakes to improve on water quality and reduce end use lag time is covered by “Filling and management of pit lakes with diverted river and mine water — German experiences”. Failing good pit lake water quality “Bacterial sulfate reduction based ecotechnology for remediation of acidic pit lakes” provides advice on sustainable water quality treatment techniques. International regulation and general expectations toward pit lake closure are covered in “Regulator guidance and legislation relevant to pit lakes”.

Pit lake water quality before and after closure is a key factor in determining risk and end use opportunities. “Monitoring the water quality of pit lakes“ provides an overview of what water quality parameters should be monitored and how. Finally, “Working near pit lakes – health and safety considerations” provides pragmatic industry leading-practice on the human health risks that pit lakes can directly pose to people working on and around them.

This book represents international leading practice for closing and managing mine pit lakes. It does not aim to provide a “recipe” approach for mine closure plans involving pit lakes as it recognises the wide breadth in climatic, legislative, bio-physical, social and economic context that relates to any particular mining operation. The aim is to provide the reader with a broad range of considerations that should be worked through for a specific operation. Although the practices described herein may even not be entirely relevant to a reader’s specific operation, through explicit closure and funding requirements, mine operators and stakeholders will still benefit from considering this advice. Mine closure regulation tends to ratchet in just one direction. What regulators and communities expect in today’s closure climate is likely to be quite different to that which we will see in future closure climates of the decades that some mines will take to close and their pit voids to fill.

This book was developed prior to the Mine Pit Lake Closure and Management Workshop held at the Sixth International Conference on Mine Closure (19–22 September 2011) at Lake Louise, Alberta, Canada, where it was first released. I sincerely thank all the authors for their time in effort and their excellent contributions to this book. My grateful thanks also to the many reviewers who improved these already leading works. Thanks also to the Edith Cowan University, Office of Research and Innovation for support of the editorial process.

I trust you find this book useful and that it makes a direct contribution to improved sustainability for your pit lake circumstances.

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Design

Management of mine wastes using pit void backfilling methods – current issues and approaches

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Abstract

Mined voids are increasingly viewed by industry as a resource for the storage of wastes such as tailings, heap leach residues, acid/solute generating waste rock and salts derived from mine water treatment and as a means to reduce post-closure risks to receiving environments. Mine closure guidelines and regulator feedback of mine closure plans are also showing a greater recognition of backfilling in the context of achieving agreed post-closure land use.

A key driver for mines, where multiple voids are developed, is that existing voids provide a cost-effective opportunity to store tailings in an existing 'engineered structure' rather than build and operate a new tailings or waste rock storage facility. Key issues for consideration include resource sterilisation which may preclude future open pit mining, long-term rates of tailings consolidation and the fate/impact of expressed tailings porewaters on water quality and the stability of the final landforms in the case of open cut mines with in-pit tailings storage and agreed end point or closure criteria for the void, e.g. need for full or partial pit backfilling.

In mine closure planning, placement of mine wastes in voids is often seen as 'best practise', particularly in environments where sensitive ecosystems exist downstream of the mine site. Generally, risks to the environment can be greatest where mine wastes are located closest to the ground surface, due to relatively high groundwater movement in near-surface aquifers and/or risks of failure of engineered structures due to extreme rainfall events or erosion. Placement of problematic mine wastes at significant depths in-pits or underground voids, as part of partial backfilling approaches, can address these risks by increasing the path length from contaminant source to receptor and enhancing encapsulation. In some instances, backfilling is used as an approach to avoid pit lakes altogether, in circumstances where the results of assessments indicate that pit lake water quality may deteriorate in the long-term and affect downstream water quality and ecosystems.

1 Introduction

Mined voids have long been viewed as an inevitable consequence of the economic benefits of mining. Historically, in open cut operations, pits have often been left in an open condition post-closure, although pit design or operational aspects have at times warranted partial backfilling to support further, safe excavation of ore, e.g. provide support due to wall instability, facilitate underground mining (Castendyk, 2011).

Increasingly, mined voids are being looked at more holistically, as an asset that can reduce costs and post-closure land disturbance and minimise both operational and closure risks. Operating mines create wastes and can expose materials that pose risks to the environment. Backfilling provides an opportunity to cover or encapsulate these materials cost-effectively, provided that assessment of this opportunity is carried out at an early stage of mine planning.

Backfilling can also prevent the development of pit lakes with poor water quality, often due to the accumulation of solutes in the water column via groundwater ingress and/or leaching of exposed waste materials.

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Backfilling can significantly reduce the areas of land left in a disturbed state (post-closure), related closure-rehabilitation costs, e.g. ongoing water management, and the safety issues associated with leaving an open pit. In addition, backfilling makes efficient use of the excavated storage space with improved containment or encapsulation by geological materials adjacent to the void rather than constructing above ground facilities such as tailings dams with specifically engineered liners and waste rock dumps with covers. In addition, regulatory agencies and indigenous organisations are increasingly seeing backfilling as a way of returning land to a form that supports pre-mining land use.

2 Key drivers of mine void backfilling

2.1 Operational imperatives for mine void backfilling

While void backfilling may be costly or not economically feasible in many instances, in some circumstances it can significantly reduce operational and/or closure costs. Backfilling is most feasible where multiple pits or underground voids have been or are being developed, permitting mine or other wastes to be deposited in the voids. There are four key issues requiring consideration in any decision-making process:

1. Operational costs, schedules and engineering considerations.
2. Resource sterilisation.
3. Water management and environmental risks.
4. Land disturbance.

The relative costs of managing wastes using an above-ground facility versus in-pit deposition are a key issue. For example, the operational and capital costs of constructing a new tailings storage facility or waste rock dump/stockpile may be high relative to deposition in a mined out pit. However, this may be offset by greater distances of pumping tailings or trucking waste rock materials. Mine scheduling, pit availability and the time required to prepare the pit for backfilling are all important considerations.

The primary engineering issues related to lining (if required), backfilling and operating a void for containment of wastes relate to the installation and long-term behaviour of an in-pit liner versus an above ground liner, geotechnical stability pit walls, geotechnical risks related to the in-pit materials and the ability to achieve construction and long-term stability of a pit lake or constructed landform. An in-pit liner becomes more practical and cost-effective if included early in the mine's operating plans, e.g. stockpile and placement of clay and other waste materials close to the pit.

In the case of open cut mining, resource sterilisation may result from pit backfilling, since it may preclude continuation, or re-commencement of future mining. However, pit backfilling may only have a slight, negative impact if economic assessments indicate that underground mining of the resource should be progressed. A 'crown pillar' between the pit and the underground mine may need to be established if the pit is backfilled with tailings and the risk of geotechnical failure, i.e. flow of tailings from the pit to the underground workings.

Comparison needs to be made of the relative operational risks to the environment between managing wastes using pit backfilling and an above-ground facility. An above-ground facility will often comprise complex liner and monitoring systems, ensuring that downstream surface water resources and near-surface groundwater resources remain protected. Depending on the hydrogeological context, and the connectivity between in-pit wastes and downstream receptors of importance, and their beneficial use attributes, backfilled pits may in themselves provide significant encapsulation of wastes. This might reduce water management effort and costs and preclude the need for the installation of extensive lining and monitoring systems.

Minimising land disturbance is increasingly being viewed by regulators, and the community, as an important objective for proposed mining operations (Heikkinen, 2008; ICMM, 2006). Pit backfilling provides the opportunity to reduce the footprint of mining operations, e.g. precluding the need to construct additional tailings or waste rock storage facilities.

In reality, a decision to proceed with pit backfilling will often require consideration of the aforementioned technical issues as well as the outcomes arising from community engagement and regulatory feedback. As an example, Newmont Australia has incorporated both economic and technical considerations, as well as community feedback, at its Granites Gold Mine in Northern Territory, Australia (DITR, 2007). Use has been made of multiple pits to deposit tailings and waste backfill, permitting re-instatement of pre-mining landforms (Figure 1).

Figure 1 In-pit tailings deposition, Granites Gold Mine, Northern Territory, Australia (DITR, 2007)

In underground mining operations, tailings backfill has been common since the 1980s, for economic, safety or mine closure reasons. The economic reasons relate to the costs of building new, above ground tailings storage dams and providing support to underground workings to maximise ore recovery.

2.2 Managing post-closure environmental risks

Studies have shown that wastes, particularly those that are sulfidic and/or acid-generating, often require minimised interaction with the hydrosphere, in order to minimise oxidation processes and generation of acid or solutes and mitigate impacts to downstream environmental receptors. Various authors (Thienenkamp and Lottermoser, 2003; Szymanski et al., 2003; Hoepfner, 2007) have determined that wastes placed above the water table and remaining uncovered within the unsaturated zone, particularly those that are highly sulfidic or potential acid forming (PAF), are exposed to atmospheric oxygen and prone to significant leaching.

Covers have often been used to limit oxygen and infiltration into wastes, and comprise either soil or synthetic liner ‘barrier’ covers, e.g. compacted soil layer or synthetic liner, or ‘store-and-release’ covers. In a comparison of the performance of covers, Paul et al. (2003) report that barrier covers have been ‘borrowed’ from landfill liner technology. They often comprise compacted clay overlain by a growth medium, are usually elevated to promote runoff and minimise infiltration and are best suited to humid climates. Barrier covers that comprise a soil layer can be problematic because they are prone to cracking due to wet/dry or freeze/thaw cycling.

According to Paul et al. (2003), store-and-release covers are more robust and sustainable than barrier covers because they are relatively easy to construct, using mine site equipment. These covers comprise a loose soil (‘growth media’) layer that provides a thick protective layer over an underlying compacted clay ‘sealing’ layer, helping to maintain moisture conditions. These covers address erosion risks by promoting infiltration, but ultimately, the long-term behaviour of soils and re-established vegetation will determine the long-term success of covers, e.g. development of macro pores and establishment of preferred infiltration pathways. Store-and-release covers are generally designed for seasonal, semi-arid climates, where pan evaporation is well in excess of rainfall and aim to capture rather than shed rainfall, to minimise clay cracking/desiccation, vegetation die-back and erosion. Depending on site conditions, a store-and-release cover might typically comprise a sealing layer about 0.5 m thick, overlain by growth media of about 1.5 m thick, to store wet season rainfall and release it during the dry season through evapotranspiration.

In the soil barrier and store-and-release cover scenarios, quality assurance/quality control of construction, geotechnical properties of soils, climate, geomorphological conditions and ecosystem behaviour all play critical roles in determining whether these covers will maintain their initial performance in the future. While sealing layers may initially provide the desired hydraulic conductivity ($<10^{-8}$ m/s), clays are prone to deterioration over time, e.g. cracking or desiccation and deterioration due to ecosystem variables. This can result in significant increases in hydraulic conductivity by one or more orders of magnitude, no longer providing a ‘seal’.

A number of mine operations have addressed these risks by constructing synthetic liners such as geosynthetic clay liners over acid generating mine wastes (DITR, 2007), although some uncertainty exists in relation to the effective life of such liners. An example of covers that have deteriorated due primarily to ecosystem variables are those constructed at the former Rum Jungle Uranium Mine in the Northern Territory, Australia in the 1980s (Figure 2) (Taylor et al., 2003). Long-term monitoring data indicate that the permeability of the covers has steadily increased over time, primarily due to cracking of the clays, penetration of deeper roots through the covers and into the underlying waste materials and termite activity. These processes have created permeable, preferential pathways for water and oxygen movement.

Partial or full backfilling of mine voids provides the opportunity to remove the connections between problematic mine wastes and the hydrosphere by placing materials in contact with deeper geological environments that are naturally stable, comprise low permeability and are less connected to the hydrosphere and local ecosystems.

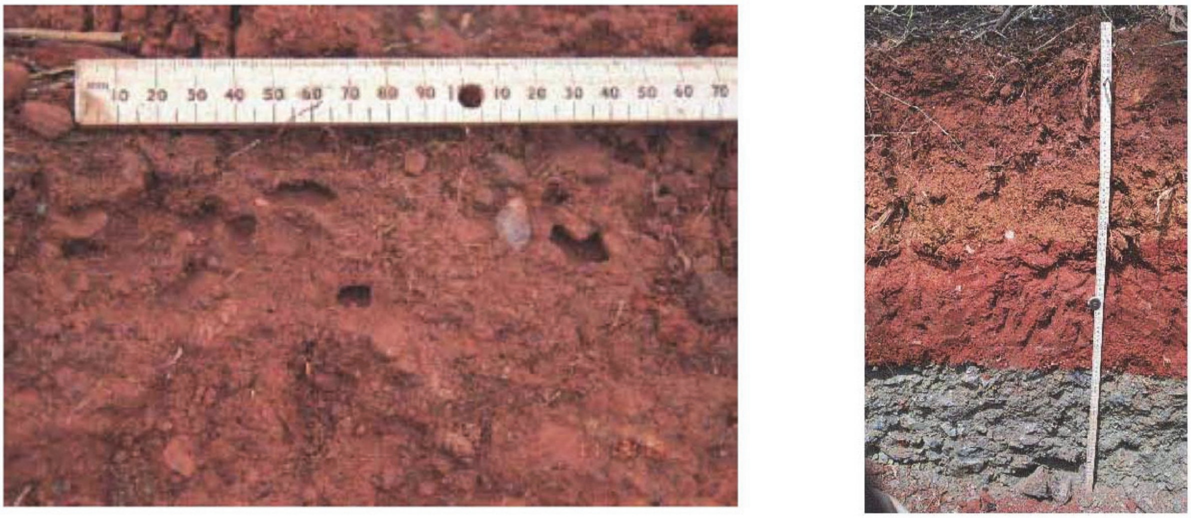

Figure 2 **Deterioration of covers due to termite activity and root penetration into wastes, former Rum Jungle Uranium Mine, Northern Territory, Australia (Taylor et al., 2003)**

2.3 Post-mining land uses and emerging community and regulatory expectations

Stakeholder expectations are increasingly focussed on mining company’s approaches to designing and constructing post-mining landforms that provide a positive, beneficial use for the future. Numerous examples exist of mining operations, particularly large-scale coal mines, which have successfully established or re-established productive lands or ecosystems, e.g. various coal mines in the Hunter Valley, New South Wales, Australia (Hunter Valley No.1, Warkworth Mine, etc.). A key consideration of the feasibility of void backfilling is the ‘swell factor’ of the excavated materials and the availability of wastes to be returned to voids and the ability to concurrently mine an advancing pit face or other pits, thus allowing progressive backfilling activities.

The geotechnical properties and behaviour of wastes to be disposed of in voids is a critical issue. Waste rock returned to pits will generally not consolidate significantly relative to processed ore/wastes, such as tailings, which will often have a much finer grained composition and will show much greater magnitudes of consolidation but at slower rates.

When depositing tailings in a pit, the upper surface of the tailings rises rapidly especially in the early stages of deposition when the pit has a large pit volume:area ratio, i.e. at the time the area of the upper surface of tailings is small. The result of this is that drying and desiccation of the tailings mass is low, the tailings are low in strength and have relatively poor consolidation characteristics. Poor consolidation behaviour can cause settlement of the final landform over extended periods after a pit has been filled. This is often a result of the low solids content of the tailings and the depth of the stored material. This leads to difficulties for mining operations to expedite the pit backfilling process, as tailings need to be deposited slowly. Once consolidation rates have declined, either under quiescent consolidation or surcharged with rock to expedite the process, a cover can be constructed to allow landform shaping and revegetation.

Notwithstanding the above challenges, pit backfilling does permit mine operations to construct pre-mining landforms, and ideally, a landscape that permits re-establishment of land access for local communities or development of productive landscapes for community use.

Regulatory expectations have also evolved over time with a greater emphasis on mining operations to more critically examine and manage long-term environmental risks and return land to a condition that does not negatively impact on legacies for future generations. Establishing healthy ecosystems in-pit lakes or void backfilling are seen as very positive approaches in this context. The following comments are pertinent to pit backfilling and/or establishing pit lakes internationally.

ANZMEC-MCA (2000) state that ... “Mine closure should not be an ‘end of mine life process‘ but should be integral to ‘whole of mine life’ if it is to be successful. Planning for closure should commence at the feasibility phase of an operation. In this way, future constraints on, and costs of, mine closure can be minimised, post-mining land use options can be maximised and innovative strategies have the greatest chance of being realised.”

WA Govt. (2010) state that ... “Proponents are encouraged to consider applying resources to achieve improved land management and ecological outcomes on a wider landscape scale, and to take into account the following hierarchy in the consultation process to determine agreed post-mining land use options: 1. Reinstate natural ecosystems as similar as possible to the original ecosystem. 2. Develop an alternative land use with higher beneficial uses than the pre-mining land use. 3. Reinstate the pre-mining land use. 4. Develop an alternative land use with other beneficial uses than the pre-mining land use.”

Similar statements can be found in other international papers describing emerging changes in community and regulatory expectations (Heikkinen, 2008; ICMM, 2006; MEND, 1995).

3 Backfilling methods

3.1 Placement of waste rock

Void backfilling with waste rock commonly utilises mining equipment such as front-end loaders, haul trucks, dozers and support equipment to maintain trafficability and safe working conditions, i.e. graders, water trucks and other miscellaneous equipment. Smaller, specialised earthmoving equipment may be used if backfilling needs to be undertaken in a specific manner, if liners or in-pit drains need to be constructed to minimise seepage from the pit or enhance tailings consolidation (respectively) or if backfill materials are to be blended with other materials such as lime to meet requirements relating to environment protection, i.e. lime can be used to neutralise seepage and reduce the solubility of metals.

Waste rock is typically excavated from stockpiles, hauled and dumped at the base of the void and spread using dozers or end dumped from benches located higher in the pit profile. Key issues for consideration in planning include understanding haulage distances and schedules, geotechnical, geochemical and moisture properties of the wastes, preparation of wastes prior to placement (if required), preparation of covers or drains and final landform design assumptions. In circumstances where pit backfilling is considered early in the mine planning process, and forms a key element of closure-rehabilitation activities, wastes may be hauled directly from the active mine face to parts of the pit being prepared for closure and rehabilitation (Figures 3 and 4).

Figure 3 Progressive mining and pit backfilling, Warkworth Coal Mine, New South Wales, Australia (Photo courtesy of Panoramio, Google)

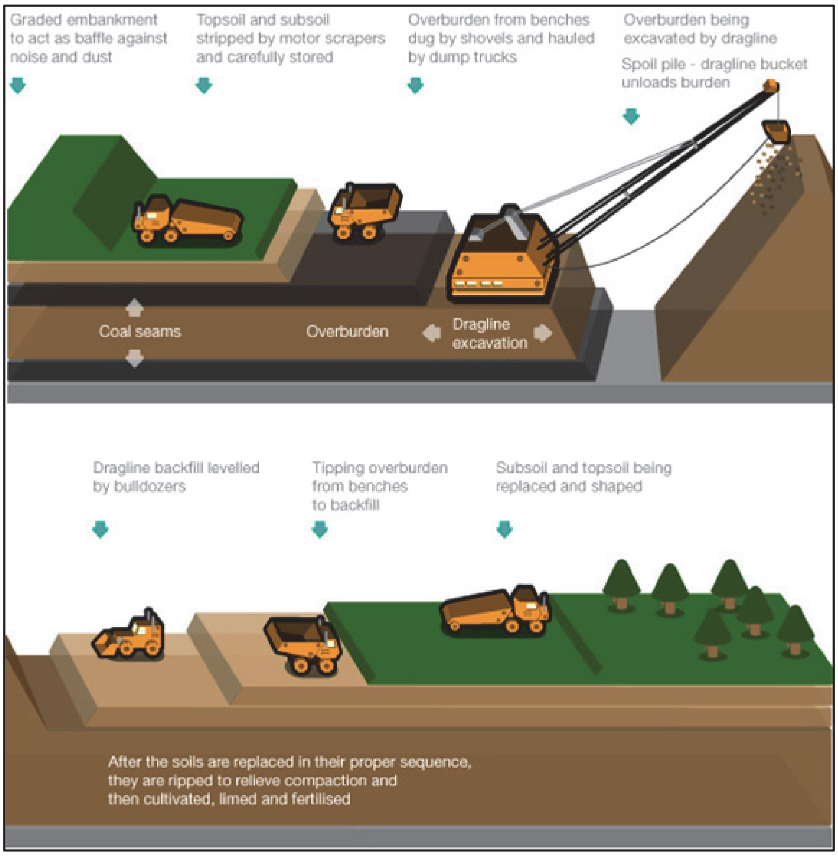

Figure 4 Typical coal mining, void backfilling and restoration activities (Photo courtesy of ERCE Trading London)

3.2 Placement of tailings

The mill (or refinery) tailings solids concentration is typically raised using conventional thickeners to conserve water and reagents and then pumped as a solids–water slurry to a storage facility. The tailings slurry is discharged into the pit via a single or multiple points (spigots) located on the haulage ramp, the pit benches, or along the pit's crest. Upon completion of tailings deposition the pit is then backfilled with waste rock to encapsulate the tailings and produce the final landform.

The deposition strategy should minimise tailings segregation, maximise tailings consolidation and water (or reagent) recovery. The tailings deposition design needs to control the tailings beach to ensure the decant pond location is maintained against the haul ramp or the pump location, and to ensure safe pit access. For example, it is possible to deposit the tailings slurry from the haulage ramp into a flooded pit without significantly diluting or segregating the discharge.

The tailings deposition can be either sub-aqueous (below water) or sub-aerial (above water). Both methods can result in the segregation, or separation of tailings particles according to their size and density. The degree of segregation is a function of the particle size distribution (PSD), slurry rheology and momentum, the beach topography, the depth of the overlying water or intersection with the decant pond (Vick, 1990). Normally the coarse fractions will settle close to the discharge point with the finer fractions distributed further afield. The segregated fines tend to exhibit higher compressive yield stresses and thus hinders the tailings consolidation producing long-term settlement issues.

Co-disposal, or co-placement, of coarse waste with the tailings slurry can reduce the site's storage footprint and produce a more stable deposit. Partial co-placement can be achieved by dumping the coarse waste from a pit bench or the pit crest. Co-disposal of the tailings and coarse waste has several advantages. For example, the tailings can be used to encapsulate coarse sulfate mineral waste. But co-disposing fine and coarse material as a single stream into the pit is problematic because the coarser material will tend to segregate and settle at the discharge point. This segregation can be reduced by thickening the tailings to a paste consistency and transferring the mixture under gravity or by positive displacement pumps.

The pit deposition strategy, particularly during the initial stage, will also determine the post-closure landform stability and the quality and quantity of water expressed. Mine pits narrow as they get deeper to maintain wall stability. When tailings are deposited into the base of the pit its shape tends to produce a high rate of rise. This rate can exceed the tailings consolidation rate and constrain the tailings densification. When surcharge with additional tailings and/or waste rock this low density tailings will continue to consolidate expressing water causing long-term water management and settlement issues.

Thus, it is advantageous to discharge the tailings slurry at high concentrations (examples are shown in Figure 5). Hence, the interest in high compression and paste thickeners, which have been proposed for the mining industry as the answer to its water and tailings storage management issues. While this may be true, the implementation of paste thickeners at brownfield operations other than alumina refineries has been slow due to a number of technical and cost issues.

Poor tailings consolidation can be partially corrected by installing geotextile wicks to encourage vertical drainage of the entrained pore waters (Figure 6). But this technique is currently limited to the maximum wick installation depth of approximately 40 m.

The pit deposition and post-closure issues can be virtually eliminated by vacuum or pressure filtering the tailings to produce an unsaturated filter cake. But the costs associated with filtering tend to make this option less favourable unless there are significant environmental and topography drivers. Examples of above ground filter tailings storage operations are the Greens Creek Mine in Alaska, USA (Davies et al., 2002) which filters its tailings to meet strict environmental requirements while the La Coipa Mine in Chile (Davies and Rice, 2001) filters its tailings to conserve water.

Ultimately, cost-effective mining and processing methods, together with water management and closure requirements, will dictate whether in-pit tailings disposal is the appropriate method.

Figure 5 Cemented paste underground backfill (left), surface paste tailings disposal (right)

Figure 6 Investigations of in-pit tailings geochemistry, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of HB Wick Drains)

3.3 Neutralisation of backfilled wastes

Tailings backfilled in underground voids are often thickened or strengthened with cement so that support is provided to previously mined ore stopes. Addition of cement, in this instance, can result in neutralisation of acidity in the tailings wastes and reduce risks of acid mine drainage to downstream environments. Waste rock that is backfilled in open pits is sometimes neutralised with lime to reduce acidity and/or solute generation, in circumstances where the materials are unable to be sufficiently encapsulated by low permeability geological materials located in the pit walls (Ayres et al., 2007; Parshley et al., 2006; Paul et al., 2003).

4 Implications of backfilling methods

4.1 Material consolidation and landform stability

Tailings consolidation is substantially greater than consolidation of waste rock backfill. This, together with the often complex geometry of pits, is a major issue that needs to be considered and accounted for when designing final landforms. Figure 7 presents an example of how the tailings mass may need to be apportioned in columns to enable predictions to be made of three-dimensional, post-consolidation elevations of the upper surface of the final landform. Figure 8 presents an example of how, utilising consolidation modelling approaches, tailings consolidation and dry density varies spatially across the pit over a given time. The conclusions here are that tailings consolidation is a complex geotechnical process and the implications to implementing mine closure and, ultimately, a stable final landform can be challenging.

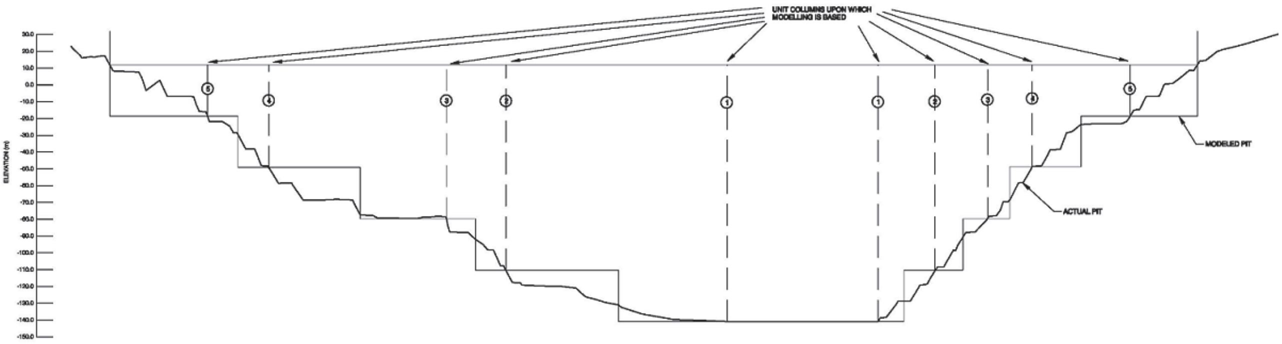

Figure 7 Assumed model 'columns' used to predict tailings consolidation, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of Energy Resources of Australia Ltd)

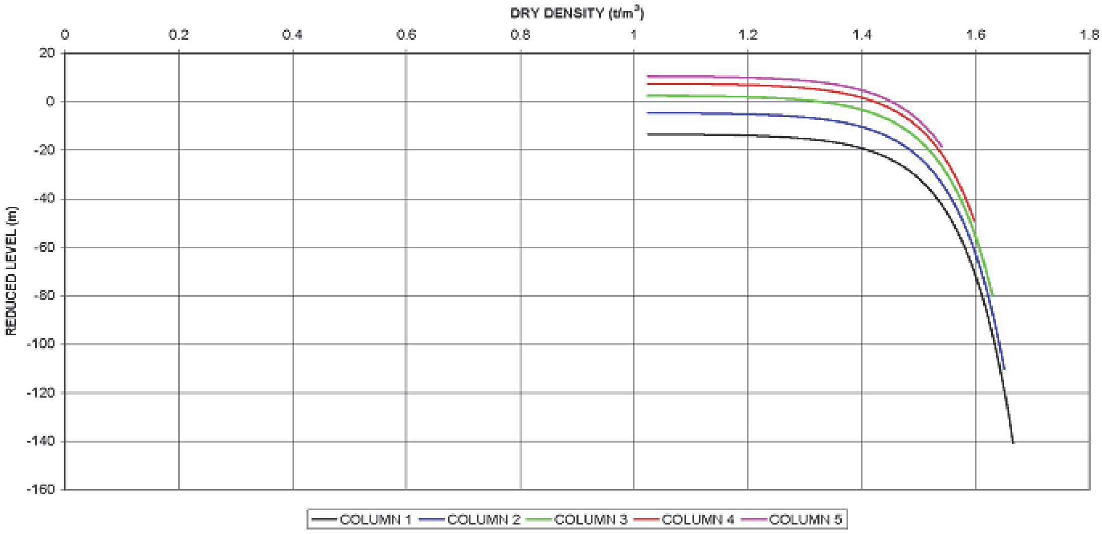

Figure 8 Prediction of changes to the dry density of in-pit tailings, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of Energy Resources of Australia Ltd)

4.2 Solute release and impacts to receiving environments including pit lakes

Backfilling will typically see leachable wastes, such as waste rock, tailings or salts (derived from water treatment), deposited from the base of the pit and covered with waste rock to the natural surface or covered with water, i.e. pit lake. Wastes will usually be placed below the lowest, seasonal water table to ensure that oxygen ingress to the wastes, and generation of acid and/or solutes, is minimised. A key objective of this strategy is to limit solute mobilisation/acid generation, place wastes in contact with low permeability geological materials (in the pit), increase the pathway distance between the wastes and downstream receptors and reduce overall solute migration from the wastes to downstream environments.

Studies are required to support the development of an in-pit wastes deposition plan, including site geological and hydrogeological investigations, geotechnical and geochemical characterisation of wastes, characterisation of the attenuation and flow pathways for solutes, in-pit water and solute balance modelling, fate and transport modelling, and importantly, derivation and agreement of closure criteria for the pit (and site) with stakeholders including regulatory agencies. An important consideration is the change in the hydrological status of the pit as it evolves from a groundwater 'sink' to groundwater 'source'. Hydrological equilibrium between the pit and downstream groundwater systems may take decades and so groundwater monitoring programmes need to be established in a way that will provide useful information to support the results of predictive modelling.

The wastes geotechnical behaviour is an important consideration and particularly important to the release of solutes in the case of consolidating tailings. As tailings consolidate, porewaters are released and will express into the overlying waste rock. The fate, transport and impact of these porewater solutes needs to be incorporated in-pit water and solute balance modelling.

In circumstances where local groundwater systems do not have an environmental or beneficial use for humans, the manner in which wastes are placed in the pit may not be constrained by the geotechnical or geochemical properties of the wastes. In other words, the leaching of solutes from the pit does not pose any specific risk to downstream environments. If on the other hand, protection of downstream environments or beneficial uses is threatened by seepage from the pit, then wastes may need to be placed in parts of the pit that have much lower inherent permeability. This approach results in minimisation of seepage rates from the pit. Alternatively, in-pit liners or barriers such as that installed at the Ranger Uranium Mine and other mines, may need to be installed or neutralisation of backfill wastes may need to be implemented.

Figure 9 Investigations of in-pit tailings geochemistry, Ranger Uranium Mine, Northern Territory, Australia (Photo courtesy of Energy Resources of Australia Ltd)

5 The future of backfilling

Backfilling of mine voids will increasingly be seen in the future as an opportunity to be considered as part of the mine planning process. This will be for two reasons:

1. Changes in regulatory regimes and community expectations are dictating that land disturbance is minimised, with affected lands returned to a condition that more closely reflects pre-mining land uses.
2. Mining companies are increasingly viewing mine planning in a holistic manner, with consideration given to risks, liabilities and costs over both the operational and post-closure life of the project. To minimise long-term environmental risks, and hence long-term costs and liabilities, whole-of-life mine plans will increasingly look at integrating the options for operational and post-closure management of mine wastes, e.g. some wastes stored in above-ground facilities, others in underground repositories.

In the future, voids will be seen as containment cells for mine and non-mine wastes. Mine wastes will be characterised during the life of the mine and assessments of the most appropriate, final containment location will be made earlier in the life of the mine. Decisions will emphasise the long-term survival of covers over geomorphological timeframes and placement of ‘problematic’ wastes in underground repositories wherever possible.

In circumstances where it is not economic or practicable to return mined voids to pre-mining land uses or viable pit lakes, placement of non-mine wastes such as domestic wastes/putrescibles will increasingly be in mine voids. An example of this exists at Bristol, United Kingdom, where a former open quarry has been converted to a landfill facility (Figure 10). In this instance, a conventional composite compacted clay and geomembrane liner was installed across the valley floor with wastes placed in containment cells.

Figure 10 Landfill liner installation as part of landfill construction in a former quarry, Bristol, United Kingdom (Breitenbach, 2008)

6 Summary

While high costs and the lack availability of wastes may preclude the backfilling of voids, there are nonetheless many drivers for backfilling. In underground mines, mine wastes are often returned to underground voids on the basis of economic and engineering considerations. In open pit operations, backfilling is often only cost-effective and feasible where it is considered during the operational (or earlier) phase of the mine and is driven by cost-savings (e.g. removing the requirement to construct a new tailings storage facility), regulatory requirements, managing long-term environmental risks, e.g. predicted potential poor quality water within a pit lake, and/or closure objectives which aim to achieve an agreed post-mining land use.

There are many different approaches to backfilling of mine voids. The method and nature of waste deposited will determine the geotechnical and geochemical properties of wastes and their long-term behaviour. This behaviour will in turn influence the manner in which solutes are released, the geotechnical stability of in-pit materials and settlement of final landforms. Understanding these behaviours is critical in predicting the long-term impacts to downstream water and ecosystem receptors, changes in water quality in-pit lakes and stability and erosion of final landforms.

Backfilling is increasingly seen as ‘best practise’ for mine closure rehabilitation and an important aspect to whole-of-mine planning. This is because long-term management of environmental risks and return of land to an acceptable post-mining land use can in some circumstances only be achieved by pit backfilling.

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Lessons learned from pit lake planning and development

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Abstract

Surface mines that extend below the water table often produce pit lakes after mine closure regardless of the type of ore being mined. The knowledge to addressing pit lake risks differs between mining industries and may be proportional to the duration of mining activity within a region. For example, the coal mining industry has over a century of experience developing pit lakes in the United States and Germany and considerable knowledge of pit lake restoration. By comparison, the metal mining industry in the western United States has less than three decades of experience developing pit lakes and the oil sands mining industry in Canada has not yet developed the first pit lakes in that region. Although each pit lake will be a unique geochemical system, enough similarities exist between pit lakes to allow companies developing new open pit mines to benefit from lessons learned from pit lake development at other mine sites. The following lessons will help mining companies minimise risks associated with future pit lakes:

1. *Use a risk management approach to minimise potential environmental hazards.*
2. *Characterise the mining environment before mining.*
3. *Avoid over-simplification of complex processes: expect each lake to be unique.*
4. *Prepare for the inevitable development of an aquatic ecosystem within the lake.*
5. *Know the site closure expectations of all stakeholders and regulators before mining.*
6. *Invest time in developing comprehensive conceptual models for each pit lake.*
7. *Predict the likely pit lake water quality and evaluate rehabilitation costs before mining.*
8. *Validate pit lake water quality predictions.*
9. *Have realistic expectations for the accuracy of predictive models.*
10. *Develop and cultivate an industry-wide culture of knowledge sharing.*
11. *Recognise that most pit lakes will discharge water to the surrounding environment and plan for offsite water quality effects.*
12. *Expect higher closure costs than initial estimates.*
13. *Set internal benchmarks for water quality before lake development, monitor lake water over time, and implement remediation activities if benchmarks are exceeded.*
14. *Seek sustainability by designing pit lakes that will become post-mining water resources valued by the public and/or future industries.*
15. *Budget for and perform decade-scale follow-up studies of post-closure pit lakes to quantify, demonstrate, and support the effectiveness of rehabilitation techniques.*

A series of questions derived from these lessons will assist mine managers in the planning of future pit lakes.

1 Introduction

Surface mining methods used in the coal, diamond, aggregate, oil sands, uranium, iron, base-metals, and precious-metals industries have similar impacts on mine site hydrology. If the open pit (also called an open cast or mine void) extends below the local water table, dewatering bores or sumps are required to lower the water table during mining in order to maintain a dry open pit. Provided that the surrounding aquifer is not entirely mined out, when mining concludes and dewatering activities cease, the water table will slowly rise towards the pre-mining level, filling the pit with water. Unless the pit is backfilled to above the steady-state water level, or evaporative loss greatly exceeds net water inputs, this process may result in a seasonal or permanent wetland or a pit lake depending on the maximum water depth once the steady-state groundwater level is reached. Pit lake closure is one facet of mine closure, and pit lake planning is most effective when developed as an integral component of the overall closure plan for a mine site.

The purpose of this chapter is to provide guidance on the design and closure of future mine pit lakes based on experience gained from the global mining industry. This chapter begins with a review of the global distribution of existing pit lakes, the regulatory and corporate expectations for pit lakes, and risks associated with existing pit lakes. The bulk of the chapter addresses lessons learned from the operation, remediation, and closure of existing pit lakes. The chapter concludes with a list of questions that mine managers should answer during the planning and design phases of future open pit mines. The knowledge gained from the answers will inform the design of future pit lakes and increase the likelihood that future pit lakes will meet corporate, regulatory, community, and stakeholder expectations.

2 Distribution, regulatory framework and terminology

Globally, pit lakes are common hydrologic features found in post-mining landscapes. Dr C. D. McCullough (written comm., 2011) notes the existence of 15 coal mine pit lakes in the Collie District of Western Australia. Shevenell et al. (1999) discuss 16 pit lakes resulting from precious-metal mining in Nevada, USA. Sánchez España et al. (2008) report on 22 pit lakes in the Iberian Pyrite Belt, Spain. Brenner et al. (1987) discuss the water quality of 60 coal mine pit lakes in Pennsylvania, USA. Yokom et al. (1997) note the existence of hundreds of iron ore pit lakes in Minnesota, USA. Geller et al. (1998) and Friese et al. (2002) observe that lignite mining in Lusatia, Germany has resulted in roughly 500 pit lakes.

Existing pit lakes provide mine planners with valuable insight on the likely behaviour and water quality of future pit lakes (Eary and Castendyk, 2009). During mine permitting, regulators may request a literature review of existing pit lakes within a given region, within a given climate, or situated within a similar ore deposit type as the proposed mine. Figure 1 provides an example of a regional survey of North American pit lakes situated above latitude 40° North that was compiled to provide guidance on the design of future oil sands pit lakes near Fort McMurray, Alberta. Published data was found for 18 pit lakes in this region.

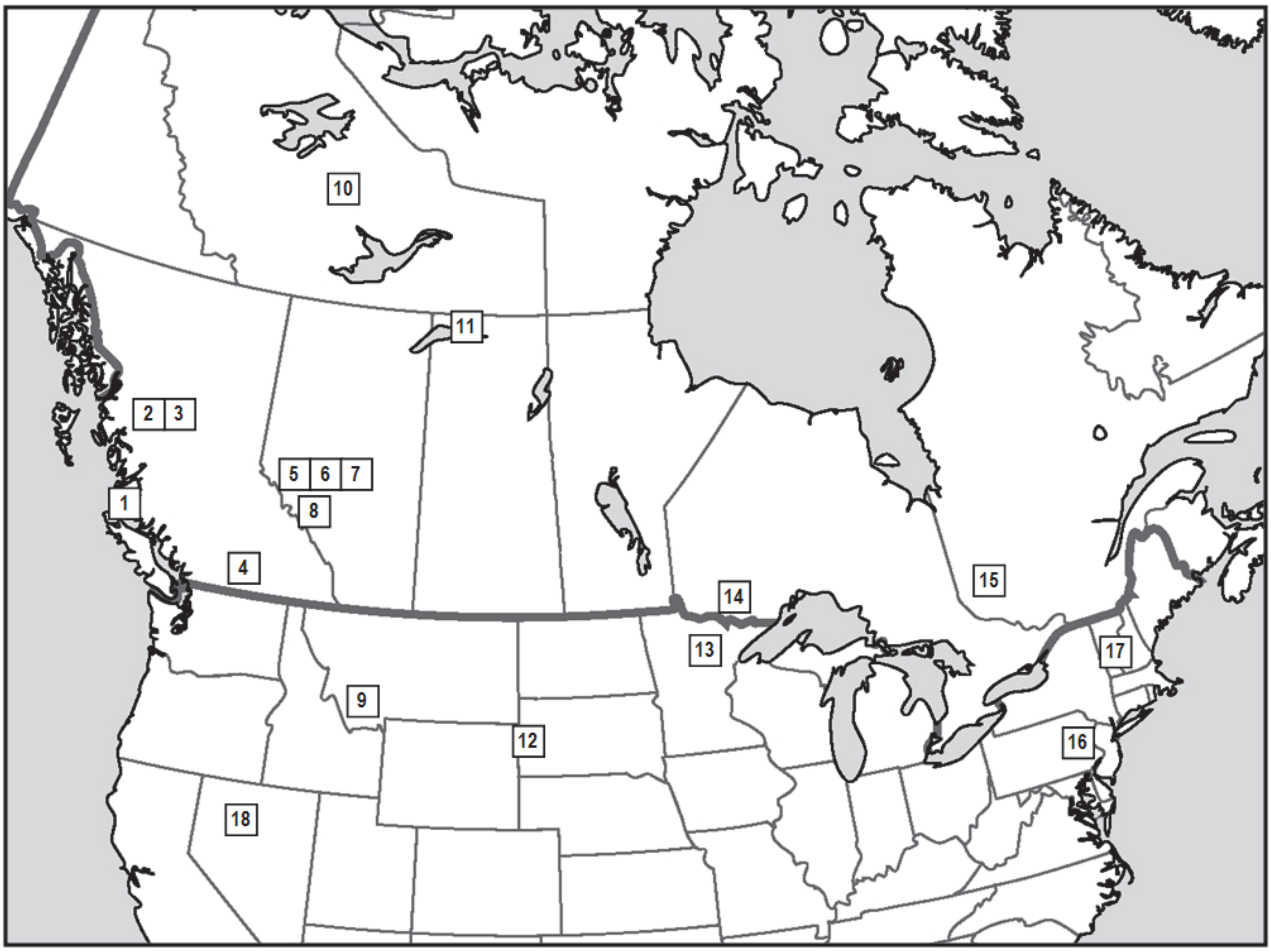

Figure 1 Map showing the locations of 18 North American pit lakes located above latitude 40° North. The name, commodity (italics), and reference for each lake follows: (1) Island Copper: *copper* (Pelletier et al., 2009); (2) Waterline: *zinc* (Martin et al., 2003); (3) Main Zone: *zinc* (Martin et al., 2003); (4) Brenda: *molybdenum* (Stevens and Lawrence, 1998); (5) Silkstone: *coal* (Luscar Ltd, 1991); (6) Lovett: *coal* (Luscar Ltd, 1991); (7) East: *coal* (Sumer et al., 1995); (8) Lac Des Roches: *coal* (Luscar Ltd, 1991); (9) Berkeley: *copper* (Gammons and Duaime, 2006); (10) Colomac: *gold* (Chapman et al., 2007); (11) Gunnar: *uranium* (Tones, 1982); (12) Anchor Hill: *gold* (Lewis et al., 2003); (13) Portsmouth: *iron* (Close et al., 2006); (14) Steep Rock: *iron* (Sowa, 2004); (15) East Sullivan Glory Holes: *copper* (Tassé, 2003); (16) Pond Creek: *coal* (Mase et al., 2008); (17) Elizabeth: *copper* (Seal et al., 2003); and (18) Sleeper: *gold* (Dowling et al., 2004)

In the United States, regulatory interest in the water quality of pit lakes began in the 1980s as a result of several factors: (1) new environmental legislation on surface water quality and coal mine reclamation, i.e. the Clean Water Act of 1972, and the Surface Mining Control and Reclamation Act of 1977; (2) the closure of several open pit metal mines in the western United States in the 1980s and the development of pit lakes on these properties; and (3) an increase in permit applications for new open pit mines on state and federal lands corresponding to rising metal prices and improved efficiency in ore recovery from bulk rock. In 1989, Natural Resources Canada established the Mine Environment Neutral Drainage (MEND) Programme to develop technologies to prevent and control acidic drainage resulting from metal, coal, and uranium mining in Canada, including open pit mining.

With the endorsement of the Minerals, Mining and Sustainable Development Report (MMSD) in 2002, members of the global mining industry formally established a precedent for attempting to engineer pit lakes into usable post-mining resources wherever possible (MMSD, 2002). Several pit lakes have now been designed to facilitate and enhance specific uses including the storage of mine waste, the storage of water supplies, recreation and tourism, ecological habitats, aquaculture, enhanced metal recovery, and scientific research (Gammons et al., 2009; McCullough et al., 2009). Four coal mine pit lakes in Alberta have been designed to support fisheries by reducing the slope of the pit walls, constructing a sufficient littoral zone, and introducing aquatic organisms from nearby streams (Luscar Ltd, 1991; Sumer et al., 1995).

The terminology used to describe phases of pit lake development varies from company to company, and region to region, which often causes confusion. In this chapter, "end-of-mining" is defined as the point in time when dewatering processes are terminated and the open pit mine begins to fill with water. "Lake filling" refers to the phase when the elevation of the lake surface and the volume of water stored in the pit lake increases from year to year. "Hydrologic steady-state" describes the phase when annual lake inputs are balanced by lake outputs, and the volume and elevation of the lake remain relatively constant over time. "Flow through" pit lakes will begin to discharge water to adjacent surface water or groundwater systems after achieving hydrologic steady-state, whereas "terminal" pit lakes only lose water via evaporation. "Geochemical steady-state" refers to the phase when the water chemistry remains relatively constant over time. Finally, "certification" refers to the point in time when environmental regulators decide that the pit lake complies with pre-mining expectations, whereupon environmental bonds are returned and the mining company is released from further responsibilities.

The timing of certification will be decided by regulators based on lake performance and will most likely apply to the entire mine site. Ideally, the pit lake will behave as a self-sufficient, functional component of the surrounding ecosystem prior to certification. However, because this state may take decades to centuries (or more) to develop, regulators may provide certification sooner if a lake demonstrates the 'potential' for future environmental performance. For example, East Pit Lake in Alberta received certification in 1994, ten years prior to achieving hydrologic steady-state, based on its potential for establishing a recreational fishery (Sumer et al., 1995).

3 Risks

The mining industry defines a "risk" in terms of the "probability" that a recognised hazard will cause an impact, the magnitude of the "severity" of the impact, and the magnitude of the public reaction upon learning of the impact, called "outrage" (Lee, 1999). Risk management programmes reduce the probability of impact occurrence, reduce the severity of impacts if they occur, and assure stakeholders and the public that incidents and accidents will be swiftly addressed. The risk assessment process begins by listing all potential impacts and quantifying the probability and severity of each.

The most severe impacts associated with existing pit lakes are listed below along with examples where impacts have occurred. Although the probability that any of these impacts will occur at a future pit lake may be very low, mining companies need to demonstrate to stakeholders and the public that each of the following potential impacts have been addressed in order to minimise public concern:

1. Human fatalities resulting from drowning in a pit lake. The US Department of the Interior, Office of Surface Mining Reclamation and Enforcement (OSMRE, 2007) has recorded several drowning accidents at abandoned coal mine lakes in Virginia over the past 50 years. Two deaths have also occurred in coal mine pit lakes in Western Australia in the past 5 years (C.D. McCullough, written comm., 2011). McCullough and Lund (2006) list drowning as a significant risk associated with pit lakes.
2. Degradation of human drinking water resources due to surface and/or groundwater discharge from a pit lake. This has occurred near Jamestown, California, where arsenic-rich groundwater discharging from the Harvard Pit Lake has degraded the water quality of local aquifers (Savage et al., 2000).
3. Chronic and/or acute health injuries to terrestrial organisms utilising a pit lake as a temporary or long-term habitat, including risks associated with bioaccumulation up the food chain. Hagler Bailly Consulting Inc. (1996) and Woodbury (1998) report on acute injuries to migratory waterfowl using the surface of the Berkeley Pit Lake in Butte, Montana.

4. Chronic and/or acute impacts to aquatic ecosystems or livestock if surface water and/or groundwater originating from a pit lake enters downstream surface water. Above a specific lake surface elevation, water from the Berkeley Lake will flow into a shallow aquifer that discharges to a nearby stream. To avoid impacts to an adjacent aquatic ecosystems, the US Environmental Protection Agency has designated a “critical level” for Berkeley Lake which cannot be exceeded. The lake elevation will be maintained by pumping and treating lake water in perpetuity.
5. Acute impacts to terrestrial and aquatic organisms caused by the rapid degassing of H_2S, CO_2, or CH_4 resulting from the unexpected turnover of a meromictic pit lake. Murphy (1997) and Schultze and Boehrer (2009) question whether meromictic pit lakes could rapidly degas and cause impacts similar to the fatal 1986 limnic eruption of Lake Nyos, a volcanic crater lake in Cameroon (Halbwachs et al., 2004). Although incidents have not been reported at existing pit lakes, the risk of an incident prompted changes to the remediation plan for the Anchor Hill Pit Lake in South Dakota. In this case, the accumulation of high concentrations of dissolved H_2S in deep lake water required the discontinuation of sulphate-reducing treatment activities (Lewis et al., 2003).

This is not a comprehensive list of potential pit lake risks but rather a summary of observed impacts reported in the literature. Other potential risks include acute or chronic injuries to humans caused by swimming in a pit lake or consuming organisms that have contacted pit lake water, e.g. fish, waterfowl, deer, and adverse effects to crops caused by contamination of irrigation water resources.

Drowning and falling risks can be minimised by removing pit high-walls and establishing a gently-sloping littoral zone. The remaining four risks involve geochemical, hydrological, and limnological processes within the pit lake, and often require computer-generated, predictive modelling to evaluate risks in advance of mining. Gammons et al. (2009) and Castendyk and Eary (2009) provide comprehensive reviews of the processes influencing pit lake water quality, and discuss how this knowledge is used to develop predictive models. The reader is referred to these references for more information on these topics. Once predictions are generated and validated, mine managers can evaluate various options for lake development, water quality mitigation (if necessary), and post-closure lake uses.

4 Lessons learned

The global mining industry has decades of experience developing, remediating, and restoring metal, coal, uranium, and aggregate pit lakes. The following section describes key lessons for pit lake planners, mine managers, environmental consultants, and environmental regulators that can be gained from this knowledge base.

4.1 Risk management

Mining companies should use a risk management approach to minimise potential environmental hazards instead of a risk response approach. Companies using a risk management approach will identify potential hazards associated with pit lakes before they cause impacts, implement strategies to reduce the probability of an impact occurring, and develop response plans to minimise the severity of impacts. Lee (1999) describes how to quantify risks for sulphur-rich metal-mines. Strategies to address risks are explicitly stated in a risk management plan. This plan is updated regularly using information gained through monitoring and research programmes that change the estimated likelihood and severity of known risks and identify new risks. By comparison, companies using a risk response approach address risks after accidents occur, which often costs more money and undermines stakeholder confidence. The US Environmental Protection Agency requires mining companies to quantify risks associated with mining (Russell, 2010).

4.2 Characterisation

Companies should characterise the mining environment in advance of mining, including local climate, hydrology, geology, water chemistry, ecology, economy and community/indigenous views. Kuipers et al.

(2006) identified a high percentage of error between geochemical predictions of water quality at hardrock mines in the United States and observed water quality. They conclude:

> *"The lack of adequate geochemical characterization is the single-most identifiable root cause of water quality prediction failures."*

Mines should collect data throughout all stages of the mine life cycle, and use these data to forecast water quality and to validate and refine water quality predictions.

4.3 Over-simplification

Pit lakes are complex geochemical systems. Companies should expect this complexity and should expect each pit lake to be unique. Even adjacent lakes in similar bedrock receiving similar meteorological conditions can exhibit differences in water chemistry and limnology (Castendyk and Jewell, 2002; Schultze et al., 2010). To avoid unexpected outcomes, separate characterisation and hydrological, limnological, and geochemical prediction studies are strongly recommended for each lake.

4.4 Aquatic ecology

At some point after the end-of-mining, all pit lakes will develop an aquatic ecosystem (Lund and McCullough, 2011). This may be a simple ecosystem consisting of only photosynthetic algae or extremophile bacteria (Woodbury, 1998), or an advanced ecosystem that sustains fish communities. It is important for companies to recognise that lakes will not be sterile water bodies and that these organisms will modify lake water quality. In some cases, exotic pest species may colonise lakes or species may be deliberately introduced by community members without the mine's consent, i.e. fish stocking. Companies may be able to use this to their advantage by deliberately establishing a particular ecosystem suitable to survive in the predicted water quality. In some cases, the introduction of nutrients to the lake surface alone has stimulated the growth of phytoplankton and resulted in the improvement of lake water quality (Pelletier et al., 2009).

4.5 Expectations

During mine planning, companies should explicitly document the expectations of all stakeholders, including corporate sustainability objectives, regulatory requirements, and local community expectations for each phase of lake development, i.e. end-of-mining, lake filling, hydrologic steady-state, geochemical steady-state, and certification. It is useful for companies to differentiate between expectations for in-lake water quality, lake-discharge water quality, in-lake aquatic ecology, and receiving environment aquatic ecology. This information will help establish performance targets during lake filling and guide the selection of mitigation and rehabilitation activities, if needed. During mine planning, planners should tabulate the concentrations of dissolved solids, especially potential contaminants and the aquatic and terrestrial ecosystem types required by regulators at hydrologic steady-state and certification. These same parameters should be monitored throughout lake filling to evaluate lake performance. To sustain positive public relations, it is equally important to ensure that any commitments made to community groups throughout the mine life are acknowledged and upheld. This includes commitments made by previous mine operators. Russell (2010) further details the need to understand the expectations of regulators, community members, and other stakeholders.

4.6 Conceptual models

Companies should invest time and other perspectives in developing a comprehensive conceptual model unique to each pit lake, and be prepared to update the conceptual model as needed over time. In predictive modelling, errors between predicted values and observed values are most often associated with errors in the conceptualisation of the processes involved (Anderson and Woessner, 1992). Companies should appreciate that the development and refinement of the conceptual model is one of the most time intensive components of predictive modelling (Bredehoft, 2005). Moreover, major changes to the mine plan after a prediction is generated typically require updates to both the conceptual model and the prediction (Castendyk and Webster-Brown, 2010).

4.7 Predictive modelling

In advance of mining, companies should predict the likely pit lake water chemistry and evaluate closure costs based on these predictions. Numerical models provide a useful tool to predict pit lake water quality during lake filling in advance of mining. This typically involves separate models of groundwater hydrology, lake water balance, physical limnology, and lake geochemistry. Castendyk and Webster-Brown (2006, 2007a, 2007b) demonstrate how pit lake predictions can also be utilised to evaluate cost-effective remediation strategies to identify strategies that provide the “biggest bang for the buck.” Their sensitivity analysis of a geochemical prediction for the future Martha Gold Pit Lake in New Zealand showed that covering acid generating wall rocks exposed above the lake surface caused a significant improvement in water quality. By knowing the post-mining water chemistry, mine managers can make realistic estimations of closure costs in advance of mining and budget for these expenses accordingly.

4.8 Prediction validation

Companies need to validate water quality predictions using direct observations, laboratory-based models, existing pit lakes, natural lakes, and other methods. The standard approach used to validate a predictive model is to compare predicted data to observed data, and to adjust the model until it consistently reproduces observed data (Anderson and Woessner, 1992). Werner (2009) and Oldham et al. (2009) provide examples of this approach where predicted pit lake water quality was directly compared to lake observations. In advance of lake filling, modellers can compare predicted water chemistry to the observed water chemistry of pit lakes existing in similar ore deposits. The INAP has developed a global pit lake database to facilitate such comparisons, available at http://pitlakesdatabase.org. Eary and Schafer (2009) describe several additional strategies to check the accuracy of prediction models. The modeller should use the validation procedure to quantify the degree of confidence in the model prediction.

4.9 Expectations

Companies and regulators should adopt realistic expectations for the accuracy of long-range predictive models. Companies and mine planners can expect geochemical predictions to provide a likely range of dissolved concentrations that will exist in the future. This information is useful in risk assessment and mitigation cost analysis. However, it is unrealistic to expect predictive models to provide the exact concentration of a given contaminant of concern decades after the end-of-mining (Eary and Castendyk, 2009).

4.10 Technology transfer

Companies should work together to develop an industry culture of technology transfer that enables the sharing of data and best-management practices. Such cooperation can minimise impacts industry-wide, reduce redundant research efforts, and improve the overall public image of the industry as a whole. Multiple collaborative technology transfer organisations have operated in the metal and coal mining industries for the past two decades, such as the Global Alliance (GA), the INAP, the International Mine Water Association (IMWA), the MEND in Canada, the Acid Drainage Technology Initiative, Metal Mining Sector (ADTI-MMS) and Coal Mining Sector (ADTI-CMS) in the United States, and the Australian Coal Association Research Programme (ACARP). These organisations reduce industry costs by reducing redundant research performed within the same mining sector and by collectively financing research into data gaps (Gallinger and Fleury, 2003).

4.11 Offsite impacts

Mine planners need to recognise that isolating pit lakes from the surrounding environment is only a long-term management option if evaporation is the only source of water loss from the lake. In most cases, surface water and/or groundwater will discharge from the lake, and offsite water quality effects need to be considered. The transportation of mine drainage away from mine sites into surrounding aquatic ecosystems via groundwater or surface water is widely recognised as the biggest environmental issue for the global mining industry (Savage et al., 2000; Younger, 2002; Kuipers et al., 2006). It is therefore important to characterise the surface and groundwater hydrology of the future pit lake, to define flow paths leaving the pit lake, and to identify aquifers and surface water bodies that will ultimately receive pit lake discharge prior to lake filling. It is equally important to predict the water quality of lake discharge, and if necessary, develop active or passive treatment systems to mitigate water quality before the drainage enters the receiving environment. The water quality and aquatic ecology of the receiving environment should be characterised prior to mining and routinely monitored during lake filling, hydraulic steady state, and geochemical steady-state phases.

4.12 Closure costs

It is prudent for mine planners to anticipate higher closure costs than initial estimates. Van Zyl (2010) notes that mining companies have a history of underestimating the full costs associated with mine closure during the planning phases of mine development. In some cases, perpetual water treatment systems may be required to meet certification criterion. For example, to maintain lake elevation below the “critical level” specified by the US EPA, managers at the Berkeley Lake, Montana are required to pump and treat lake water in perpetuity. It is unlikely that the cost of this treatment was considered during mine planning.

4.13 Benchmarks

Prior to lake filling, companies should establish internal benchmarks for water quality and ecological structure over time, monitor the development of lake water quality and ecology, and be prepared to modify the lake closure plan if necessary. Predictive models can be used to determine the likely trajectory, or trend, of water quality development in a pit lake over time. Lakes that develop along a ‘healthy’ trend are unlikely to exceed the closure guidelines, called maximum concentration limits (MCLs), for contaminants over time, whereas lakes developing along an ‘unhealthy’ trend are likely to exceed MCLs for one or more contaminant at some point in the future. By defining these trends, companies can establish internal ‘benchmarks’ for healthy lake development, and ‘action levels’ for unhealthy lake development in advance of lake filling. During lake development, if monitoring data show that a given contaminant exceeds an action level, the company can modify the lake management plan to include remediation measures that will reduce the likelihood of exceeding the MCL. These plans can be directly incorporated into the risk management plan for the pit lake and assure stakeholders that a proactive plan for risk avoidance is in place. Using benchmarks requires a well-defined monitoring programme with short time intervals between sampling events, predictive geochemical modelling during lake filling, and a flexible lake management plan that can be modified if needed.

4.14 Sustainability

Companies should seek sustainability by developing pit lakes into post-mining water resources valued by the public and/or future industries. Ideally, pit lakes should become an integral part of the surrounding landscape. This is the goal of the global mining industry (MMSD, 2002), as well as the expectation of regulators and community members. Moreover, the successful development of several open pit mines into pit lakes with post-closure value has established a precedent for the post-mining use of pit lakes globally (McCullough et al., 2009). Companies may be able to shorten the time required to establish a useful post-mining resource by designating a particular use for a pit lake in advance of the end-of-mining and engineering the lake to support this use. McCullough et al. (2009) provide multiple examples where usable pit lakes have been established, particularly in low-sulphur coal, aggregate, and iron mines. It is important to note that not all pit lakes have the potential to be useful post-mining resources on account of poor water quality, an example being pit lakes in porphyry copper deposits and massive sulphide deposits.

4.15 Post-audits

Companies should budget for, perform, and disseminate decade-scale follow-up studies of pit lakes to quantify, demonstrate, and support the effectiveness of rehabilitation techniques (also known as proof-of-concept). Such long-range studies, sometimes called "post-audits," are typically not performed due to a lack of funds or incentive, or if they are performed, the findings are poorly disseminated such that the mining industry as a whole cannot learn and benefit from the experience. However, such studies are essential to validate the effectiveness of closure techniques proposed at new mine sites. Mining companies may wish to perform their own post-audit of another company's pit lake if similar closure strategies are proposed, or if similar environmental conditions are predicted to exist. Contemporary post-audits will demonstrate whether or not a given closure strategy 'worked', thus reducing a company's reliance upon older, possibly outdated, information gathered during the pit lake planning process.

4.16 Summary

Table 1 summarises the 15 lessons learned on the development of future pit lakes derived from 30+ years of pit lake experience in the global mining industry. Ideally, most of these lessons will be considered during the planning phase of mining before surface excavation begins. Proactive consideration allows the results of each analysis to be integrated into the mine plan, and allows the costs associated with closure and certification to be factored into initial profit estimates for the mine.

5 Questions to answer during lake planning

From the consideration of pit lake risks and lessons learned from existing pit lakes, a list of questions can be generated about future pit lakes that should be addressed during mine planning and before the end-of-mining. These questions are listed in Table 2 under five categories: lake use, water quality, hydrology, limnology, and lake ecology. Owing to the site specific nature of existing pit lakes, it is important to answer these questions for each lake individually even though some similarities will exist between lakes. The answers to these questions will aid the design of pit lakes that meet company, regulatory, and public expectations, and minimise the need for unexpected remediation efforts.

6 Conclusion

Pit lakes constitute one of the largest potential environmental legacy issues associated with the closure of surface mine sites. Within the mining industry, there is a wealth of knowledge on the prediction, development, remediation and sustainable management of existing pit lakes. The 15 lessons learned presented in this study will minimise the risks associated with pit lake development and will increase the likelihood of developing pit lakes that are valued post-mining resources. These lessons will have the greatest effect if they are considered by mine managers, planners, and engineers during the planning phase of mine development, before pit excavation begins. Experience suggests that these lessons should be revisited throughout the mine life, especially prior to the end-of-mining and the flooding of the open pit. Mine managers should implement studies to address each of the lessons and questions discussed herein, and should be willing to adapt the mine closure plan to reflect new findings from ongoing investigations, predictive modelling results, proof-of-concepts from existing pit lakes, and mitigation innovations.

Table 1 Lessons learned from the development of pit lakes

No.	Lesson
1	Use a proactive, risk management approach to minimise potential environmental hazards instead of a reactive, risk response approach.
2	Characterise the whole mining environment in advance of mining, including local climate, hydrology, water chemistry, ecology, communities and economy.
3	Avoid over-simplification of complex processes: expect each lake to be unique.
4	Prepare for the inevitable development of an aquatic ecosystem within the lake.
5	Know the site closure and certification expectations of all stakeholders, including corporate sustainability objectives and commitments, regulatory requirements, and local community expectations, before designing the pit lake.
6	Invest time and other perspectives in developing a comprehensive conceptual model unique to each pit lake, and regularly update the conceptual model as needed over time.
7	Predict the likely pit lake water chemistry and evaluate closure costs using these predictions.
8	Validate water quality predictions using laboratory-based models, existing oil sands pit lakes, natural lakes, and direct observations.
9	Have realistic expectations for the accuracy of long-range predictive models.
10	Develop an industry-wide culture of technology transfer and best-management sharing to minimise impacts industry-wide in an effort to reduce redundant research and improve the overall public image of the industry.
11	Recognise that hydrologic pit lake isolation from the surrounding environment is not often a long-term management option: evaluate, plan and prepare for offsite water quality effects in groundwater and surface water.
12	Expect higher closure costs than initial estimates; in some cases, perpetual water treatment systems may be required to meet regulatory closure criterion.
13	Set internal benchmarks for water quality over time before lake development, monitor lake water over time, and be prepared to modify the lake development/management plan if necessary.
14	Seek sustainability by developing pit lakes into post-mining end uses valued by communities, integrated with the environment, and/or providing future economic opportunities, if possible.
15	Budget for and perform decade-scale follow-up studies of post-closure pit lakes to quantify, demonstrate, and support the effectiveness of rehabilitation techniques.

Table 2 Questions to ask prior to pit lake design

Category	Questions
Lake Use	What are the expectations for pit lake use(s), if any, held by the mining company, regulators and local communities?
	What potential lake uses, if any, will be required by regulators for lake certification?
	What is the projected water, soil, and land resource needs of the mining region for the century following hydrologic steady-state, taking into account the affects of climate change and human population growth?
Water Quality	What is the predicted annual chemistry of pit lake surface water over a sufficiently long time period (e.g. 50 years) following the end-of-mining?
	What are the principle contaminants of concern (COCs), and how have these been identified?

Category	Questions
Water Qual. cont.	What are the maximum concentration levels (MCLs) for acute and chronic impacts to aquatic ecosystems for each COC? What vectors (plants and animals) are likely to bioaccumulate COCs and move COCs up the food chain? What water quality criterion, including specific concentrations of COCs, will be required by regulators for certification and for the transfer of the lake to public custody? What is the monitoring programme for pit lake water chemistry, i.e. what parameters will be tested, how often, by whom, and from which lake depths, who will finance monitoring, and how many years after the end-of-mining will monitoring be conducted? What are the 'action concentration levels' for each COC which, if exceeded, will prompt additional mitigation by the mining company to avoid exceeding chronic and acute MCLs? What redox conditions best promote the sequestration and/or bioremediation of COCs over time, oxidising conditions or reducing conditions, and should these conditions be the same in each lake layer? If the pit lake is designed to be a 'bio-reactor' for any period of time, during or after lake filling, what specific chemical reactions/biological processes will organisms facilitate? Will waste rock or mine tailings be deposited in the bottom of the pit prior to lake filling? How will these materials influence lake water chemistry?
Hydrology	How many years will it take the lake to completely fill, beginning at the end-of-mining and ending at the achievement of hydrologic steady-state? What will be the final surface area, the maximum depth and the volume of the pit lake after reaching hydrologic steady-state? Will the hydrologic steady-state pit lake be a terminal or a flow-through lake? If the lake is flow-through, how much water will annually discharge from the lake on average, and what local aquifers and/or surface water bodies will lake water discharge into?
Limnology	Will the pit lake fully circulate on an annual basis or will it develop permanent or semi-permanent stratification? What is the expected depth of the summer epilimnion? What is the expected depth of the hypolimnion? Will the lake stratify during the summer and/or winter months? Are the epilimnion and hypolimnion expected to mix twice a year (during both the fall and the spring), once a year, or throughout the winter? What is the light extinction coefficient of the lake? Base on this parameter, what is the maximum depth and thickness of the littoral zone? Will the lake surface freeze during winter months? If so, how many months of the year will the lake remain frozen? If the lake is permanently stratified, what is the expected depth and volume of the bottom-most layer, i.e. the monimolimnion? What dissolved gasses are likely to accumulate in the monimolimnion over time, such as CO_2, H_2S, and CH_4? What is the likely water quality of the monimolimnion? If the lake is meromictic and generally stratified, what meteorological conditions (i.e. wind speed) would be required to fully mix the lake, and how frequently do these conditions occur? What is the density and size of a wall-rock landslide needed to fully circulate the water column? How frequently are landslides of this magnitude expected to occur? Does the mining company wish to induce permanent stratification with the intention of utilising monimolimnion water for the disposal of mine wastes? If so, what is the density of the fluid portion of the waste and is it denser than the monimolimnion water? How will the addition of the waste affect lake stratification and the depth of the hypolimnion/monimolimnion boundary over time? How will changes in lake stratification be monitored?

Category	Questions
Ecology	What aquatic ecosystem structure is desired for the pit lake? What is the monitoring programme for pit lake ecology, i.e. what parameters will be tested, how often, by whom, and from which lake depths? Who will finance monitoring? How many years will monitoring be conducted? What percentage of the lake surface area will function as a littoral zone, and will this be sufficient to support the desired ecosystem? What slope grade and vegetation community should surround the lake? Will any constructed features be added to the lake to promote aquatic habitats? What are the nutrient (nitrate and phosphate), temperature, salinity, and dissolved oxygen concentrations expected in epilimnion and hypolimnion waters? What are the nutrient, temperature, salinity, and dissolved oxygen requirements of the desired lake ecosystem? Do any parameters need to be artificially manipulated to generate or sustain the desired ecosystem? Will the turbidity of lake water be low enough to enable the growth of plants in the littoral zone? Will the toxicity levels of any COCs impair ecosystem development or bioaccumulate up the food chain? If the lake is meromictic, the habitat for cold water fish will be restricted to water between the warm epilimnion layer and the anoxic monimolimnion layer. Will this hypolimnion layer be sufficiently large to sustain the desired fish species? During ice covered conditions, what is the potential that dissolved oxygen levels will drop below 2 mg/L resulting in “fish winterkill” of cold water fish species, as discussed by Doudoroff and Shumway (1970) for fish in northern regions? If the lake is intended to be used as a bio-reactor during or after lake filling, what organisms will participate in modifying water quality and what environmental conditions are needed for these organisms to effectively treat water quality, i.e. nutrient levels, salinity, turbidity, and redox conditions?

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What type of lake do we want? Stakeholder engagement in planning for beneficial end uses of pit lakes

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Abstract

Although current mine management strategies often include the progressive rehabilitation of pit lakes into public amenities, experience with the adverse outcomes at historic pit lakes creates anxiety and scepticism among stakeholders. Inclusive, equitable and transparent stakeholder engagement and decision making processes rebuild trust and lead to consensus-based objectives for pit lakes. They are also useful for bringing engineers and scientists together with stakeholders at the beginning of the design process, this increases the probability of a truly sustainable pit lake. Stakeholder engagement must reach out to all stakeholder groups. Stakeholder mapping to identify high-impact, high-influence individuals should be an early activity. These high-impact, high-influence individuals can then form the nucleus of the engagement programme. Traditional and cultural values of local communities (including Aboriginal communities) must be understood and woven into the discussion and identification of options for end use of the pit lake. These options can then be analysed using decision making processes such as structured decision making (SDM). SDM is a step-by-step framework for a carefully organised analysis and selection of options. Key SDM concepts include making decisions based on clearly articulated fundamental objectives, dealing explicitly with uncertainty, and responding transparently to legal mandates and public preferences or values in decision making; thus, SDM integrates science and policy explicitly. Examples of the use of fully integrated stakeholder engagement and decision processes are rare. Effective engagement with stakeholders requires a significant commitment of time and resources, but the rewards for this commitment include constructive participation in planning and implementation of strategies for pit lakes, reduced costs, fewer delays and, ultimately, acceptance of the pit lake project.

1 Introduction

Pit lakes are a common feature at mine sites throughout the world. Until fairly recently, most of these pit lakes were allowed to flood and develop on their own, with little or no intervention. More recent pit lakes (over the past 20–25 years) have had varying degrees of engineering and biogeochemical design applied to their commissioning, monitoring and management (Schultze et al., 2011). A review of the mining industry's experience with the creation of beneficial end uses for pit lakes illustrates that it is possible to achieve at least some level of consensus among regulatory agencies, local Governments and stakeholders (McCullough et al., 2009). However, McCullough et al. (2009) point out that the documentation of the processes and approaches used to achieve consensus around beneficial use is often missing or inaccessible. Thus, opportunities for learning from others' experience have been very limited.

The broader literature on stakeholder consultation and engagement contains relevant guidance and offers some food for thought for companies planning to embark upon stakeholder consultation and engagement in closure planning, including planning for end pit lakes in the post-closure landscape. This chapter uses examples from the literature as well as experiences of the author in western and northern Canada to illustrate how public consultation and engagement can contribute to successful planning of sustainable pit lakes.

2 The usual practice

The most common inclination among mining companies when embarking upon a planning process for pit lakes is to gather together a group of engineers and scientists (Charette and Wylynko, 2011). This group may be given a set of known or assumed regulatory requirements or constraints. There may also be some sense of public expectation gleaned through public consultations conducted during environmental impact assessments or via the company's ongoing public consultation programme. The engineers and scientists are then asked to develop a conceptual plan for the pit lake, to be followed by increasingly more detailed engineering specifications. The risks and benefits of alternative pit lake designs are then analysed and a decision is made, usually driven by cost and risk management (especially long-term liability risk). Any role played by regulatory or public expectations up to this point is via internal translation of those expectations by company staff or consultants.

Public consultation often starts after the company already has made a significant commitment to the design. The inclination is to focus on education of the public regarding the merits of the chosen design. The scientists and engineers involved in the design are on a mission to inform and explain – to overcome ignorance and convince the public and regulators of the logic that contributed to the pit lake design. This means that the consultation falls into a type that relies more on one-way communication.

The focus on informing has been viewed as a more immature form of participation, e.g. it is the third rung on Arnstein's (1969) 8-rung "ladder of participation" (Figure 1). However, as Reed (2008) observes, different levels of engagement are likely to be appropriate in different contexts, depending on the objectives of the work and the capacity for stakeholders to influence outcomes. The "wheel of participation" may be a more useful model for typing the usual practice (Figure 2). There is no hierarchy of participation in Davidson's wheel model; rather, the wheel can be used to plan the appropriate level of community involvement to achieve clear objectives, without suggesting that the aim is always to climb to the top of the ladder.

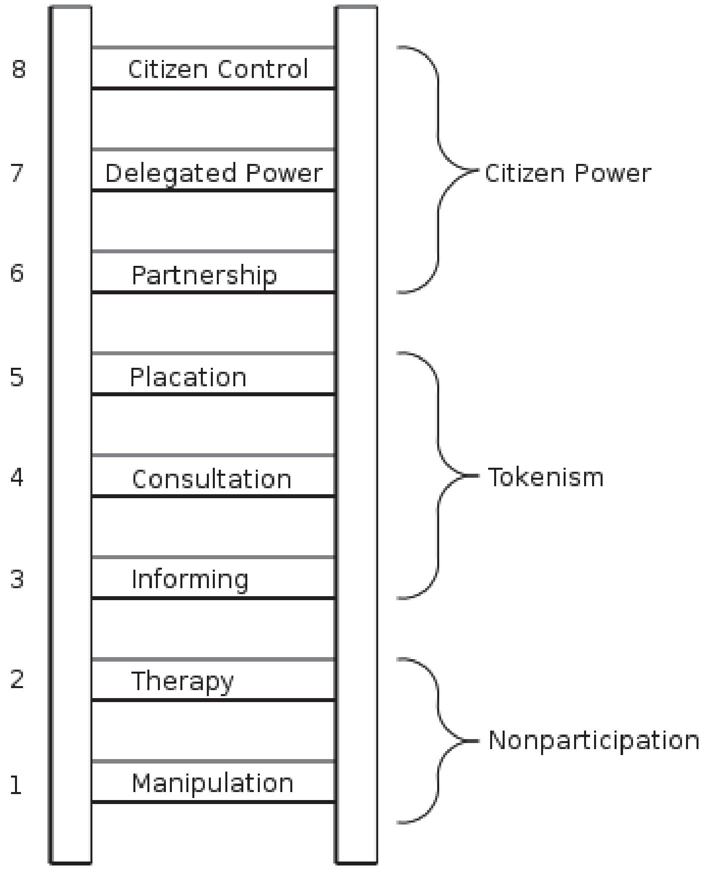

Figure 1 **The ladder of citizen participation (Arnstein, 1969)**

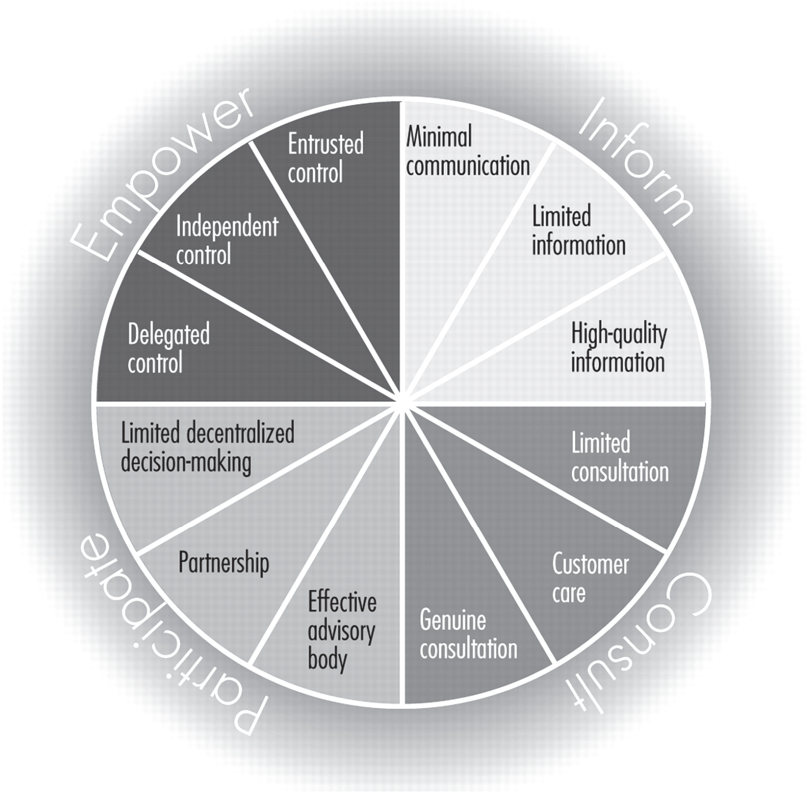

Figure 2 **The wheel of participation (adapted from Davidson, 1998; cited in Heritage and Dooris, 2009)**

Providing good quality information which the community wants and needs certainly can be valuable part of a participation programme; however, if most of the information regarding the design of pit lakes is provided after much of the design work is complete, there may be significant disconnects between the company's preferred design and the needs and requirements of regulators and the public. There can be a significant loss of time and money if the disconnects are serious enough to require a re-design.

Published examples of the advantages of advance consultation are rare. However, one of the best examples dates back to the 1970s in the Rother Valley, United Kingdom, where a joint committee of five counties established a community consultation programme to provide input into the design of a park to be developed after the cessation of open cut coal mining (Figure 3). The rehabilitation and restoration achieved four lakes with adjacent open land with a variety of recreational uses, habitat for plants and wildlife and a flood control system. The Rother Valley example "incorporates many of the features of the world's best practice rehabilitation such as early planning, community involvement, strong local council involvement, a long time frame for the development, and commitment from all of the parties involved in the closure process" (McCullough et al., 2009).

Figure 3 **Sailing at Rother Valley County Park, United Kingdom**

Despite successful initial planning processes that involve multiple stakeholders, the final concept for a pit lake may be a significant departure from what was originally envisaged; therefore, engagement does not guarantee lower costs and/or shorter timelines. For example, the operators of the Golden Cross Mine in New Zealand established a peer review panel and a Community Consultation Group consisting of a broad cross-section of regional regulators, environmental groups, professional peer reviewers, local residents and Maori traditional owners. The closure plan centred on ensuring that water quality was sufficient for possible recreational use and possible commercial trout fishing. The final rehabilitation resulted in the site becoming a wetland and native animal habitat as well as being used for grazing and recreational purposes. The final concept cost many millions more than allowed for in the original closure plan. "*The mining companies in this case..... decided that it was wiser to bear the extra rehabilitation costs rather than risk future environmental problems and the potential negative publicity associated with it*" (McCullough et al., 2009). The possible future environmental problems were not discussed by McCullough et al. (2009); however, concerns related to recreational and commercial fishing are often related to uptake of chemicals of concern into fish flesh. This uptake can lead to potential human health concerns via consumption of fish taken from the pit lake.

3 From information to dialogue and engagement – using more sections of the wheel of participation

The lessons from the "usual practice" have convinced many companies and organisations to move beyond informing and educating to having conversations or dialogues. Dialogue can lead to engagement. Engagement can reduce uncertainty within the company regarding the acceptance of pit lake plans and increase confidence in the investment in time and effort required (particularly if commitment to a pit lake plan adds to operational costs). Engagement also reduces uncertainty within regulators and the public because they have participated in key decisions leading to the final pit design and have gained knowledge about constraints and trade-offs that are required to achieve a sustainable design.

Dialogue means an exchange of ideas or opinions. Implicit in this definition is the assumption of a free exchange of ideas, with no screening out of "illogical" or "emotional" issues.

Engagement is an interactive and iterative process of deliberation among citizens with the purpose of contributing meaningfully to specific decisions in a transparent and accountable way (Phillips and Orsini, 2002; cited in Powell and Colin, 2008). Engagement goes beyond dialogue – it requires true participation of all stakeholders who will have a say in agenda-setting and decision making. Engagement is a big leap from the usual practice because it takes companies, regulators and the public into shared decision making, with associated increases in real or perceived risk. Thus, it requires a substantial shift in thinking on the part of all participants in the process.

Regulatory agencies are often more constrained than industry when it comes to engagement because of a policy vacuum at the political level. For example, McCullough et al. (2009) point out that only a select few countries and regions clearly regulate end uses for pit lakes. If their agencies do not have a framework or boundaries for determination of acceptable end uses, regulators may be reluctant to be pulled into an open-ended engagement process. Furthermore, there are often several regulatory agencies with overlapping jurisdictions. For example, in Canada, federal, provincial, regional and local Governments all have varying degrees of jurisdiction with accompanying regulations related to water and its uses. Recently, there has been a move to watershed-level management, although the accompanying regulatory authority required to implement watershed management plans is often lacking. Thus, it is common that mining companies and the public are given no clear, prior advice on regulatory acceptability of end use options. This creates a reactive situation, where plans for pit lakes are developed and then submitted to various agencies (who often do not talk with each other) who make judgments as to whether the end use and accompanying design are acceptable. These regulatory judgments often are made with no public engagement beyond that already done by the company. This, in turn, creates a situation where there is scepticism within the public not only towards the company but also the regulators – reflecting the multiple disconnects that can occur without an inclusive and continuing engagement programme bounded by agreed-upon principles or policy frameworks.

In Canada, the lack of clear policy regarding pit lake end uses can be traced to a stalling of the evolution of water resource management policy and execution as well as a lack of policy for mine closure. In the 1980s, the dominant model was the product of negotiations and bargaining between regulators and industry based on debatable scientific information (Johns and Sproule-Jones, 2009). By the 1990s, Governments also began shifting to a broader range of more market-based instruments such as voluntary guidelines and financial incentives. Combined with a political shift away from environmental priorities and a focus on the economy by Governments at all levels, the development of next generation water policy slowed (Johns and Sproule-Jones, 2009). Meanwhile, there continued to be a lack of mine closure policy, regulations and procedures. In a review conducted for the National Orphaned and Abandoned Mines Initiative (NOAMI) in Canada, Cowan et al. (2010) noted the lack of clear policies regarding closure objectives, including for pit lakes. The authors called for a “design for relinquishment” approach rather than a “design for closure” that includes specifically when and why relinquishment is not acceptable to the regulatory jurisdictions.

In the midst of the lack of clear policy and regulation, the powers of Government agencies and industry are increasingly being contested. Demands for public participation in decisions related to water use are increasing. Engagement programmes that are merely “add-ons” to the traditional decision making approaches have proven to further marginalise and alienate stakeholders.

Engagement is also constrained by lack of knowledge of state-of-the-art rehabilitation strategies and pit lake management capabilities among regulators and the public (and often within companies). This is where the provision of information, as part of Davidson’s (1998) Wheel of Participation, can play an important role in an overall engagement programme. The transfer of knowledge to regulators and the public may help avoid the situation where mining companies are either reluctant to implement state-of-the-art pit lake designs or they need to incur the risk of liability in order for beneficial end use development to be approved by regulators (McCullough et al., 2009).

3.1 Getting started

3.1.1 Goals and objectives of the dialogue and engagement programme

The first task for anyone planning dialogue with the public about pit lake end uses is to establish the goals of that dialogue. There is a difference between the goal of giving the public a meaningful voice in deciding the end use of a pit lake and the goal of building trust in the company to make the most socially and environmentally responsible decision. The public will quickly sense which goal is the driver of engagement activities, even if not stated explicitly. A company may not be ready to give stakeholders a seat at the decision making table but may be ready to receive input and be transparent about how that input was considered. As engagement proceeds and trust increases, a more active role for the public may evolve.

The goals for a programme of public dialogue and engagement may grow out of guidance or requirements set by regulators or by industry associations. For example, the US EPA has identified four key conditions related to beneficial end uses for contaminated lands (US EPA, 2008):

1. Creation of a site reuse vision through community consultation.
2. A sustainable community involvement that is inclusive and driven by a community champion.
3. A process for monitoring outcomes.
4. A close liaison with regulatory authorities.

These conditions provide a useful framework for the development of goals for public engagement. The requirements of member companies in mining associations may provide another basis for the development of goals for public engagement. For example, the Mining Association of Canada (MAC) has developed a framework (MAC, 2008) for sustainable mine closure that includes the following requirements:

- Through consultation with Communities of Interest (COI), MAC members will:
    - Identify values that are important to COI and develop reclamation objectives that incorporate those values.
    - Evaluate a variety of potential end land uses that address the needs of users.
    - Establish finance and implement comprehensive closure plans that wherever practicable return mine sites to viable and diverse ecosystems that will serve the needs of post-mining use recognising that mining can permanently alter landscapes.
- Members will work with communities to develop the closure plan and strategies to mitigate the socio-economic impacts of mine closure and to help them develop plans for long-term economic development.

The objectives of a public engagement programme will differ with the stage of planning. First contact should be prior to or at least parallel with the first deliberations of scientists and engineers. The objectives of initial dialogue would be largely exploratory and could include: (1) identifying foundational values held by the stakeholders and any conflicts in those values; (2) achieving agreement on values held in common; and (3) developing the framework for continuing the dialogue that meets the needs of all participants.

3.1.2 Identification of key stakeholders

The identification of stakeholders to be included in the dialogue and engagement programme is a critical first step. Relevant stakeholders need to be analysed and represented systematically (Reed, 2008). There are various tools and approaches for stakeholder analysis available from the literature (Reed, 2008). The key to the successful use of such tools is a thorough understanding of the communities of interest. This understanding includes community history, values and aspirations. Understanding a community and its drivers requires a structured analysis that includes tools such as stakeholder mapping, formal community surveys, interviews, and reviews of community history. Company employees resident in the community provide a valuable reservoir of knowledge about the community; through their interactions with arts and culture organisations, sports teams, clubs, volunteer organisations and others they will be able to identify key opinion-leaders and people with the time and inclination to be involved in what can be a significant commitment of time and effort. Key regulatory personnel should be well-known to company environmental managers. There may need to be a targeted approach to Aboriginal groups since many of these groups will require a “Government-to-Government” relationship with no delegation of decision making authority to other members of their community. Notwithstanding this requirement however, best practice engagement should endeavour to include community members who are not the designated decision-makers and who may not subscribe to the views held by those decision-makers. These “dissenting” community members may comprise a substantial portion of the population. This point applies to both Aboriginal and non-Aboriginal communities.

Stakeholder analysis can identify the “high-impact, high-influence” people that should be involved in the dialogue and engagement programme. High-impact stakeholders can have a direct effect on company decisions, e.g. senior regulators or senior municipal officials who approve land use permits. High-influence stakeholders can affect or change opinions and attitudes because they have the trust and respect of the public and/or they are very skilled communicators and use the media effectively, e.g. the president of the most active service club in the community or the leader of the local branch of an environmental group.

Stakeholder analysis will also ensure that the range of interests and perspectives within the community are represented. Interests common in any community such as education, health and amenities should be included as well as those relevant to pit lake planning, e.g. recreation, conservation, and water supply. In addition, stakeholders with direct connection to the closure landscape, e.g. adjacent landowners, should be identified. Local demographics should be considered and reflected as much as possible. In an exercise that led to a plan for an urban river restoration, Petts (2007) focussed on recruitment of participants who were potentially gatekeepers in the community, i.e. people who through their own interests, activities or work had access to and engaged with, others in the community. The gatekeeper mechanism proved to be effective in spreading learning through the community via the social interactions of the gatekeepers. This mechanism also helped counter fears that small group processes bring only particular voices to the table.

The high-impact, high-influence individuals (or gatekeepers if the Petts approach is preferred) can form the nucleus of the dialogue and engagement programme but they may not always be the sole participants. The programme will develop and evolve as the pit lake design and rehabilitation programme progresses and the needs of the programme for input from specific stakeholders changes. For example, as the programme moves from the conceptual stage to more detailed design, the emphasis may shift to consultation with user groups with experience and expertise in specific topics, such as recreational fishing groups with expertise in the types of shoreline habitat required for successful spawning and rearing of desired fish species. The stakeholders themselves may suggest a change, particularly since the time commitment for involvement in these programmes can be significant. Furthermore, it is very important that suggestions for participants be solicited by the company from community representatives. Otherwise, the programme may be viewed as biased from the outset, consisting of hand-picked individuals.

3.1.3 Identifying and addressing the barriers to engagement

In many communities, the past history of the mining industry, with its legacy of closed and un-reclaimed properties and general lack of public engagement has created a level of distrust and cynicism that can be difficult to overcome. There may be longstanding and entrenched bad feelings among different stakeholders, so much so that they may refuse to have anything to do with an engagement programme that would require them to interact with people with whom they have had serious disagreements. In some cases, unfortunately, the mining company's own stakeholder interaction methods may have contributed to these bad feelings – pitting groups against each other and leading to an "us versus them" mentality. This is particularly true in communities where mining is a significant contributor to the overall economy, and thus the stakes are high.

If a history of division and bad feelings is present, there may be little to be gained in embarking on group stakeholder activities until some significant groundwork has been accomplished with the key stakeholders. On the other hand, group engagement processes can gain traction given sufficient time and skilled facilitation. In either case, time and concerted and consistent effort are required. The team assigned with rebuilding a willingness to engage should consist of people with a talent for active listening without judgment. Most of the early interactions will be one-on-one and will often consist primarily of downloading grievances and issues. There needs to be a careful match between the people acting on behalf of the company and the stakeholders; preferably, the people doing the initial outreach should either reside in the community or be very frequent visitors. Experts in communication arriving in town for a few days and then leaving again will not be effective. The experts can be used to train and coach local people to be the front-line outreach team and to set up the standard approach and to design the documentation system required to track progress in overcoming the barriers to further engagement.

If there is sufficient goodwill to embark on the group dialogue and engagement activities, other barriers will need to be recognised and addressed. Engagement activities sponsored by an important employer may create a power imbalance that is difficult to overcome. For example, engagement and trust improved when Teck Coal (the dominant local employer) stepped back from its engagement programmes dealing with issues created by the discharge of selenium to the Elk River watershed in British Columbia and delegated engagement to an arm's length advisory panel (Swanson et al., 2011). The local, front-line outreach team referenced above may be an effective approach to overcoming the power-based barriers to participation and engagement. Ideally, facilitation of the engagement programme will gradually evolve into a situation where a local leader can step in and take over the process.

A power imbalance can also be created via the over use of expert scientists and engineers in the engagement programme. While information will always be a vital part of the process, activities that are seen to be run by and/or dominated by experts will alienate many stakeholders. This is particularly true if the experts are poor communicators and/or do not have a genuine interest in and desire for effective engagement. Of course, technical experts will always be an important part of any engagement process because of the need for dialogue between experts and the community. However, a balanced engagement programme will be built upon the principle that diverse forms of public knowledge and social intelligence are all valuable and contribute to the common good. In other words, there are many kinds of experts – not just people with science or engineering degrees. If this principle is applied, there will be a much greater potential for full and long-term participation and, ultimately, buy-in to a common vision regarding the end uses of the pit lake.

One of the most serious barriers to true engagement is when a company (often without acknowledging this itself) embarks on an engagement programme not to empower citizens but instead to quell potential public resistance to and assure acceptance of its own vision for the pit lake. If the aim is to build acceptance rather than to generate open debates or have actual impacts on decisions, genuine public engagement may not be desirable and a different strategy will be required.

3.2 Setting the stage for successful dialogue and engagement

There are many examples of attempts at dialogue regarding scientific or technical issues (including pit lake design), but fewer examples of successes. What often happens is a tightly moderated event with expert presentations on a raised stage with minimal public input or dialogue before, during or after the event. Another variation on this theme is the Open House, where the public are invited to ask questions of people manning information booths. People are often given the opportunity to submit written questions or comments in a suggestion box. Open Houses are at least an improvement on lectures because they are more interactive; however they are still primarily about informing the public rather than hearing their suggestions or empowering them to have impacts on decisions (Powell and Colin, 2008). The public attending these events is unlikely to feel that their views have been heard and respected unless there is clarity regarding what will be done with the questions and opinions submitted during the Open House. Any dialogue event that is highly structured and short-term is unlikely to contribute to the empowerment of the public or to a higher level of trust.

Hands-on events such as field tours and workshops are more likely to build engagement and understanding (Figure 4). Viewing existing pit lakes and touring current mine operations can increase greatly stakeholder's understanding of the nature and extent of the pit lake planning process as well as an appreciation of some of the constraints created by natural physical, chemical and biological features and processes.

Figure 4 Stakeholder meeting at Lake Stockton, Collie, Western Australia (Photo courtesy of C.D. McCullough)

Dialogue and engagement activities that are co-designed and co-organised with citizens have a greater probability of long-term success. The key stakeholders, if identified correctly, will have a natural tendency to contribute their own ideas and are often quite willing to participate in sub-committees that ensure momentum, participation, and results. A broadly based, grass-roots organisation that already exists in the community may be an excellent place to start – particularly if it shares some of its vision and goals with the company's goals for a sustainable closure landscape. An example of such an organisation is the Elk River Alliance (ERA), based in the Elk Valley of southeastern British Columbia – home to the employees of several metallurgical coal mines run by Teck Coal, as well as the home of passionate advocates for the conservation and enhancement of the Elk River and its watershed. It is worth noting that many of the coal mining employees are themselves passionate advocates of the environment and Teck Coal is one of the sponsors of the ERA. The ERA started as a project of a regional environmental group (Wildsight), but has developed into a truly multi-stakeholder group with active participation of industry, Government, and local citizens (www.elkriveralliance.ca/). It has the potential to be a highly valuable resource to decision-makers in Teck and in Government, its members include people with formal training in public outreach and education as well as sustainable development.

Traditional and cultural values of local communities (including Aboriginal communities) must be understood and woven into the discussion and identification of options for end use of the pit lake. Public engagement programmes can be a way to generate a shared lay and expert vision of the priorities for a pit lake closure plan. In the process of developing this shared vision, people inherently gain a better understanding of technical issues sufficient to identify which elements are negotiable and which are not. The aim is a balance between bringing public concerns and values into an expert discourse while making the technical accessible (Petts, 2007). Agreement on a set of physical and values-based criteria can increase the likelihood of ultimate acceptance and approval of a pit lake design. Physical criteria can include safe access, recreational opportunities, and a variety of habitats (lake and wetland). Values-based criteria can include natural, safe, tranquil, or interesting.

Capacity-building and succession planning are keys to effective engagement. The plans for pit lakes will evolve and change as technology develops and societal values change. Many years can pass between initial plans submitted during environmental impact assessments and the actual implementation at mine closure. The time, energy and resources required to build capacity and sustain that capacity within stakeholder groups should not be underestimated.

Figure 5 Sphinx Lake, Alberta – A pit lake designed and implemented by Teck Coal that includes littoral habitat that is 23% of total surface area and other habitat enhancements; the lake supports rainbow trout (*Oncorhynchus mykiss*) and bull trout (*Salvelinus confluentus*)

Public engagement in the design and implementation of pit lakes can be a mechanism for connecting sustainability and corporate social responsibility (CSR) commitments to actual on-the-ground innovations in mine closure. For example, the desires of stakeholders for fish habitat led to innovative approaches to the design and construction of fish habitat features and enhancements in Sphinx Lake, Alberta by Teck Coal (Figure 5). A stronger connection with the innovation agenda can produce tangible (and measurable) value, e.g. a technology for rendering pit lake water quality suitable for potable use, as has been demonstrated in Australia (McCullough et al., 2009). Such successes can help move public engagement and CSR from the margins, where they are often bolted on to the communications and public affairs departments, to a more integrated role in business strategy.

Dialogue and engagement processes can become an end in themselves, lacking the measurement and verification of the value they add to the business. The trade-offs between the effort expended by the company and the pay-off in increased certainty around mine planning and closure planning or in marketable innovations need to be clearly identified and measured. Tools for measurement of effective engagement can range from formal polling, informal polling during stakeholder meetings, tracking of time-to-approvals or permits, a decrease in the number of complaints received, or tracking income and profits from marketing innovative pit lake technologies. Internal tracking of the time and money spent versus results, e.g. in terms of reduction in regulatory risk, would be part of the measurement process.

3.3 Making decisions regarding pit lake design and implementation

If one of the goals of stakeholder engagement is to provide input to and participation in decision making, the engagement can be designed to contribute directly and explicitly to decision support systems and processes. One such process is structured decision making – a process endorsed by the British Columbia Ministry of Environment. Structured decision making (SDM) is an organised approach to identifying and evaluating alternatives that focusses on engaging stakeholders, experts and decision makers in productive decision-oriented analysis and dialogue and that deals proactively with complexity and judgment in decision making (Compass Resource Management, 2008). The SDM framework does not prescribe any particular decision analysis tool or model; rather, it provides an overall process within which decision analysis tools are applied. Key SDM concepts include making decisions based on clearly articulated fundamental objectives, dealing explicitly with uncertainty, and responding transparently to legal mandates and public preferences or values in decision making; thus, SDM integrates science and policy explicitly.

The explicit combination of a stakeholder engagement programme within a SDM framework helps ensure measurable results from the engagement effort. The choice of decision support tool will, in part, dictate how well stakeholder input can be incorporated into the decision analysis. Tools that are designed to handle values-based criteria and substantial uncertainty may be the most applicable. Collaboration between the company's public engagement experts and decision support experts will be vital to the selection of the most appropriate decision analysis tools. Participatory modelling can be a powerful tool that can enhance stakeholder's knowledge and understanding of a pit lake system and its dynamics under various conditions (Voinov and Bousquet, 2010). Participatory modelling is a generic term that includes a number of specific approaches and methods that all rely upon direct stakeholder involvement in the development of conceptual models and, in some cases, the decision models themselves. Thus, stakeholder involvement in a shared process of model construction is the backbone of the decision making process. For example, multi-criteria decision analysis (MCDA) may be the decision analysis tool chosen for use within an SDM framework for deciding on a pit lake design. Participatory modelling using MCDA would involve stakeholders in every step of building the MCDA model, including selection of the suite of alternative pit lake designs to be analysed, the criteria with which to judge performance of each alternative pit lake design, and the scoring system used to rank the alternatives. The advantage of incorporating participatory modelling in the MCDA is that stakeholders become engaged in the co-learning exercise, which helps to clarify and homogenise values among participants (Voinov and Bousquet, 2010).

Stakeholder participation can make the modelling process truly adaptive so that models can adequately incorporate new information and adjust to new goals driven by decision making and management needs.

Any decision support process must also consider the fundamental issue of fairness. A decision that is regarded as unfair, no matter how logically-based and scientifically defensible, will not gain wide acceptance by stakeholders. A study by Besley (2010) found that believing one receives a fair outcome is associated with support for the decision. Fairness is related to receiving a fair share of risks and benefits of the proposed facility or project. Besley (2010) found that procedural fairness was a dominant variable explaining the acceptance of a decision. Application of the work by Besley (2010) to decisions regarding pit lakes would involve ensuring that the decision process is viewed as fair and equitable.

3.4 The Ridgeway Mine case – an example of community engagement lessons learned

The ten-year life of Kennecott's Ridgeway Mine in South Carolina, USA covered a period where relationships within the local communities changed from one of mixed scepticism and outright opposition to one of mutual support and trust (Fox, 2003). This was achieved through the active engagement of mine opponents and local community groups. Consultation revealed that allowing the site to return exclusively to the native state of mixed forest typical of the area was considered to be a less desirable or productive outcome of the post mining land use for the local communities. Instead, Kennecott ensured long-term physical, chemical and ecological stability, including stability of the reclaimed tailings impoundment surface cover and created wetlands for surface water runoff management and control (Figure 6).

Figure 6 Wetland near the reclaimed Ridgeway pit lake (Photo courtesy of www.riotinto.com/sustainablereview/common/PDFs/Ridgeway.PDF)

Kennecott worked with a local group of educators who saw opportunities for the site to be developed as a facility to provide extracurricular outdoor activities for local school children. Accordingly, Kennecott signed a Memorandum of Understanding with the South-eastern Natural Sciences Academy with the vision to create a sustainable development environmental research and education centre.

Delivering on community commitments was an essential element in the development of trust. Kennecott was an active supporter of local education. The company also constructed a 6.44 km water main pipeline linking the mine site to the town of Ridgeway allowing local citizens the opportunity to connect to communal water supplies.

Fox (2003) outlined lessons learned during the Ridgeway public consultation and engagement process:

- Develop best practice principles and reporting criteria (indicators) well in advance of project implementation.
- Informed, transparent, inclusive and equitable decision making processes with all known stakeholders are needed well in advance of deciding project scope, budget and schedule, along with reclamation and closure objectives. This can be accomplished by establishing formal advisory committees for specific areas.
- The difference between short-term local community contributions and resultant benefits versus long-term sustainable development opportunities for local and regional communities are distinct and should be understood. Both bring good will and benefits to the communities, each having different objectives and outcomes.
- Regular active engagement with key stakeholders and information sharing is a key to community respect, trust, and ultimate acceptance of a project and company. There are many ways to accomplish this, including regular project updates and scheduled site tours.

- Traditional and cultural values of local communities need to be thoroughly understood and respected to be able to improve the wellbeing of people in the area of operations.
- Specific studies will be required that focus on the socio-economics and cultural values, including governance within local communities.
- Institutional arrangements are preferred (e.g. formal agreements) to improve the processes associated with stakeholder engagement, documentation and sign off, and the capacity of the local communities and Government to address the consequences of a project.

4 Recommendations for successful stakeholder engagement

The following recommendations for successful stakeholder engagement are adapted from Fox (2003), Wilsdon and Willis (2004), Powell and Colin (2008), Reed (2008) and experiences gained through the author's involvement with public consultation and engagement activities over the past 25 years. The author has adapted the recommendations where necessary to be more applicable to planning for pit lakes.

1. The company must decide what its motivations are for the engagement programme and what it will do with the results of the engagement programme. It must decide how much public input into its decisions about pit lakes it can accept and still meet its obligations and duties to its shareholders. This decision should be transparent and communicated clearly within the context of the company's declared commitment to sustainable closure principles (if such a commitment exists). The worst outcome would be one in which techniques for engagement are incorporated into the processes of decision making without changing the way that decisions are made. In this case, public engagement is no more than a box that gets ticked (Wilsdon and Willis, 2004).
2. The company's philosophy underlying its stakeholder engagement programme should be clear, ideally focussing on empowerment, equity, trust and learning.
3. Company representatives and their experts must be willing and able to engage with the public early and often, face-to-face and during longer periods of time than the few days required for typical engagement exercises. This will require substantial company support.
4. Key stakeholders need to be selected based upon a systematic analysis to ensure that there is adequate representation of the community and that high-impact, high-influence stakeholders (or gatekeepers) are included. The selection process should also identify vulnerable groups or those who may be outside of the power structure and decision making groups in the community.
5. Methods of engagement should be selected once the objectives of the engagement process are clear, the level of engagement appropriate to those objectives has been identified, and the key stakeholders have been identified. The level of engagement is a major factor determining the methods that are likely to be most relevant and effective (Reed, 2008). Methods must also be adapted to the decision making context, including socio-cultural and environmental factors. For example, depending on the power dynamics of the group, methods may need to be employed that equalise power between participants. A multi-method engagement process will help ensure that engagement reaches and includes a broad representation of the community.
6. The engagement process must be designed carefully to ensure that stakeholders experience it as fair and equitable.
7. Stakeholders should have a say in the goals and purpose for the pit lake, who will be involved as plans move forward, and what kind of decision processes will be used.
8. Engagement projects should be as open ended as possible. Companies must be willing to accept and be responsive to outcomes of the engagement project, not just the outcomes they want. If the motivation is to shut down debate about the pit lake design, then public engagement is not the appropriate approach.

9. Local and scientific knowledge should be integrated. Engagement must be based upon a broader understanding of “expert knowledge and analysis”, extending to the recognition of the legitimacy of traditional knowledge (Aboriginal as well as the general public’s), and social understanding. For example, there is a wealth of practical knowledge and experience regarding the value of the various uses of lakes and wetlands – although this knowledge may not be expressed in the same units as those applied by ecological accounting experts.
10. Engagement programmes should not focus solely on risk management, which produces an emphasis on how well we can quantify and manage risks associated with pit lakes and how we deal with uncertainty, but should also connect with the fundamental questions that motivate public concern. Why this design or technology for the pit lake? Why not another? Who will control the lake after the mining company is gone? Who will benefit from the lake? Can they be trusted? What will it mean for me and my family? Will it improve the environment?
11. The engagement process should include making a distinction between short-term local community contributions and resultant benefits and long-term sustainable development opportunities for local and regional communities. Each has different objectives and outcomes.
12. Public engagement should include capacity building and training among lay people as well as scientists and engineers. People do not necessarily know how to engage with each other and many scientists and engineers have no experience or training in communication with lay publics (other than in lecture mode).
13. Highly skilled facilitation is essential. The outcome of any participatory process is far more sensitive to the manner in which it is conducted than the tools that are used (Reed, 2008). Facilitating effective public engagement is highly skilled work and also involves considerable tacit knowledge gained only through experience.
14. Outcomes of public engagement programmes must be measured against criteria for value added to the pit lake planning and implementation process.

5 Conclusions

Stakeholder engagement can increase the quality of decisions made regarding pit lake design; however, the quality of decisions is strongly dependant on the nature of the process leading to them. There is substantial economic, social and environmental risk associated with poorly-supported decisions on pit lake design and end uses. By focussing on the process of public engagement and adoption of some recommendations based upon best practice, the risk associated with pit lakes can be reduced, leading to sustainable pit lakes in the closure landscape.

Effective engagement with stakeholders requires a significant commitment of time and resources, but the rewards for this commitment can include constructive participation in planning and implementation of strategies for pit lakes, reduced costs, fewer delays and, more confident decision making.

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Stella has owned and operated Swanson Environmental Strategies since 2007. The focus of her current work is the strategy behind management of environmental and social risk. Stella began her career with the Saskatchewan Research Council (SRC) where she first learned the importance of effective interaction with stakeholders during her research on the effects of uranium mining on the aquatic environment. After her move to private consulting with Beak Associates (now Stantec) in 1991, Stella became involved in multi-disciplinary research and monitoring programme that often involved extensive stakeholder consultation. Stella joined Golder Associates Ltd. in 1993 and became a Principal in 2002. During her time at Golder, Stella directed a group of risk assessment professionals who conducted human health and ecological risk assessments for a wide variety of clients. Stakeholder consultation and engagement (with associated risk communication) were important components of many of the risk assessments conducted by the Golder team.

Generating regional guidance for best practice pit lake closure and reclamation

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Abstract

The mining industry is required to operate in an increasingly demanding environment. Regulations are becoming stricter and public scrutiny is greater than ever. In response, more and more mining companies are collaborating in the management of environmental and cumulative effects. The mining industry in the Athabasca oil sands region of northeastern Alberta, Canada – which possesses a concentration of mineable oil sands – provides an apt example of this trend.

In 2000, the Cumulative Environmental Management Association (CEMA) was created by the provincial government to assess the cumulative impacts of oil sands development in the region. It is a multi-stakeholder group that includes representation from the provincial government, the mining sector, oil sands regulators, Aboriginal groups and non-governmental organisations (NGOs). CEMA is tasked with developing a number of regional cumulative environmental management best practices, and with advising the provincial government on cumulative environmental management in the Athabasca oil sands region.

This chapter describes a consensus-based model that CEMA has developed in order to provide general regional reclamation guidance for the oil sands mining industry. Although it was developed for this industry, the process and principles that were applied can be used in other industries to generate regional guidance. Components of the model include determining industry needs, achieving consensus among mine planners, closure planners and environmental reclamation teams, incorporating leading practices from researchers and regional and international experts, integrating lessons learned from ecosystem science and the broader reclamation industry, and obtaining peer acceptance. This model is discussed in the context of the development of a guidance document for end pit lakes in the oil sands region.

1 Introduction

Pit lakes in various forms are common legacies for the mining industry, in particularly hard rock and coal mines. At present, nine major oil sands mining projects are underway in the Athabasca oil sands region of northeastern Alberta, Canada, where there is a concentration of mineable oil sands. Several additional projects are pending regulatory approval. These projects are approved with the caveat that operators work toward demonstrating the viability of end pit lakes (EPLs) as a reclamation option and bioremediation tool. Operators are required to work collaboratively, through CEMA, on developing regional approaches and guidance for end pit lakes. Such collaborations in the management of cumulative effects are becoming more common internationally (Brereton et al., 2008).

In 2007, CEMA published an EPL Technical Guidance Document (EPLTGD) (Clearwater Environmental Consultants, 2007). Upon review, the Alberta Energy Resource and Conservation Board (ERCB) deemed the document unacceptable for use as regional guidance for the reclamation of oil sands EPLs because of a perceived lack of scientifically defensible information. CEMA commissioned 12 experts from academia and industry to undertake an exhaustive review of the document. Published in 2009 (CH2M Hill, 2009), the review concluded that the document was not acceptable in its current form. They found it contained unexamined assumptions and suffered from several shortcomings, including lack of references, technical and factual errors, an absence of certain important research, contradictory statements and overly general treatment of critical subject matter. The reviewers emphatically rejected one of the document's key underlying assumptions: that the oil sands EPLs are not comparable to pit lakes developed for other resource sectors. The review also indicated that the document contained insufficient content of practical use to the technical managers, planners and engineers who would constitute its intended target audience.

CEMA found that the failings of the 2007 guidance document were not attributed to shortcomings of the authors but as a failure of the authorship process to treat the subject in the necessary detail. The review recommended that a second document be prepared with sufficient resources for the immensity of the task. The Synthesis of Reviewer Comments on the CEMA EPLTGD (CH2M Hill, 2009) recommended an entirely new process, one more akin to a scientific study than a consultant report. The steps set out for developing a viable guidance document, slated for release in 2012, were as follows:

- Retain managing editors to oversee the development of the document and to work with the authors, reviewers, and the task group (see 2.1), and to edit and design the final product.
- Retain expert authors and expert peer-reviewers, and provide a forum for coordination and exchange of information across disciplines.
- Use the peer-review process to ensure quality control and to review draft chapters.

This process is not new. It draws on established techniques from the academic and research communities. But it is not commonly used to generate regional guidance for mine closure and reclamation. To that extent, embracing the recommendations represents a groundbreaking commitment to taking advantage of necessary expertise and to converting the knowledge of these experts into a quality guidance document on mine reclamation.

2 Principles for developing regional reclamation guidance

2.1 Selection of project team

The creation of a project team that is comprised of key personnel with a stake in the oil sands mining industry was critical to deriving a common suite of regional reclamation guidelines. The project team was created to develop the project approach and steer the project. The team members are familiar with regional oil sands industry issues and have the technical background that enables them to provide relevant input. The project team's responsibilities include:

- Developing a suitable approach (process) and providing direction for the duration of the project.
- Deciding on general content of guideline document.
- Approving the international suite of authors established by the managing editors.
- Approving draft documents.

The project team's involvement is crucial to ensuring that the needs of the regional industry, government representatives and stakeholders are addressed. In the oil sands mining context, CEMA established a project team from its membership, named the End Pit Lakes Guide Task Group (EPLGTG). The EPLGTG includes representatives of several oil sands operators and Aboriginal stakeholders, in addition to federal, provincial and regional government agencies. The task group has been instrumental in directing the scope of work. This has resulted, at times, in vigorous debates. Disagreements among stakeholders are resolved by a commitment to the consensus model. Ultimately, these discussions are building the base of the foundation to ensuring that the guidance meets regional needs.

2.2 Selection of an experienced managing editor

Coordination of submissions from multiple authors requires careful management. For this purpose, selection of an experienced managing editor is critical. The responsibilities of a managing editor were to:

- Establish a list of authors and act as their point of contact.
- Ensure communication and coordination among authors and reviewers.
- Ensure knowledge gaps are addressed and that the objectives of the task group are met.
- Ensure regular contact with the project team.
- Ensure consistency in language usage, composition and style.
- Eliminate redundancy among authors' skill-base and chapter content and ensure appropriate cross-referencing between guideline authors.

The task group did not consider it critical that the managing editor be intimately familiar with the technical aspects of the subject matter. Indeed, it was considered preferable that this individual provide a fresh perspective, allowing the expert authors to be primarily responsible for the expertise contained in their chapters. Moreover, a non-technical managing editor was thought better able to ensure that the end document is comprehensible to an audience that may include individuals not fully specialised in the subject matter (although industry operators are the main audience).

However, the task group did consider it essential that the managing editor become familiar with the industry and important contacts. The task group openly tendered the service. The winning company was West Hawk Associates Inc., a communications and editing firm with over 15 years experience and a specialisation in environmental issues and natural resource industries. The company has extensive experience producing large documents, including guidance documents, for committees with government and industry representation. The firm often works on projects involving extensive stakeholder consultations. West Hawk was charged with ensuring that an independent peer-review would be integral to the process of preparing the next guidance document.

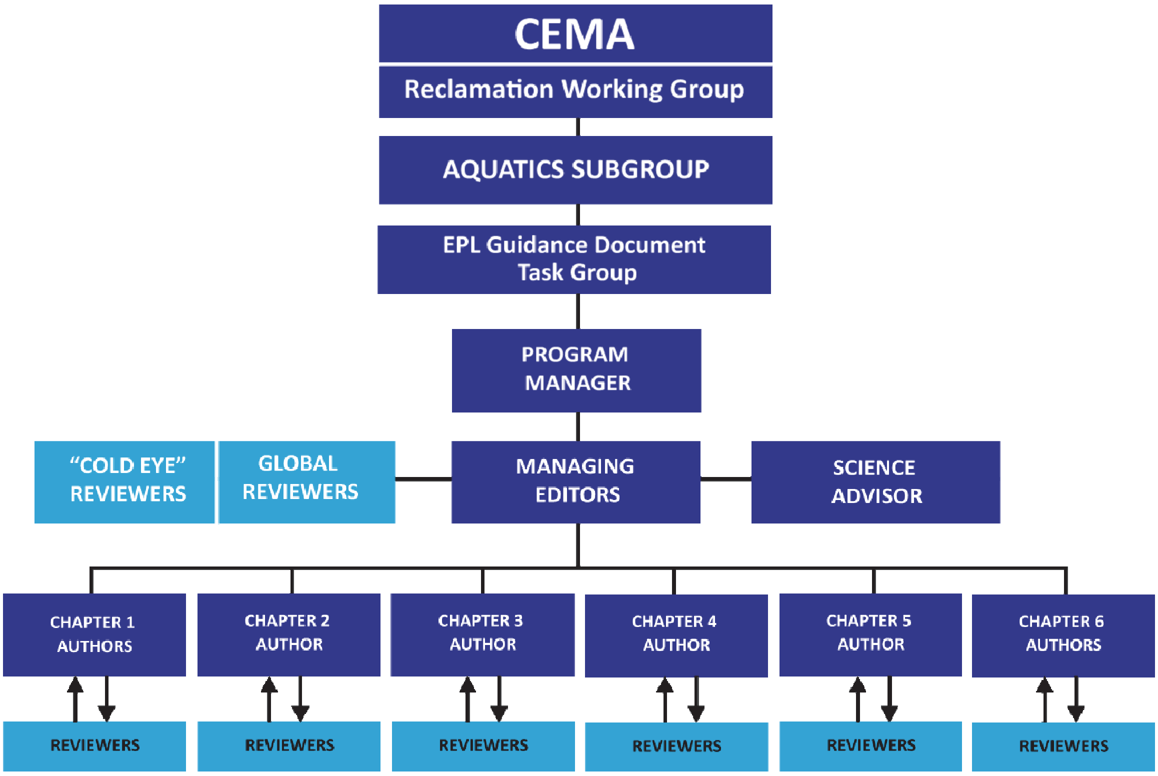

Figure 1 The EPLTGD management and production process

West Hawk assigned its two senior associates, David Wylynko and James Hrynyshyn, to the project. Both are former journalists, each acquiring 25 years of professional writing and editing experience. They began by working to familiarise themselves with the industry by reading background material, interviewing key industry contacts as provided by the task group, and conducting a site visit to the oil sands. West Hawk is devoting considerable resources to overseeing the research, writing and review processes. The firm is working closely with the task group. Regular conference calls and frequent meetings in Alberta are held to monitor each step of the document's evolution. These meetings are crucial to ensuring that the project remained on-track, especially in the early stages.

2.3 Determine and adjust to user needs

2.3.1 Determine the primary users of the guidance

To ensure maximum usability, the guidance document must be tailored to its primary users. Guidelines intended for all members of industry, government and stakeholders may provide high quality broad information, but tend to lack the specific direction that is sought by the primary users. A specific target audience must be identified and the document must be written according to the requirements of that audience. In the oil sands context, during project scoping, the task group decided that oil sands industry design engineers would be the primary audience for the guidance document on EPLs. The managing editors conducted a user needs assessment, holding interviews with mine and reclamation planners in the oil sands industry to gather input on potential authors, content, style and format.

2.3.2 Add experience to the team, where needed

To meet user needs, it is important that the task group draw upon the experience of the target audience. In the oil sands context, the user needs assessment revealed that additional experience was needed in the design of large landforms in the oil sands region. Indeed, the review of the 2007 report indicated it contained insufficient content of practical use to the technical managers, planners and engineers who are the document's intended audience. Thus, the task group decided to contract an independent science and engineering advisor (Dr Gord McKenna, BGC Engineering) to the project team with substantial experience in the industry in designing aquatic landforms in the oil sands region.

2.4 Ensure that stakeholder perspectives are understood

Depending on the stakeholder, there may be a number of objectives, directions and desired outcomes for EPLs. It is critical to understand stakeholder perspectives related to EPLs, such as performance and management expectations and desired end land uses. Knowledge of these perspectives provides context for design decisions, research direction and the development of performance objectives and criteria.

The purpose of stakeholder involvement is to:

- Ensure that stakeholders are kept informed about the project throughout the process.
- Allow stakeholders the opportunity to comment and provide input.

Stakeholder input should be viewed as a multi-step process where input is sought from stakeholders, this input is considered in the document and communication occurs with the stakeholders to advise them on how their input was used and the reason if it wasn't used.

Attempting to include traditional knowledge in processes or institutions of authority will meet with limited success without allowances for the many ways by which these stakeholder groups typically develop or transmit this knowledge (Ellis, 2005). Aboriginal stakeholders, in particular, draw on a broad range of knowledge and experience. Even in relation to relatively narrow technical subjects, environmental knowledge, cultural values, history, politics and a range of concerns and aspirations can influence the perspective of Aboriginal community stakeholders. Their contributions are rarely limited to a specific topic, but rather provide holistic analyses and broad scope. Metaphors may often play a large role in the communications of Aboriginal stakeholders. Their communication is often framed in personal experience and may take the form of stories (Paci et al., 2002). These discussions can encompass many subjects, including personal history, Aboriginal identity and values, and experience of previous industrial developments and the impacts of these developments on people and the land (Ellis, 2005).

End pit lake design, construction and management are often very technical in nature and commenting on this subject can require prior familiarity with the subject. Among many stakeholder groups, it is difficult to find individuals who are technically able to participate in environmental governance processes. Because of these challenges, much thought is put toward ensuring the appropriate approach is taken when seeking stakeholder views.

Figure 2 **CEMA stakeholder meeting**

2.4.1 Interviews

To obtain stakeholder input, the managing editors and the task group arranged interviews with stakeholders with a direct interest in the development of end pit lakes. This included non-governmental groups, Aboriginal groups, industry and government. This process included two of four caucuses that oversee the work of CEMA: the NGO Caucus and the Aboriginal Caucus. Through their involvement with CEMA over the years, members of both caucuses familiarised themselves, generally, with the technical aspects related to reclamation. A semi-directed interview process (Huntington, 2000) was used to obtain stakeholder input. By this method, participants are guided in the discussions by the interviewer, but the direction and scope of the interview are allowed to follow the participants' train of thought. The semi-directed interview is more a conversation than a question-and-answer session. Through this method, participants shared considerable insight in terms of their views on the design and construction of end pit lakes. The input generated from stakeholders was drafted and vetted by each group. This input is being considered in the guidance document, and stakeholders will be informed on how their input was incorporated.

2.5 Production of content

2.5.1 Assemble a strong team of authors

The design of a pit lake is a multi-disciplinary exercise, requiring input from several areas of expertise, including but not limited to hydrology, hydrogeology, geotechnical, biology and lake physics. Thus, a team approach is usually adopted to design and construct a pit lake. A similar approach should be adopted for generating regional design guidance for pit lakes.

In anticipation of preparing the EPLTGD, the managing editors and the task group identified the leading experts in several fields with knowledge of EPL design. This process included identifying experts with knowledge of existing pit lakes and aquatic ecosystem evolution in reclaimed environments. Much of the expertise necessary to ensure that the document would reflect the latest and most sophisticated understanding of the challenges involved in designing EPLs for the oil sands was available in Canada. However, input from experts in the US and Australia was also pursued in order to ensure that the design and construction of end pit lakes in the oil sands benefited from the most current knowledge on pit lakes. In detail, the process for author selection was as follows:

- Review of the previous version of the EPLTGD (Clearwater Environmental Consultants, 2007) and its critique that CEMA commissioned in 2009. The critique was prepared by a senior manager/editor who had the 2007 document reviewed by 12 pit lake experts in Canada, the US, Australia, and Germany. The managing editors reviewed the work and expertise of these 12 reviewers to gauge their knowledge and interest.
- Through the collective knowledge of the managing editors, the task group, the technical programme manager and the technical advisor (Dr Gord McKenna, BGC Engineering), 12–15 potential authors were identified who were well qualified, and might be available, to contribute chapters of the 2012 guidance document.
- The managing editors interviewed these potential authors either in person or on the telephone. It was critical to determine the availability and interest of these experts, as well as their qualifications given that designing and constructing end pit lakes in the oil sands is a relatively new area of reclamation.
- The managing editors, in consultation with the task group, narrowed down the list of potential authors by concentrating on those individuals with the greatest related expertise to the task of writing an end pit lakes guidance document. Previously published materials of these authors were also consulted to ensure their writing and general communication skills were adequate.
- Once the final set of authors was identified, the managing editors negotiated their contracts and drafted the terms of reference of their responsibilities. These documents were vetted and approved by the task group and senior CEMA administration.

2.5.2 Outline of guidance document

The managing editors and the task group went through an exhaustive process of establishing the outline for the guidance document:

- Initially, the review of the 2007 guidance document proposed a table of contents.
- The task group developed the table of contents further and provided it to the managing editors of the 2012 guidance document for consideration.
- The managing editors consulted various experts to review and refine it, reporting back to the task group with assorted revisions.
- Once a final table of contents was agreed upon, the managing editors finalised the chapter authors in consultation with the technical programme manager, the science advisor and the task group.
- Authors presented their outlines at a workshop and presented their draft chapters at a subsequent workshop.

Table 1 lists the authors, their affiliation and expertise. West Hawk Associates created a web page that provided a draft table of contents, chapter outlines and chapter drafts, and other related documentation for review by the task group, authors, advisors and reviewers.

The outline is as follows:

- Chapter 1: Context
- Chapter 2: Objectives
- Chapter 3: Natural Lakes
- Chapter 4: Non-oil Sands Pit Lakes Lessons Learned

- Chapter 5: Watershed Geography
- Chapter 6: In-Lake Processes
- Chapter 7: Design and Construction
- Chapter 8: Adaptive Management
- Chapter 9: Knowledge Gaps
- Chapter 10: Appendices

Table 1 Authors involved in the production of the oil sands EPL guidance document and their areas of expertise

Author	Affiliation	Expertise
Devin Castendyk	State University of New York College at Oneonta	Hydrogeologist
Théo Charette	CPP Environmental and CEMA	Watershed specialist
James Hrynyshyn	West Hawk Associates	Editorial, biology
Angela Küpper	AMEC	Geotech engineer
Dr Gord McKenna	BGC Engineering	Design engineer
Brent Mooder	BGC Engineering	Hydrogeologist
Aaron Sellick	Norwest Corp.	Mine planning engineer
Jerry Vandenberg	Golder Associates	Water quality modeller

2.5.3 Create opportunities for authors to work together

Numerous teleconferences, meetings and workshops were held during the guidance document production in order to ensure that:

- Authors understood what was required of them. The managing editors clarified with each other their precise responsibilities, including what was expected of them according to their chapter outline, the deadlines, and the interactive process they were expected to undertake with one another and the reviewers.
- Authors could present their ideas and get feedback. The task group, the programme manager and the managing editors organised workshops where the authors presented the concepts for their chapters and, once the drafts were ready, presented the actual chapters themselves. This created for a highly interactive process with immediate feedback and discussion on each chapter.
- Information flows were established between authors and reviewers working on different chapters. The managing editors established an interactive process of communication, whereby authors would consult with one another and reviewers throughout the drafting of their chapters, such that no author would be working in isolation or unaware of what the other authors were doing.

The task group considered it essential to ensure that all authors, and as many reviewers as possible, meet in person to review each chapter and ensure all relevant steps in the creation and management of an end pit lake were covered. By having the reviewers participating from the initial development of the document's structure, significant issues in the preparation of the chapters have been resolved, since all reviewers are familiar with the chapter outlines and in agreement that the assignments to each author have been appropriately made. Workshops were considered critical to ensuring consistency and avoiding repetition between chapters.

In all, three workshops were held to generate input for the oil sands EPL guidance document. The intent was for the authors to present the contents of their chapters, the main themes and topics of their chapters, and to solicit feedback from the task group members, the programme manager and the managing editors. The first workshop gathered potential, available and interested authors to communicate project scope and outcomes and determine interest. This workshop fine-tuned the EPL guidance document outline and resulted in an approved list of authors, chapter reviewers, and three global reviewers. In addition, during this workshop, the managing editors and authors decided to develop the EPL guidance document in two phases: Phase 1 consisted of contextual and environmental information and key messages to feed the Phase 2 chapter, which focuses on EPL design and construction guidelines. During the second workshop, authors of Phase 1 presented their chapters and obtained feedback from reviewers, other authors and members of the task group. The third workshop provided an opportunity for the design and construction (Phase 2) chapter authors to present their material, allowing them the opportunity to ensure that they interpreted the direction from Phase 1 authors correctly. At the editing stage, the managing editors – working with the task group and the authors – will determine how the final document should come together. Possibly, much of the material from the Phase 1 chapters will be merged into the design and construction chapter, or moved into the appendices.

2.5.4 Global reviewers

Once the draft guidance document is produced, three expert global reviewers will ensure that the document is not only scientifically accurate and current, but provides the necessary information to industry operators working on EPL planning. The managing editors and the task group chose the global reviewers from the list of 12 experts who reviewed the 2007 guidance document (although others outside this group were also considered). The review and revision process will continue through the winter of 2011, with task group and stakeholder review occurring at each step. Although stakeholders are not formally responsible for approvals, their views are critical in ensuring the document is well received. It is important to getting industry support for the document to ensure that the oil sands operators understand that the document has been embraced by stakeholders. It is expected that sections of some chapters will be relocated to sections that better reflect their content. Redundancies will be avoided through a careful process of cross-referencing that will be undertaken by the global reviewers and the editors. While the final product will be lengthy, it should nevertheless be concise and easy to navigate.

2.5.5 Revision, editing and layout

Following production of their drafts, all authors' chapters were reviewed by other chapter authors, the task group and the three global reviewers. The authors were then asked to produce revisions from these drafts according to the feedback received. In some cases, the feedback from the task group members, reviewers, and other authors was extensive. The managing editors reviewed the comments and, working with the reviewers, prioritised them in preparation for assigning revisions to the authors. In some cases, the comments pointed to concepts or information that couldn't realistically be incorporated into a revision, either because the work was monumental or the data simply doesn't exist. In these cases, the managing editors retained the comments for inclusion in the "Knowledge Gaps" chapter that will come at the end of document. Once the revision of the chapters is completed, the managing editors will copy-edit the document to improve clarity and ensure the document will be comprehensible to a wider, more general audience. Although the document is intended for mine planners and operators, it is important that the broader stakeholder community also understand its intent (non-governmental groups, industry, and government agencies). The copy-edit also reduces the duplication of information from one chapter to another. West Hawk will then design the layout of the document, and produce the final guidance document as a pdf file for distribution and placement online.

2.6 Review and approvals

2.6.1 Independent peer-review

When the document is considered near to final, three national and/or international experts in mine closure and reclamation will be retained to perform a ‘cold-eye’ review of the guidance document. These will be individuals from Canada and abroad who have not previously been involved in the project in any way. They will review the final press-ready document.

2.6.2 Industry and government champions

Once final revisions are performed, the managing editors and the task group will present the final guidance document to representatives of oil sand mining companies that intend to use it in practice. They will also provide it to municipal, provincial and federal government agencies responsible for the oil sands. These individuals will, in turn, become the document’s ‘champions’ by familiarising themselves with it and presenting it to their staff so that all personnel relevant to mine design and reclamation are familiar with the guidance for designing end pit lakes. The concept of establishing corporate ‘champions’ is considered critical to ensuring the essence of the document is conveyed to mine operators and those involved in reclamation. This buy-in is intended to ensure that each company becomes well acquainted with the provided guidance, and ideally that at least one contact person is established as the resident expert on end pit lakes design and construction for each oil sand mining company. In this way, knowledge of the guidance document, and its contents, will prove useful to operators throughout the intended lifespan of the 2012 version (five years) and hopefully beyond.

Acknowledgements

We graciously thank members of the End Pit Lake Guide Task Group of CEMA (Rod Hazewinkel, Carol Jones, Ainsley Campbell, Samantha Tavener, Xiaoying Fan and Tara Rogers), the EPL guidance document authors (see Table 1), and global reviewers (Dr George Dixon, Dr CD. McCullough and Dr Gord McKenna) who, through numerous debates and discussions, generated the reclamation approach described in this chapter. We also thank the CEMA Reclamation Working Group programme manager, Kyle Harrietha (CEMA Reclamation Working Group programme manager), and Glen Semenchuk (CEMA executive director) for assistance in the project.

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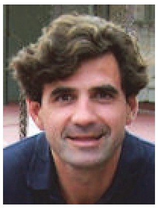
Théo completed his Masters degree at the University of Alberta in 2001. Since then, he has contributed to a number of publications, including the "Treatise on Geochemistry", and the Sustainable Forest Management Network publication: "Towards the Sustainable Management of the Boreal Forest." Currently, Théo is an aquatic ecologist and director of Charette Pell Poscente Environmental Corp., a boutique environmental consulting company that focuses on incorporating environmental objectives and outcomes into land and watershed planning and management processes. As technical program manager for the Cumulative Environmental Management Association (CEMA), Théo works with multiple stakeholders on leading practice reclamation in the oil sands region of Alberta, Canada.



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Hydrologic and geomorphic design of pit lakes for long-term sustainability

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Abstract

As constructed facilities, pit lakes can be equipped with engineered features that enable them to provide the desired aquatic habitat, water quality and longevity (capability for long-term functionality without intervention, just like natural lakes). Pit lakes may not accomplish these qualities over the long-term without careful attention to water balance, inlet/outlet locations, outlet channel designs, re-suspension of lake-bottom sediments, hydrologic function, littoral zone configuration, shoreline erosion and shoreline stability. Design of these features requires the attention of a broad array of specialists including engineers, geomorphologists, biologists, mine planners, closure designers and operators. This chapter addresses engineering considerations for design of these physical features of pit lakes that impact aquatic habitat and water quality, and that govern long-term hydrologic and geomorphic sustainability.

1 Introduction

Many natural lakes are highly valued because of their biological productivity that complements the surrounding environment. They may also serve desirable functions such as flood flow attenuation and water quality conditioning while providing valued aesthetic appeal. An essential feature of natural lakes is that they have typically undergone many centuries of morphologic evolution that has resulted in sustainable function, uninterrupted biological productivity and permanent landform configurations that are subject to very slow rates of change. As a consequence of this morphologic evolution, natural lakes are generally less vulnerable to rapid changes that may be caused by degradation of the lake outlet channel, shore erosion and re-suspension of lake bottom sediments. Rapid changes such as these would result in deterioration of the environmental values associated with reduced zone areas, elevated suspended sediment concentrations and destruction of littoral zone vegetation. The littoral zone is a shallow area of the lake that supports rooted vegetation and may be submerged or partially submerged. Unlike natural lakes, mine pits are formed as a result of the exploitation of a natural resource and therefore the outcome may not readily suit the development of physical features that lead to the conditions and sustainability that one might expect of natural lakes. Thus, it is important to design a pit that is to become an end-pit lake in a manner that meets biological, water quality and sustainability goals. Key features of a pit lake that might achieve these goals are the relative locations of lake-inlet channel and outlet channel for through-flow systems, the permanence of the outlet channel, the quantity of inflows relative to seepage and evaporation losses, water depth and resistance to shore erosion and shoreline configuration that affects littoral and riparian vegetation.

Without attention to these key features, a mine pit filled with water is unlikely to be equipped with the required physical configuration that will naturally develop the desirable characteristics at closure that are expected of natural lakes. Improper location of inlets and outlets may result in short circuiting and low hydraulic retention time that leads to poor water quality. The lake outlet may be highly erodible and subject to degradation that deteriorates the quality of the aquatic habitat. Furthermore, the lake depth may not suit the target aquatic species. Without suitable littoral zone conditions, a mine pit filled with water may result in minimal biological productivity.

This chapter presents pit lake design criteria that have been applied to many mine pits. In particular, they have been applied to almost all closure plans of operating and planned oil sands mines located north of Fort McMurray, Alberta, Canada. Design criteria, design features and design guidelines presented herein were developed by the authors to support the development of mine closure plans used in environmental impact assessments required for each oil sands mine in Alberta.

2 Water balance constraints

Water balance is the first hydrologic consideration in the design of a pit lake. A pit lake that is designed to prevent surface discharges will be configured so that water losses to evaporation and seepage exceed inflows. A pit lake that is designed to provide biologically productivity and aquatic habitat will be configured to ensure adequate through-flows. High through-flows do not normally impede the capability of a lake in providing the desired biological productivity and aquatic habitat, however, biological productivity may be severely constrained if inflows are insufficient to compensate for water losses to seepage and evaporation. Lakes without through-flows will either dry up or reduce their lake level until the lake area is small enough to reduce evaporation losses and thereby achieve a new water balance. Lakes with minimal through-flows are subject to drawdown of the lake level during dry periods. They are also subject to deteriorating water quality as lake evaporation increases the concentration of salts and undesirable constituents.

The planned pit lakes in the oil sands region of northern Alberta provide a useful example of pit lakes that are required to provide optimum biologic productivity and aquatic habitat, and how pit lakes can be designed to achieve a suitable water balance to achieve this function. Most of the planned pit lakes in the oil sands region are at or below the regional ground water table so that seepage losses are minimal. Inflows from seepage and from surface runoff in the contributing drainage area must exceed evaporation and evapo-transpiration (from littoral vegetation) losses. In northern Alberta, mean annual net lake evaporation losses amount to about 140 mm. This compares to 60–150 mm surface runoff per unit area, depending on the type of terrain and vegetation. Accordingly, the minimum ratio of drainage area to lake area would vary from 0.9 to 2.5 for a hydrologic average year, assuming minimal seepage into the lake. However, the actual ratio of drainage area to lake area must be much larger to account for the reduced runoff and increased evaporation during dry years. In the absence of sufficient inflow, drought-period reductions in water levels may result in prolonged exposure of shoreline vegetation, potentially resulting in changes to vegetation composition and littoral zone productivity. A minimum ratio of drainage area to lake area of 5:1 is being used in the oil sands region for the design of pit lakes where the maintenance of downstream creek flows are not of concern. This minimum is based on a medium-sized lake in the region, McClelland Lake, which was found to have the smallest ratio among productive natural lakes in the oil sands region. A review of historic air photos and hydrologic simulation shows that even McClelland Lake, with a catchment ratio of about 5:1, was subject to zero outflows and a declining lake level for several hydrologic dry years during the late 1940s and early 1950s.

The 5:1 ratio for drainage area to lake area is a good general rule-of-thumb in the oil sands region for situations where minimal or zero flows in the outlet channel are acceptable. The actual ratio will vary depending on the quantity of runoff and seepage that might be expected from the contributing area (wetlands or upland) and the relative difference between precipitation and lake evaporation at mine sites in other areas of the world. For lakes where the outlet channel is important aquatic habitat, significantly higher drainage area ratios (10:1 or higher) are preferred.

Other climates will require different drainage area ratios. Wet climates where rainfall far exceeds evaporation will require lower ratios of drainage area to pit lake area. Equally, cold climates where rainfall is relatively low but evaporation is lower will require smaller ratios of drainage area to pit lake area. Larger ratios are required in dry climates.

3 Inlet and outlet locations to control lake mixing

Inlets and outlets should be situated far apart, ideally on opposite sides of a pit lake whose main function is to provide biologic productivity including littoral vegetation and aquatic habitat. Inlets and outlets located at opposite ends of the lake promote mixing of inflows with lake water. Without sufficient mixing, short circuiting may leave a portion of the lake without fresh water (Figure 1). Such stagnation will likely produce inferior water quality in the stagnant parts of the lake, thereby affecting biologic productivity and aquatic habitat. This risk is particularly acute at shallow lakes.

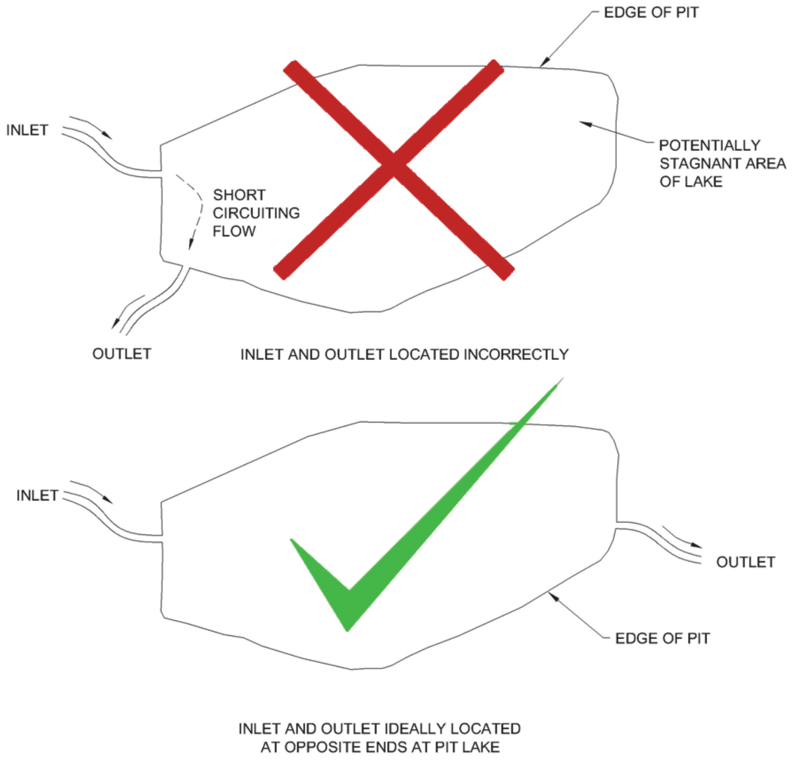


Figure 1 Preferred locations of inlet and outlet

The optimum location of inlet and outlet channels depends on the purpose of the lake. Pit lakes designed to provide biological productivity and excellent fish habitat as in the oil sands region of northern Alberta for example, should be designed to suit the above criteria. Pit lakes that are designed to treat contamination or to prevent discharge of undesirable lake water would need to be designed differently, possibly with inlet and outlet close together to enhance short circuiting.

4 Outlet channel design to prevent degradation (lowering) of lake outlet

A degrading lake outlet channel and associated lowering of the base lake water level should be avoided because it would seriously affect an engineered littoral zone and associated biologic productivity. Ideally, the outlet channel should be set in bedrock to minimise the risk of outlet degradation. However, competent bedrock may not be present at the required location of the lake outlet channel. This is the case in the oil sands region where competent bedrock is not normally present at the desired level. Therefore, alternative erosion protection is required at the outlet channel. The recommended approach is to use robust armouring similar to the channel armouring observed in many natural lakes. Natural lake levels are often controlled by outlets comprised of bedrock, shallow outlet channels or robust erosion ‘protection’ composed of multiple layers of large stones. Use of heavy riprap sized for an extreme flood is recommended for outlet channels that have a steep gradient. The erosion protection should be robust so that failure of the top layer does not cause rapid degradation. The recurrence interval for sizing the riprap should be a minimum of 1,000 years to qualify for walk-away, maintenance-free closure. The outlet should also be designed to prevent significant seepage losses through the channel bed armouring so that the surface of the armour layer controls the lake level. This can be accomplished by providing a shallow sloped outlet channel bedded on relatively impervious soils, upstream of any steep gradient outlet channel that requires large armour stone. Details of common outlet channel configurations from the oil sands region are illustrated in Figure 2.

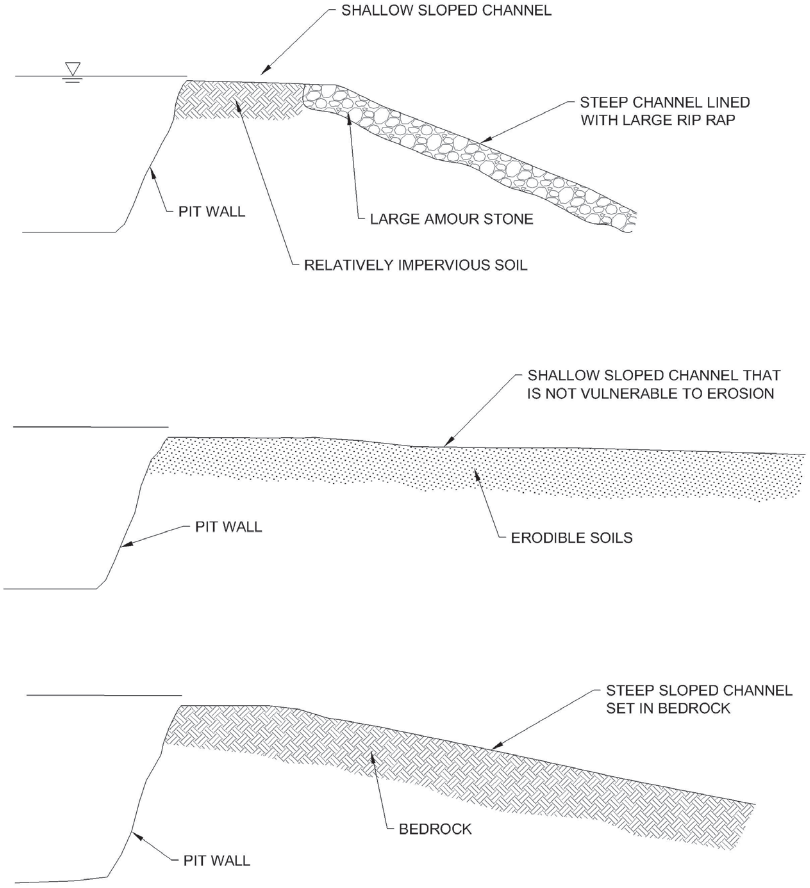


Figure 2 Typical pit lake outlet channel configurations

5 Provision of required littoral zone area

The littoral zone is one of the most important physical features of a lake that is required to provide biological productivity and aquatic habitat (van Etten, 2011). The littoral zone extends from the shoreline to the maximum depth at which aquatic plants will grow, and the maximum littoral depth is therefore dependent upon light penetration (euphotic depth), which is affected by water turbidity and colour (Wetzel, 2001). Based on observations of natural lakes in the oil sands region, a maximum littoral depth of 3 m has been used as a general rule-of-thumb guideline for design of constructed lakes in this region.

The typical littoral area requirement for pit lakes in the oil sands region is 10–30% of the lake area (Golder, 1995). That is, 10–30% of the lake should have water depths less than 3 m with the remaining lake area having greater water depths. The littoral zone proportion of natural lakes in the region ranges from 9–36%, with a mean of 19%, based on morphometry information available for 35 regional lakes (Mitchell and Prepas, 1990). This indicates that a lake with a littoral zone proportion between 10% and 30% of total surface area is within the range of natural, fish-bearing lakes in northeastern Alberta. Actual littoral area requirements vary depending on the desired aquatic habitat and target fish species, and the need to provide suitable dissolved oxygen for overwintering. Water quality simulation modelling to predict winter dissolved oxygen depletion, which is influenced by lake depth, volume, littoral zone area and productivity, is typically used to assist in determining an appropriate littoral zone area on a case-by-case basis.

Without special measures to expand the littoral zone, pit lakes will normally offer insufficient littoral vegetation to provide for significant biologic productivity or associated aquatic habitat. Mine pits normally have steep side walls resulting in a relatively small area of shallow water that is able to support rooted vegetation (van Etten, 2011).

Several methods can be used to develop the required shallow water area for provision of the littoral zone. One method is to select a lake level that exceeds the crest level of the mine pit wall at a portion of the perimeter so that the lake inundates the surrounding area to a depth that suits the littoral zone depth criterion. This scheme was used to create the littoral zone area of Syncrude's Base Mine Lake located in the oil sands region of northern Alberta, Canada. Where adjacent vegetated areas are flooded rather than stripped of vegetation, care had to be taken to evaluate the potential for and effects of elevated methyl mercury concentrations in the lake during the initial decades of operation. Similar considerations may need to be explored with other mine pits that are subject to acid and metalliferous drainage (AMD). A second method of littoral zone creation is to select a bench level and lake level such that the depth of inundation on the highest bench falls within the range of depths required for littoral zone. A third method the excavation of the perimeter of the pit to achieve the required depths for littoral vegetation may also be feasible for some pit lakes.

A fourth method that is common in the oil sands region applies to pits that are bounded by an earth fill embankment that separates the final pit from tailings infill areas. At such locations, it is convenient to plan the lake level and/or tailings fill level so that the lake floods the tailings infill area to the depth required to suit littoral vegetation. This method requires that the tailings infill area be capped with suitable overburden to isolate the tailings from the lake and also requires erosion protection so that the tailings infill area and the earth embankment are not vulnerable to wave erosion.

These methods of providing the required littoral zone area are illustrated in Figure 3.

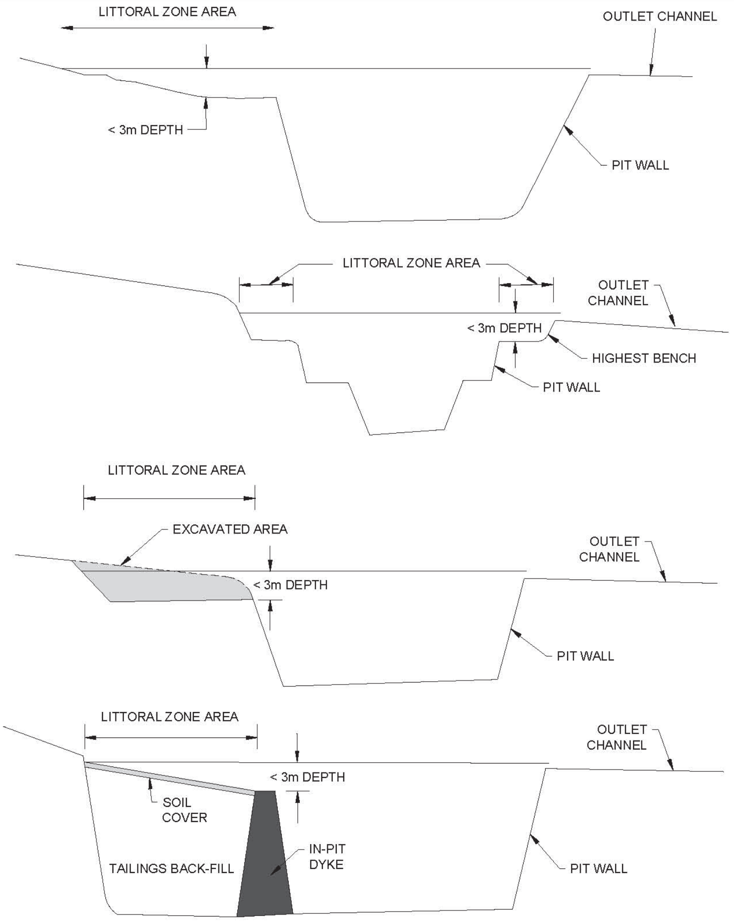


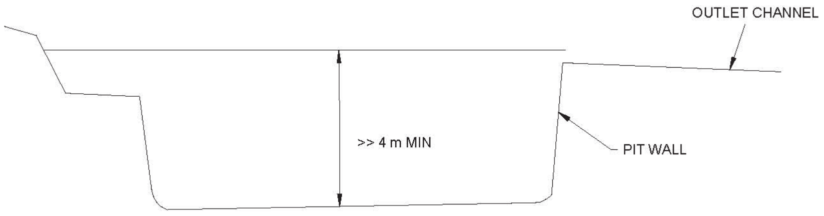
Figure 3 Methods of providing littoral zone area

6 Providing lake depths for overwintering habitat

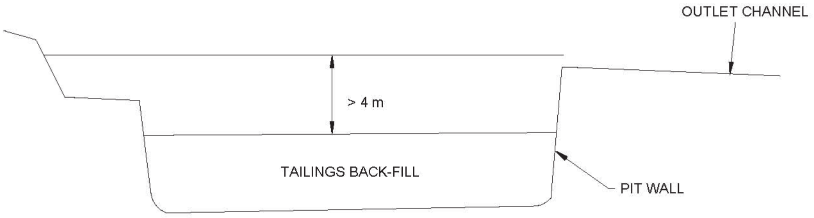
A typical lake design criterion for constructed lakes in the oil sands region is to provide sufficient water depth to achieve suitable overwintering conditions for target fish species. Limitations to overwintering capability result from depletion of dissolved oxygen, under ice-covered conditions, to levels below what is required to sustain the target fish species. Based on results of water quality simulation modelling for a small number of constructed lakes in the oil sands region, it appears that lakes with an average depth of at least 4 m and a maximum depth of at least 7 m are generally capable of providing suitable winter dissolved oxygen levels in that region. Other mining regions will similarly require habitat design to specifications based upon their target aquatic species/communities (van Etten et al., in press).

This criterion can be easily achieved by most mine pits including all of the planned pit lakes in the oil sands region, since most oil sands mine pits exceed 40 m depth. However, many of the mine closure plans call for storage of end-of-mine residual fluid fine tailings in the end-of-mine pit. Depending on the actual volume of the end-of-mine fluid fine tailings, partial filling of the pit lake with tailings could compromise the overwintering lake depth criterion. Where there is the potential for limitation of overwintering capability, due to dissolved oxygen depletion in the hypolimnion, water quality simulation modelling can be used to assist in determining required lake depth on a case-by-case basis (Vandenberg et al., 2011).

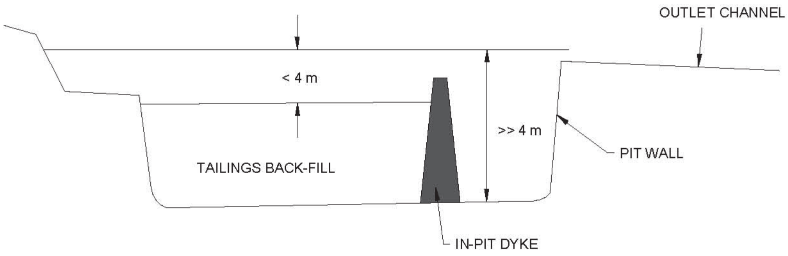
Several measures can be invoked to maintain the minimum overwintering depth criterion. The preferred option is to avoid tailings storage in the pit that will be used as an end pit lake. If tailings must be stored in the pit lake, the tailings storage volume must be derived conservatively to ensure the required minimum depth for overwintering. A third method that has been planned for pit lakes in the oil sands region is to develop the overwintering habitat at an area of the lake that is isolated by way of an earth embankment or pillar of overburden as illustrated in Figure 4.



PIT CONTAINS NO TAILINGS BACK-FILL



PIT CONTAINS TAILINGS WITH A WATERCUP > 4 m



PIT CONTAINS TAILINGS AND SHALLOW WATER CAP WITH
OVER-WINTERING PROVIDED IN AN ISOLATED AREA

Figure 4 Methods of providing over-wintering fish habitat

7 Controlling shore erosion

Pit lakes in the oil sands region are normally vulnerable to shore erosion due to large waves that can be generated by high winds, long fetch lengths and relatively deep lakes. Pit walls are typically composed of consolidated and unconsolidated sand, silts and clays. Thus, in the absence of deliberate shoreline protection, significant shoreline erosion and recession could occur, potentially extending several hundred metres from the initial pit edge. Special erosion protection measures are required where the in situ materials contain little or no coarse fractions, especially where the fetch is longer than 1,000 m and the pit wall is steep. One method is to flatten the pit wall slopes to dampen the wave energy. Another method is to construct an armour layer along the shoreline. A third method is to build rock groins to dissipate the wave energy before it encounters the pit wall. The latter is applicable to earth fill embankments that separate the pit from tailings infill areas. These three methods are illustrated in Figure 5.

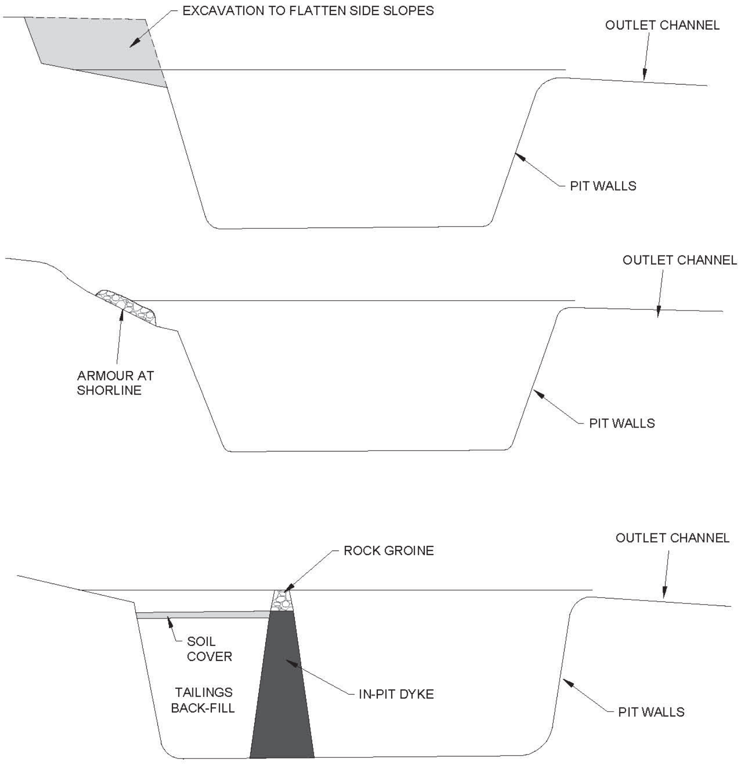


Figure 5 Methods of shore protection at pit lakes

8 Preventing re-suspension of lake-bottom sediments

Re-suspension of lake-bottom sediments can be caused by wind-driven lake circulation velocities that can exceed 1 m/s at the lake surface, depending on the fetch length, water depth, wind speed and wind duration, and by the generation of wind waves that may have strong orbital velocities extending to several metres depth (Huber et al., 2008).

Re-suspension of lake-bottom sediments is not normally a problem at natural lakes that have been subjected to many thousands of years of conditioning. However, unlike natural lakes, pit lakes may be contained by steep pit walls composed of erodible materials. This source of fine sediment entrainment can easily be controlled by some means of erosion protection.

The main source of fine sediment entrainment at pit lakes in the oil sands region is from fine tailings that may be stored in the pit. Currently, many pit lake designs are based on the findings (Lawrence et al., 1991) that predicted no tailings entrainment for fine tailings that has formed a distinct lake bottom, if the depth of water exceeds five metres and under certain wind conditions and fetch. This is a critical issue and the conclusion may not be applicable to the conditions at all pit lakes where tailings will be used to partially fill the pit. In particular, Lawrence et al.'s (1991) conclusion may not be applicable to lakes where the tailings and process water have higher levels of sodium due to ore processing with large amounts of caustic soda and incorporation of saline connate water, resulting in highly dispersed fines that may not form a distinct lake bottom. Additional research is required for pit lakes in the oil sands region to identify the sediment and lake treatment measures required to control the settling of fluid fine tailings at the base of the water column.

9 Sizing pit lakes for attenuating downstream flows

In addition to their function in providing aquatic habitat and treatment of process waters, pit lakes can be used to attenuate flood discharge to downstream receiving waters. This is a valuable function in the oil sands region where the pre-disturbance landscape comprises large flat areas and muskeg terrain, characterised by relatively small water yield during periods of high rainfall and snowmelt. Following mine disturbances and reclamation, much of the disturbance area is composed of reclaimed tailings storage areas and waste dumps that tend to shed water more quickly resulting in high water yield following mine closure and reclamation. Increased water yield, especially during floods, can lead to undesirable changes in the morphology and erosion of downstream water courses. Pit lakes can be used to restore the natural flow attenuation characteristic of the pre-disturbance terrain in the oil sands regions.

Hydrologic simulations of pit lakes planned for the oil sands region have shown that the area of a pit lake in this region of northern Alberta needs to be at least 5% of the drainage area to have an appreciable effect on flow attenuation. Other climates will have greater/lower needs for drainage area. The magnitude of the attenuation will depend on the ratio of lake inflows to lake area and the hydraulic efficiency of the lake outlet, with wide flat outlets resulting in less attenuation than narrower, more incised outlets.

10 Controlling factors that affect stratification

The development of vertically-stratified layers of water in a lake can lead to depletion of dissolved oxygen in the lower layer, and consequently to profound changes in the biological and geochemical processes that occur there. In certain pit lake applications, meromixis may be a preferable, as in the case of Island Copper pit lake, where meromixis was induced to promote anaerobic sulfide precipitation (Poling et al., 2002). Conversely, it may be preferable to avoid meromixis if the objective is to promote aerobic degradation of toxic organics, as in the case of oil sands pit lakes. Therefore, the ability to control the stratification may be desired, though not always practical.

There are two main factors that influence the formation and stability of meromixis: vertical density gradients and lake geometry. Density gradients can be established by differences in temperature or salinity. Thermal stratification is typical of lakes in temperate regions and is generally seasonal (Wetzel, 2001). Salinity-driven stratification can be very stable due to the relatively large difference in density in saline versus fresh water. This type of stratification is particularly relevant in pit lakes that will (1) be used to dispose of saline process water or (2) receive inflows of saline groundwater. In these pit lakes, meromixis can be promoted by allowing these sources to establish a lower layer before capping with freshwater, or it can be inhibited by rapidly filling with freshwater to minimise the gradient established by the saline sources.

Lakes with short fetch relative to depth are more prone to become meromictic, because in such lakes, wind-driven mixing may not penetrate the entire depth of the lake. This is particularly relevant in mine pit lakes, which are often both narrower and deeper than natural lakes (Boehrer and Schultze, 2006). Given that lake geometry will normally be a determined by mining considerations such as ore recovery, the fetch and depth may be beyond the control of pit lake designers. However, lake geometry can be modified to promote meromixis by incorporating in-pit dykes (Figures 3 to 5), which reduce the effective fetch within each segment of the lake. Meromixis may be overcome by partial backfilling to reduce the lake depth. One solution that affects both density gradients and lake geometry is to dispose of waste rock in the pit and then fill the waste rock pore space with saline process water (De Beers Canada Inc., 2010).

While the above suggestions may be useful in some cases, the designer will often have little or no ability to control the long-term mixing behaviour of a pit lake. Thus, the designer should take steps to understand and anticipate the behaviour of the pit lake to be filled. To this end, modelling can be completed to anticipate behaviour (Vandenberg et al., 2011); monitoring plans can be designed to measure vertical mixing behaviour (Gammons, 2011); and mitigation strategies can be adapted to meromictic or dimictic conditions (Kumar et al., 2011).

11 Conclusion

Pit lakes at reclaimed mines can be designed to provide the physical features needed for a productive biological environment and aquatic habitat for endemic communities. Pit lakes can be designed with the features needed for water conditioning and for flow attenuation while meeting the criteria for long-term physical and biological sustainability. Design criteria for these features for many mining areas are well established and, for example, have been incorporated in the closure design for many of the planned and operating oil sands mines in northern Alberta, Canada.

Acknowledgements

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Use of water quality models for design and evaluation of pit lakes

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Abstract

This chapter provides an overview of water quality model approaches that can be applied to pit lakes. Water quality models are tools that can be used from the early stages of mine development to design and promote water bodies that will meet end-use objectives. Models assist in planning the filling period of pit lakes, up to initial release into the receiving aquatic environment, and beyond into the post-closure phase. This chapter first describes the application of water quality models to pit lakes, including typical implementation steps to follow, the possible spatial discretisation of the water bodies with the models, the typical hydrodynamic water quality components assessed with the models, and the geochemical analyses usually undertaken to support the modelling effort. The challenges and limitations of water quality models are then presented, notably data sources, sensitivity and uncertainty. This chapter concludes with a case study of a multi-phase water quality model being developed for pit lakes in the oil sands region of northern Alberta, Canada.

1 Introduction

The environmental and engineering studies that are typically required for permitting, mine planning and mine closure require an estimation of water quality during all stages of life of mine. Pit lakes are a key component of mine closure and aquatic reclamation for many existing and planned open pit mines. As ultimate discharge points from a reclaimed mine, the design and evaluation of these water bodies is essential to the overall success of the mine closure plan.

Forecasting and evaluating pit lake water quality poses a challenge because of the variety of geological environments, ore deposits and mine waste types that may be encountered. Furthermore, many planned pit lakes will not be constructed until decades after the initial mine design. Due to these challenges, the most practical way to obtain estimates of pit lake water quality is generally through predictive modelling. Water quality modelling can be completed as part of the design stage for the mine development, with increasing model complexity according to the level of design details.

Development of a conceptual pit lake model (Figure 1) is a key component of the preliminary design phase to ensure that an appropriate set of field data is collected. Based on the physical dimensions, geology and catchment area of the open pit, inflow rates and chemistries may be characterised for natural and reclaimed areas within the catchment area. Model inputs may be estimated from geochemical testing, baseline sampling, proxy systems or other literature sources. Mechanistic models can then be used with this information to simulate water quality under the anticipated closure scenarios defined in the conceptual model.

This chapter discusses the use of models for predicting water quality in pit lakes. The discussion covers: basic steps in a modelling application; model frameworks; variables of interest; limitations; uncertainties and sensitivities. It concludes with a case study of a recent pit lake model being developed for the Cumulative Environmental Management Association (CEMA). The case study describes a multi-phase lake,

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sediment and gas modelling software that has been developed for use by oil sands mining operators for pit lake planning, assessment and design.

2 Modelling framework

2.1 Why model?

One objective in developing a mine closure plan is to identify and implement mitigation strategies that may be required to achieve long-term sustainability and to minimise aquatic impacts on receiving streams. For many open pit mines, pit closure is accomplished by actively or passively filling the final pit with water to create a pit lake (Castro and Moore, 2000). It is generally in the best interests of both operators and regional stakeholders to design and construct a walk away lake if possible that meets end-use goals without the need for perpetual, active treatment. Depending on the jurisdiction and type of mine, pit lakes may be expected to have water quality that is within the range of natural levels of regional lakes, meet water quality guidelines for the protection of aquatic life and human health and/or provide habitat for valued ecosystem components such as sport fish.

From the early stages of the mining development, several years and often decades may pass before the pit lakes are developed in the mine area. However, assessment of pit lake water quality is required for each stage of the mining development to evaluate the adequacy of the proposed closure and reclamation plans. Water quality modelling allows such an assessment in the early stage of the mining development. As the closure period approaches, modelling will provide support for the detailed design of pit lakes. In the later stages, modelling can be used to predict long-term outcomes of the post-closure pit lake with increasing levels of confidence.

2.2 Modelling steps

General modelling advice is given below, following the themes laid out in more detailed guidance documents (Anderson and Woessner, 1992; Castendyk and Eary, 2009; Kuipers et al., 2006; Maest et al., 2005; USEPA, 2002, 2009). In addition, most model software packages have very detailed user manuals that lay out the steps for setting up modelling applications. A common theme of these guidance documents is the general workflow that should be followed when modelling, regardless of stage or complexity. Although there are subtle differences in the recommendations of the documents listed above, modelling of pit lakes should follow these fundamental steps:

- **Define the objectives for modelling**. All subsequent modelling tasks should be completed with a clear aim of meeting these objectives. Among other things, the objectives will determine the type of modelling that is required. For example, sensitivity analyses can be completed to determine key driving variables, without putting too much weight on absolute values. In contrast, stochastic modelling can be used for risk assessment modelling, where each output value or consequence is attached to a frequency or likelihood of occurrence.
- **Develop a conceptual model**. Define the inputs to the lake and physical characteristics of the system. Describe the key processes that will influence the possible water quality of the pit lake. Process diagrams or schematics can be helpful to visualise the relevant physical and chemical processes in the conceptual model, (Figure 1 and Section 4).
- **Select the appropriate model software**. The model software selection will be a function of physical and chemical factors that could influence pit lake chemistry, model objectives, the conceptual model and available data. Consider domain, dimensionality, functionality, input data requirements, reliability and computational effort. More than one model software package may be necessary to simulate all key processes. For example, it may be necessary to employ a groundwater model, a geochemical model, a hydrodynamic model and a water quality model. If an appropriate model is not available that fits the conceptual model, development or modification of an existing model may be necessary.

- **Establish key output metrics**. Examples of output metrics are water concentration, turnover rate, outflow rate or water level. The model must be able to predict and report key metrics.
- **Establish screening criteria in advance of model runs**. Examples of screening criteria are applicable regional water quality guidelines, concentrations of natural lakes and aquatic health benchmarks. Choosing the appropriate screening criteria to meet the objectives of the modelling will allow the modeller to view preliminary results in context, and to adjust assumptions and inputs throughout the modelling exercise.
- **Gather input data**. Compile and assemble all necessary input data for the selected model. Data could include surface water and groundwater flow, surface water and groundwater chemistry, geochemical characterisation of the main rock types that will be exposed in the pit walls, climate data or analogue data from comparable sites. In many cases, the pit lake in question may be decades from construction, so input data may be unavailable. If data are not available, the modelling exercise may need to be delayed while data are collected, or a simpler model may need to be developed. Methods for dealing with lack of data will vary, depending on the stage of modelling and objectives.
- **Implement quality assurance procedures**. Screen input data for outliers, unit conversion errors, analytical or instrument malfunctions and other perennial pitfalls. An important consideration in geochemical models is charge balance of the input solutions; as a general best practise, input solutions should be charge-balanced prior model simulations with geochemical speciation software. Another useful procedure is to view graphs of all model input time-series along with the raw data used to generate the formatted inputs. Additionally, graphing inputs and outputs on the same figure can be done to compare the model software response with the expectations of the conceptual model. For example, graphing meteorological input data next to simulated water temperature can indicate whether model software is responding appropriately.
- **Calibrate and validate, if possible**. If the lake is in the filling stage, compare model predictions with observed data. If a future lake has not been filled, validate and refine inputs to the model whenever information becomes available. Validation can also be done at a smaller scale using bench-top physical models, or by evaluating surrogate systems such as pit lakes with similar characteristics.
- **Conduct an uncertainty or sensitivity analysis**. Quantify confidence limits and identify key sensitivities.
- **Compare results to criteria**. If the model predicts concentrations that are less than the screening criteria, the modelling exercise may be finished. If not, changes to the closure drainage plan or additional mitigation may be required.
- **Continue improvement loops**. Once changes have been made to the closure plan, the updates should be fed back into the process and modelling can be resumed. Depending on the type and magnitude of change, the feedback may warrant updates to the conceptual model, additional data collection and revisiting the model software selection.
- **Conduct a post audit**. Once the lake develops, compare predicted values to observed values and calibrate the prediction model as needed to match observations (Andersen and Woessner, 1992).

2.3 Model frameworks

The model framework should be rigorous enough to consider all key geochemical, hydrological and limnological processes that could contribute to pit lake water quality over time. Several complex, contemporaneous processes occur during pit lake development, such as exchange of water between the pit lake and the surrounding hydrologic system, development of vertical density profiles in the lake, geochemical interactions that occur within the damaged rock zone of the pit walls and within the water column, as well as biological growth and decay cycles. It may be necessary to use several numerical models to address the individual processes occurring within a pit lake, using the results of one model to define the basis of a model of an interdependent process (Castendyk and Eary, 2009).

The number of dimensions used to define the geometry of a water body is an important component that differentiates one model from another. Several publicly or commercially available water quality models exist that allow a 0-, 1-, 2- or 3-dimensional definition of a water body. Table 1 summarises model characteristics according to dimensional capability. Compendia of water quality models, with their capabilities, are available in USEPA (1997) and WERF (2001).

Geochemical models may be included in a zero-dimensional model (0D) capacity, consisting of a coupled water and mass balance. These models are often used to check processes that may be occurring to influence the water quality of the pit, such as chemical speciation, mineral dissolution, mineral precipitation, oxidation, reduction and surface adsorption. Furthermore, geochemical models may also consider exchanges of gases with the atmosphere, which may influence the chemical composition of near-surface lake water.

Geochemical models are developed based on assumptions related to the hydrodynamic properties of the pit lake, using the output from other geological, limnological and hydrological models. To apply these models to a stratified pit lake, the models can be set up in separate cells to simulate vertical stratification. Alternatively, they can be coupled with hydrodynamic models of higher dimensions.

Lake hydrodynamics, including the possible formation of meromixis within the pit lake, are important determinants of water quality. Hydrodynamic models will consider variables that affect water density and circulation, such as temperature, total dissolved solids (TDS) and total suspended solids (TSS). If an evaluation of lake hydrodynamics is required to evaluate the pit lake water quality, a 1D, 2D or 3D model will be required.

Other distinguishing components of water quality models are their capability to characterise specific groups of water quality constituents, and the interrelations between these groups. Typical groups would include the constituents required to characterise: oxygen dynamics; nutrient cycles; pH and alkalinity; specific species of concern; and generic conservative and degradable constituents. These water quality components are addressed in Section 2.4.

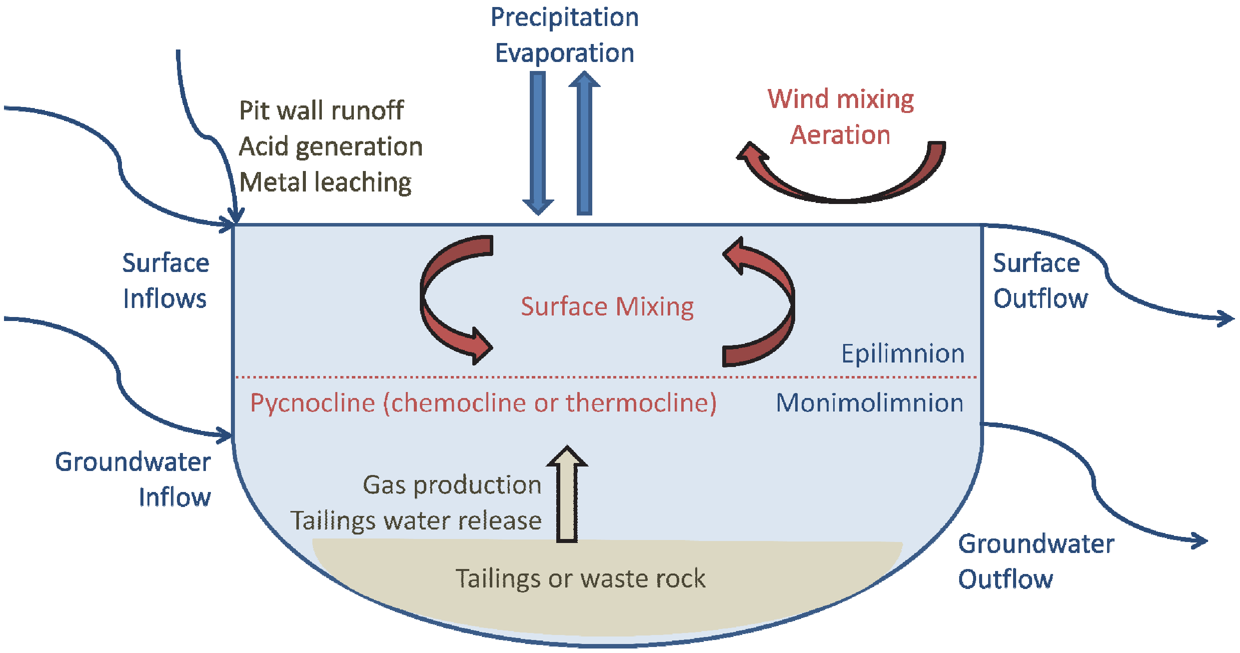
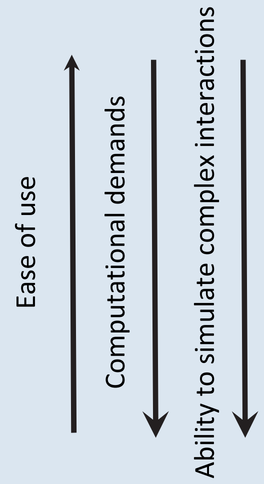


Figure 1 Example of conceptual pit lake model

Table 1 Description of options for pit lake modelling

Model type	Description	Capabilities	Limitations	Example of models	Considerations
0D chemical	Water and mass balances assuming full mixing of water within the lake; balances can be made within separate cells to account for stratification.	These tools are usually user-developed, made on a case-by-case basis, and should normally be quick to run.	No spatial representation; applicable to fully-mixed systems such as shallow lakes.	Excel or general simulator such as Goldsim, Matlab or Stella; may be coupled with geochemical model, such as PHREEQC (Parkhurst and Appelo, 1999).	
1D physical and chemical	Modelling formulations that allow discretisation of geometry as a function of depth.	Will typically provide basic representation of lake hydrodynamics (including stratification) and water quality, are relatively quick to run.	Lack of horizontal discretisation makes these mainly applicable to lakes with small surface area relative to depth.	DYRESM coupled with CAEDYM (Hipsey et al., 2006), or any 2D and 3D model reduced to 1D; PHREEQC may simulate 1D changes in composition.	
2D physical and chemical	Two modelling formulations are available: laterally-averaged and depth-averaged.	Models available with relatively detailed representation of lake hydrodynamic and water quality components.	Laterally-averaged models are applicable mostly to long and narrow lakes; depth-averaged models are applicable to shallow lakes.	Laterally averaged CE-QUAL-W2 (Cole and Wells, 2008), depth average MIKE21 (DHI, 2011), or any 3D model reduced to 2D.	
3D physical and chemical	Models provide longitudinal, lateral and depth discretisation, and therefore can be used for any geometry.	Models available with detailed representation of hydrodynamic and water quality processes; geochemical models can be coupled to 3D hydrodynamic models.	Requires significant user and computational time to operate and develop; existing data not always sufficient for 3D representation.	ELCOM coupled with CAEDYM (Hipsey et al., 2006), EFDC coupled with HEM3D (Ji, 2008), MIKE3 (DHI, 2011), GEMSS (Buchak and Edinger, 1984), MODFLOW (Harbaugh et al., 2000).	

2.4 Modelling components

While there are many processes that affect water quality in pit lakes, there are three main categories of models that simulate these processes. Hydrodynamic models simulate the density, circulation and stratification of water and the resulting advective transport of constituents. Geochemical models simulate chemical reactions among minerals, water and substrates, such as oxidation/reduction, dissolution/ precipitation and sorption/desorption. Water quality models simulate the fate and transport of oxygen, nutrients and other constituents that can settle or degrade in the water column. As mentioned, some models can be coupled together to simulate physical and chemical behaviour; some models are internally coupled. The following sections list some considerations for each type of model.

2.4.1 Hydrogeological considerations

The local and regional hydrogeological conditions can influence pit lake water quality in both the short and long-term. A groundwater model can be used to simulate the movement and quality of groundwater both upgradient and downgradient from a pit lake. Specific processes and considerations that will require a groundwater model are as follows:

- **Groundwater table recovery:** Groundwater will generally be depressurised and drawn down for some distance away from an open pit mine in advance of mining operations. Transient groundwater modelling may be used to determine the time to re-establish a stable groundwater table, and steady-state modelling may be used to predict the final water table elevation.
- **Groundwater discharge and recharge:** In some areas, groundwater flow to the pit lake will comprise the largest inflow. Thus, groundwater inflows will affect the residence time of the pit lake, which in turn affects water quality. Recharge of the groundwater system from the pit lake is also an important consideration for groundwater resources downgradient of the lake.
- **Groundwater quality:** Mass loading associated with groundwater solutes can directly affect pit lake water quality. This is especially true if the local groundwater system has been impacted by mining operations. Likewise, poor pit lake water quality can impact downgradient water resources. Solute transport and particle tracking may be used to simulate both of these interactions.

Hydrogeological conditions may include an evaluation of the short and long-term influence of surface water feedback to the groundwater system. Depending on the conceptual model, a separate model may be required to quantify the surface water inputs to the groundwater system. An evaluation of the potential formation of feedback loops between surface and groundwater systems should be considered during the development of the hydrogeological conceptual model.

2.4.2 Hydrodynamic considerations

Characterising the hydrodynamics of a lake, primarily the velocity and density fields in the water body, is essential for modelling any water body that is not fully mixed. The hydrodynamic component of the modelling effort determines the movement of masses, including water and water quality constituents, in the lake. This component also determines whether stratification occurs in the lake, at which periods it occurs, and how it affects movement of masses and oxygen aeration. Many water quality models include hydrodynamic modules in their formulation. Water quality models that do not have such inclusion must then have the capability to read and use results from a separate hydrodynamic model. Following are additional considerations for a hydrodynamic model:

- **Ice cover:** For modelling lakes in a Nordic environment, the hydrodynamic component of a model must incorporate the formation and thawing of an ice cover on the lake. An ice cover will provide thermal insulation and shielding against wind, which will impact movement of masses in the lake, and will also prevent aeration, thus temporarily eliminating the oxygen supply to the water body.

Ideally, the ice cover should also account for salt rejection, which can affect the concentrations of all species in a lake and the overall mixing regime.

- **Mass transport:** Chemical mass transport into and out of the lake can include contributions from pit wall runoff (as detailed previously), surface water flow and groundwater flow. Surface water flows typically affect the epiliminion of the lake by the transport of acidity, alkalinity and dissolved metals. Groundwater inflows can influence the whole lake.
- **Dilution/concentration:** Direct precipitation on the lake surface can result in dilution of dissolved constituents. Evaporation and salt exclusion, on the other hand, increase concentrations of salinity and dissolved constituents. In net evaporative climates, pit lakes may become meromictic and/or terminal due to long-term evapo-concentration.
- **Mixing:** Mixing of the pit lake during annual or biannual lake turnover, or by wind and wave action can contribute to processes that may affect lake chemistry, such as vertical homogenisation of dissolved chemical parameters, vertical distribution of dissolved oxygen stored in the epilimnion, sediment re-suspension and vertical distribution of carbon dioxide stored in the hypolimnion followed by ex-solution at the lake surface.

2.4.3 Geochemical considerations

The chemogenesis of a pit lake is a function of many geochemical processes that can occur within a pit lake. Each of these processes must be quantified with respect to its contribution to the ultimate pit lake water quality. A brief summary of some of the key geochemical processes that should be considered in a pit lake model is provided below. The reader is referred to Castendyk and Eary (2009) for a detailed description of the layers in each pit lake where these processes may occur, and the effect of each process.

- **Reactions within the damaged rock zone:** The damaged rock zone of a pit lake includes the shell of highly fractured rock or sediment around the pit perimeter. Mineral reactions, such as sulfide oxidation or dissolution of soluble mineral phases, result in the addition of acidity, sulfate and trace metals to pit wall runoff. The rate of reaction of these mineral phases in the range of conditions defined by the conceptual model is of key importance to the pit lake water quality predictions.
- **Mineral precipitation:** Dissolved mineral phases may precipitate from mixed pit lake waters, which can reduce the concentrations of some chemical parameters and provide surfaces for metal adsorption. The reader is referred to Nordstrom and Alpers (1999) in mine pit lakes.
- **Metal adsorption:** Surface adsorption of metals to hydroxide precipitates, clay minerals or organic material with reactive surfaces in solution can decrease concentrations of metals and metalloids.
- **Speciation and redox:** The speciation and redox state of anions and metals in solution can be influenced by geochemical processes that occur within the pit lake, resulting in transformations of one species to another, oxidation or reduction reactions, precipitation or dissolution of mineral precipitates, or desorption/adsorption onto surfaces. Vertical changes in redox conditions are common in meromictic lakes.

Geochemical predictions of pit lake water quality must quantify each source in terms of its contribution to the overall system. The post-mining hydrologic system, including anticipated future geochemical and limnological conditions, must be considered in order to estimate post-closure pit lake water quality. The geochemical conceptual model will define the key processes that should be accounted for in the numerical model during the various stages of pit lake formation. However, simplifying assumptions should be verified with field monitoring data as the pit lake forms over time. Field data should then be used to adjust the conceptual model to reflect actual field conditions.

2.4.4 Water quality considerations

Understanding the end use of the water body will influence the type of water quality model and degree of complexity of the modelling effort. If it is clear through simple mixing models that constituents will concentrate or degrade with time in the pit lake, or that active mitigation measures such as treatment will be required, then it may not be necessary to conduct more detailed modelling. In most instances the goal is to create a pit lake that will eventually become productive habitat. To design such a lake, it is necessary to investigate specific aspects of water quality, such as nutrients and key parameters of concern. General purpose water quality models are available for a wide range of applications, including characterisation of the components detailed below:

- **Generic constituents:** Most water quality models also include the ability to model user-defined constituents. These can be conservative constituents, meaning they do not undergo fate processes, or settleable or degradable constituents. Settling and decay rates are normally set according to first-order or constant rates. These constituents do not interact with other components of the model, except in the case of biochemical oxygen demand (BOD) constituents. This category of model constituents can be used to simulate the concentration any number of toxic and non-toxic substances of interest.
- **Oxygen cycle:** Oxygen consumption, production and replenishment are important processes that should be included in any water quality modelling effort, because the dissolved oxygen (DO) status of a pit lake will affect the fate and behaviour of a host of other constituents. For example, the redox state will affect most geochemical processes described above, as well the aerobic degradation of organic compounds, nitrification, denitrification, iron reduction, and sulfate reduction. A basic oxygen balance will consider atmospheric aeration and inflows as a sources, and biochemical, chemical and sediment oxygen demand (SOD) as sinks. More complex models will account for photosynthesis and respiration at one or more trophic levels.
- **Nutrient cycle:** The nutrient cycle forms the primary basis of many water quality models, as it determines the trophic status of the aquatic system. Nutrients consist of inorganic and organic forms of nitrogen, phosphorus and carbon. Sources of nutrients include loadings in inflows and available fractions of sediment and dissolved and particulate organic matter. Nutrients may be lost through uptake, adsorption or settling. Interaction with primary producers includes consumption through photosynthesis and release through respiration.
- **Primary production:** The nutrient and oxygen cycles are primarily related through the growth and decay of phytoplankton, periphyton and macrophytes. Typical formulations of growth and decay of these organisms are incorporated in water quality models and are dependent mainly on temperature and the availability of light, oxygen and nutrients. Algae loss is usually defined in terms of mortality, i.e. transformation into dissolved and particulate organic matter, settling for phytoplankton, burial for periphyton and grazing by zooplankton.

The geometric domain of pit lake water quality models is often limited to the water column in the water body, although interactions do occur at interfaces such as the water surface and lake bed. Features are often included in the models to incorporate loadings from sediment. Precipitation and evaporation at the lake surface is often incorporated in the modelling formulation, and chemical loadings associated with precipitation may also be defined. Precipitation loadings should account whenever possible for impacts of aerial emissions from industrial activities if there are any near the pit lake.

3 Challenges and assessment of limitations

3.1 Data sources

The development of a database for pit lake modelling should be initiated from the early stages of the mining project. Climate, hydrometric, surface and groundwater water quality, and geochemical baseline studies will normally be undertaken to determine the environmental setting of a mining project. The data from these studies and the mine plan of the project are generally used to populate the database for pit lake modelling. Continuing monitoring during the planning, construction and operational stages of the project should be completed to refine the database and fill in any data gaps identified during the preliminary modelling stages. Thus, as the mining project progresses, so does the ability to model and design the desired pit lake. The types of data described below are normally required as model inputs:

- **Geological model:** The geological block model for the open pit is typically available in the early stages of a mining project. The geological block model provides important information about the rock types that will be exposed at the various levels of the open pit. This information forms the basis for defining the geochemical characteristics of pit wall runoff.
- **Lake geometry:** Pit geometry will typically be available in the early stages of the mining project, as part of the ore evaluation assessment. In the initial stage of modelling, the pit geometry may be represented in the model as a simple shape, such as a cylinder or cone. Such simple shapes should provide a reasonable approximation of the expected geometry of the pit, notably surface area, depth and volume. A more exact geometry will be required in 2D and 3D models, if more refined modelling is required in the early stages of the project and later once a final pit geometry is established.
- **Climate:** Long-term climate characteristics for the mine area will normally be developed from climate and hydrological studies in the early stages of the project. Climate change forecasts should be incorporated into these predictions. It is recommended that an onsite meteorological station will be installed and operated in the mine area from the early stages of the project to provide local climate characteristics, then be maintained and operated through the mine life, including during the closure and post-closure stages. Climate variables that are expected to affect the hydrodynamic and consequently water quality of the pit lake include precipitation and evaporation; air temperature; dewpoint; solar radiation; cloud cover; and wind speed and direction.
- **Inflow rates:** Establishing inflow rates for all water sources is required to assess the water quality and hydrodynamics of pit lakes. Sources may typically be divided into surface water and groundwater, as determined from their expected point of entry into a pit lake. Surface water inflow rates may be determined from a hydrologic assessment of the watersheds draining into the lake and overland flow, and may also consist of diverted waters from adjacent watersheds. Groundwater inflow rates will be evaluated from a hydrogeological assessment determining flow pathways through the ground using a model such as MODFLOW. The inflow rates should be combined into an overall pit lake water balance to evaluate the rate of filling, the relative volumetric proportion of each source of water contributing to the lake, the long-term water level, and outflow rates.
- **Inflow temperatures:** Water temperature affects the hydrodynamics of lakes, including stratification, and therefore will influence water quality. Temperature time series must be assigned as part of the modelling effort to all water sources to a pit lake. These time series should be established from observations of water temperatures in the mining areas, although it is not unusual for such data to be scarce in the early stages of the project. Climate data, notably air temperature, and regional water temperature data may assist in deriving water temperature for surface sources to the pit lake. Seasonal variations of groundwater temperature are not expected to be as high as those of surface waters. Time series for groundwater may be derived from regional groundwater temperature data, and will vary more with depth than with time.
- **Inflow total suspended and dissolved solids:** These two general water quality parameters affect water density and will therefore affect the hydrodynamics of a pit lake. Time series of these parameters must be developed as part of the modelling efforts for all water sources. Except in rare cases, groundwater sources can safely be assumed to contribute negligible suspended solids.

Assessment of these two parameters should normally be part of monitoring programs through all stages of the mine development. The levels of these parameters may vary significantly on a seasonal basis and depending on the watershed characteristics.

- **Oxygen characteristics:** Two components of the oxygen balance should be considered for each inflow source. First, the DO concentration in the inputs will be a direct source of oxygen to the pit lake. Second, chemical oxygen demand and BOD in inflow sources will lead to DO consumption within the lake. Dissolved oxygen is easily measured in the field, and this task should normally be incorporated into monitoring programmes throughout the stages of the mine development.
- **Geochemical characteristics:** Chemical weathering of rock exposed in the damaged rock zone of the open pit can contribute acidity, alkalinity, sulfate and metals to pit wall runoff. The results of the geochemical characterisation are required to assess the relative contribution of each rock type that is exposed in the pit walls. An understanding of the geochemical characteristics of pit wall rock, namely the rate of acid generation and metal leaching from the main lithologies, can have important implications with respect to mitigation strategies for the pit lake.
- **Inflow chemistries:** A chemical profile or time series will need to be developed for all inflow sources. This category of data can vary widely, and will depend on the objectives of the modelling and the parameters of concern. The list may include general parameters such as: pH, alkalinity, acidity and redox potential, major ions; nutrients and algae; organic compounds; and metals. Monitoring programs through the stages of the mine development constitute one source of data for constructing these time series. Deep groundwater inflow chemistry is particularly important in Canadian Shield waters as it is difficult to obtain but may substantially influence the major ion chemistry and TDS of the pit lake.
- **Sediment characteristics:** Loadings from sediments may impact water quality, particularly in the lower layers of pit lakes, and should therefore be incorporated in the model formulation. Sediment oxygen demand is an important driver of DO and is notoriously deficient from model input data. Metals, ions, nutrients and biogenic gases constitute typical loadings from sediment, which may be assessed from water quality analytical results from samples and geochemical analysis. The model described in Section 4 was developed to deal with these issues.

Data within the lakes themselves, if available, including general chemistry, nutrients, water temperature, TDS, TSS, DO, BOD and generic and toxic constituents, are also required. Such data will not be available in the early stage of the mining development, when the pit lake is not yet created. Therefore, data from similar lakes may serve for comparison with model predictions, in order to check the validity of the model until data from the pit lake itself are collected. Expert judgment is required to determine the adequacy of surrogate data.

3.2 Sensitivities

In the early stages of pit lake modelling, input data are limited, however, models may be used to identify key sensitivities. In a sensitivity analysis, one input variable is modified per model scenario, and the model results are compared to show a relative change in one or more output variables. For example, a sensitivity analysis might ask “if this pit lake is 10% larger, how will that change the salinity of the outflow compared to the base case?”, or “if this pit lake is filled in 10 years rather than 50 years, how will that change the overall chemistry of the pit lake compared to the base case?” The results of a sensitivity analysis can be used to define the design criteria to be applied to the pit lake at future stages of modelling. The sensitivity analysis serves also to identify the most sensitive input variables, which indicates that these variables are key drivers of the overall outcome of the pit lake.

Suggested input variables to use in a sensitivity analysis are listed below, along with their possible effects on water quality:

- **Lake residence time:** A long hydraulic residence time may enable appreciable aerobic decay of degradable and toxic constituents, and may serve to smooth seasonal variability in concentrations. Too long of residence times may lead to excessive evapo-concentration, which could contribute to meromixis and lack of outflow.
- **Lake depth, shape, and orientation:** The depth of a pit lake will normally be determined by the characteristics of the final mining pit and the amount of waste material to be disposed of at the bottom of the pit. Where flexibility exists, lake depth may be varied to optimise the balance between evapo-concentration in shallow lakes and meromixis in deep lakes. Meromixis may be favourable if the intention is to isolate waste from the outflow, but may be unfavourable if the intention is to promote aerobic degradation of constituents.
- **Lake filling time:** The desired rate of pit lake filling is dependent on site specific conditions. When rock with a high acid generation potential or metal leaching potential is exposed in the damaged rock zone of the pit walls, it is generally preferable to fill the pit rapidly to reduce the geochemical reaction rates. Conversely, in the case of oil sands pit lakes, longer filling periods will likely improve water quality at the time of initial discharge because of the additional time for degradation of toxic constituents.
- **Excavate or cover reactive wall rock:** When rock with a high acid generation potential or metal leaching potential is exposed above the projected final lake surface or within the watershed, it may be possible to cover this rock with a permanent geotechnical liner.
- **Water sources for lake filling:** Depending on local restrictions, natural background flows from local streams may be used to supplement inflows into a pit lake if the lake is to be filled more quickly than the rate that could be supported by the lake’s catchment. Filling with background water sources may also provide dilution to improve the quality of water at the time of initial release. The placement of different water types with different salinities may also be used to promote or inhibit meromixis.
- **Deposition of mine wastes in the open pit:** Deposition of mine wastes, such as tailings or waste rock, at the bottom of pit lakes can result in a reduction of lake volume and depth and the introduction of contaminant sources through pore water release and geochemical fluxes. Deposition of potentially acid generating tailings or waste rock below a water cover is a commonly used practise for mine waste management, as the water cover could reduce the rate of mine waste oxidation. In-pit disposal of mine wastes should be considered as part of the conceptual model, to ensure that the potential range of geochemical implications of deposition of mine wastes in a saturated environment is appropriately assessed in the pit lake model.

Other model parameters that are representative of natural processes impacting lake hydrodynamics and water quality, e.g. wind sheltering from topography, shading from surrounding vegetation, constituent decay rates, and reaction rates of rocks exposed in the pit walls may also be incorporated in a sensitivity analysis. Further field studies and design criteria can then be developed to support a more precise definition of the range of values applied to sensitive parameters.

3.3 Uncertainty

The goal of water quality modelling for pit lakes is to determine the characteristics of a lake (e.g. concentration of water quality constituent) under a reference assessment case (e.g. best, worst or likely case). The intent of uncertainty analysis is to develop confidence bands around the results of the assessment case as a function of the uncertainty of the inputs fed to the model. A standard approach for uncertainty analysis is Monte Carlo simulations (Figure 2), which consist of running and processing a large number of simulations (e.g. 200 to 1,000), each with its own sets of probable inputs. For this approach, probabilistic formulations must be defined for each input. These formulations are then used to develop a set of inputs for each simulation.

Examples of probabilistic formulations are given below for specific group of inputs:

- **Process inputs:** These inputs consist of model coefficients such as geochemical reaction rates, decay rates, nitrification rates, mortality rates and settling rates. Variations of these inputs may be defined according to a standard distribution, such as a uniform and normal distribution. The central value of that distribution may consist of the average or median of values available in the literature for the associated parameters. The upper and lower bounds forced on the distribution may be based on extreme values found in the literature or other calibrated models or expert judgment.
- **Flow and water temperature inputs:** If possible, flow and water temperature time series should come from hydrological and hydrogeological models. Sets of time series would result from an uncertainty analysis conducted with these models. Otherwise, variations of the characteristics (e.g. mean and standard deviation) of the time series of flow and water temperature time series of the assessment case may be defined according to standard statistical distributions. These distributions can then be sampled to develop one unique set of flow and water temperature time series per simulation.
- **Water quality inputs:** These consist of time series of water quality constituent concentrations, including TDS and TSS. Like flow and water temperature, water quality inputs may be characterised, and variations of the characteristics can be used to develop one unique time series per simulation.

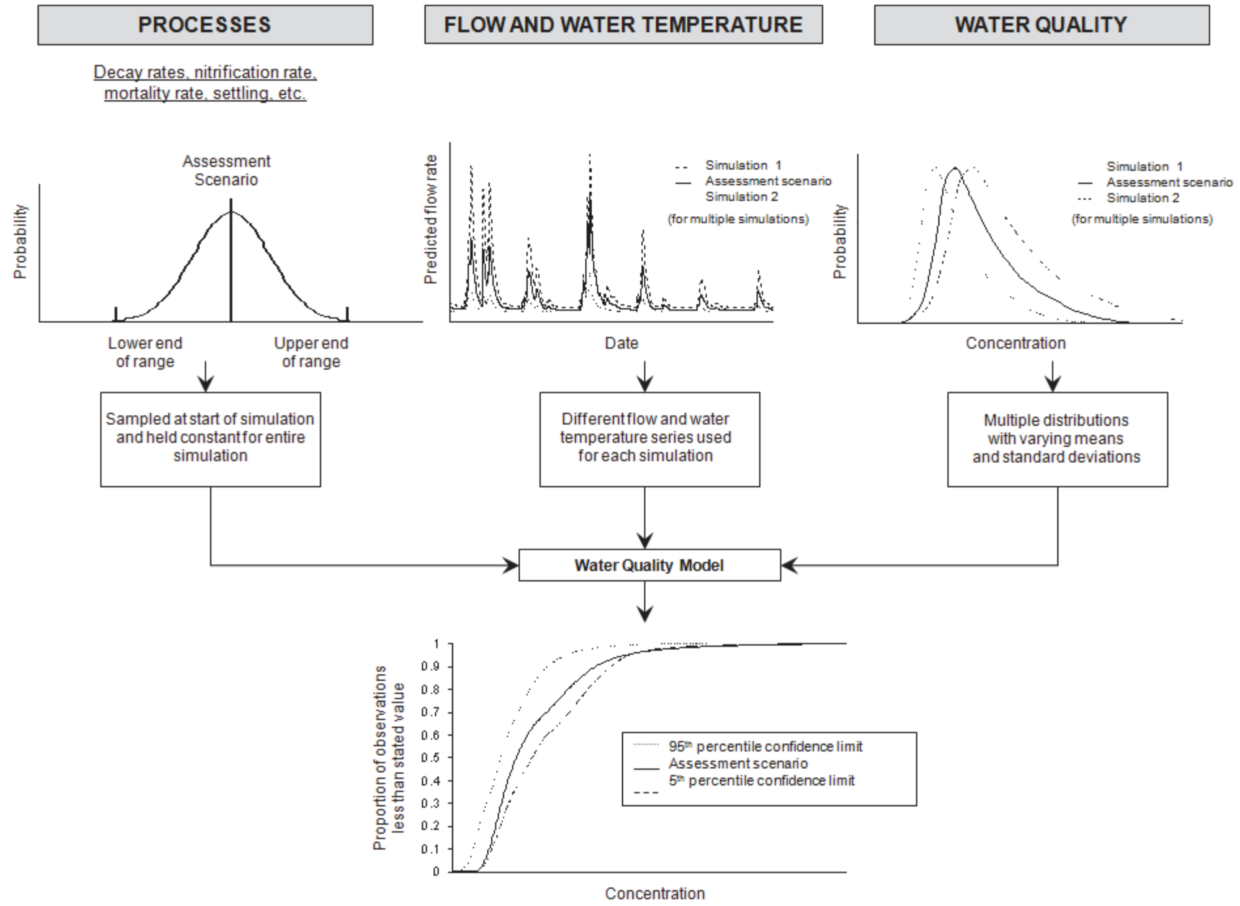


Figure 2 Schematic of uncertainty analysis applied to pit lake water quality modelling

4 Case study – modelling oil sands pit lakes

Several case studies exist with respect to hard rock mining applications of pit water quality modelling (Castendyk and Eary, 2009; Maest et al., 2005). Following is an alternate scenario whereby the principals as discussed previously are applied to modelling an oil sands pit lake.

The oil sands of Alberta, Canada represent the world's second largest reserve of oil, much of which is presently being or will be mined by conventional strip mining techniques. Similar to other mining operations discussed earlier in this chapter, oil sands mines will include pit lakes in their closure and reclamation strategy. In some of these pit lakes, mature fine tailings (MFT) will be placed in the pit before it is flooded with water to create a lake. The MFT poses challenges to reclamation because it contains organic substances as well as dispersed clay materials that settle very slowly (Mikula et al., 1996).

4.1 Oil sands pit lake model

The inclusion of MFT in a pit lake carries the implication of several processes that are not covered in existing water quality models. In particular, observations on operational tailings ponds indicate that physical and chemical processes within the sediment layer may have important implications for lake water quality (Holowenko et al., 2000). Physical effects include deepening of the lake as time progresses and the tailings consolidate and re-suspension of sediments when biogenic gas production leads to bubble ebullition. Chemical effects include the direct release of pore water to the water column, diffusion of gases from biogenic bubbles and consumption of oxygen as reactions take place at the sediment-water interface. A schematic of the conceptual model is presented in Figure 3. Because there is presently no model that accounts for the processes in the conceptual model, an oil sands pit lake model (OSPLM) was developed as a regional initiative by CEMA.

Figure 3 Schematic of the processes added to the CE-QUAL-W2 under the present phase of OSPLM development

The OSPLM is currently being developed for predicting sediment and water quality in oil sands pit lakes that contain MFT. Although OSPLM is designed specifically for oil sands pit lakes, it could be applied to other systems. Its primary focus is to incorporate chemical reactions within MFT that may result in the release of aqueous and gaseous compounds into the water column, leading to changes in pit lake water quality. The model simulates the anaerobic decay of these compounds and production of gases such as methane, which could alter the physiochemical nature of the pit lake water column.

4.1.1 Model platform

The OSPLM is being developed by programmatically adding processes relevant to oil sands pit lakes to the freely-distributed hydrodynamic and water quality model CE-QUAL-W2 Version 3.6 (Cole and Wells, 2008). The additional programs are added in the form of modules written to separate FORTRAN files to preserve the original CE-QUAL-W2 code.

4.1.2 Model setup

Several key processes were identified for the present development phase of OSPLM. The key processes can be categorised by the layers where these processes occur. These two compartments are the MFT bed and the overlying water column. CE-QUAL-W2 does not include a sediment transport model and thus the MFT bed was added as a separate sediment bed compartment to the existing CE-QUAL-W2 modelling framework. Additional constituents were added to the existing water column compartment within the CE-QUAL-W2 framework.

4.1.2.1 Sediment bed

The additional processes added within the sediment bed compartment for OSPLM include the bed consolidation, pore water release, sediment diagenesis, oxygen demand exerted on the overlying water column, gas production and release, and oxygen-demanding constituent decay. The sediment compartment added to the existing framework of CE-QUAL-W2 calculates the MFT bed consolidation and updates lake bathymetry for subsequent hydrodynamic calculations by adding active model grid layers below the lake bed. This approach provides a dynamic linkage between the hydrodynamics and the lake deepening. Consolidation of the MFT bed also adds expunged pore water to the overlying water column.

Methanogenesis has been found to be an important process within the oil sands pit lakes (Fedorak et al., 2002). To estimate the amount of methanogenesis and other gas production, a detailed sediment diagenesis model based on DiToro (2001) formulations was added to the module. The framework for this diagenesis formulation is shown in Figure 4. The gases produced during diagenesis processes build pressure within the MFT bed until the cracks appear. The bubble formation formulae were based mainly on the work of Boudreau et al. (2001). At the onset of crack formation, the produced gas is released into the water column. The diagenesis process consumes DO from the overlying water column, increasing the net SOD.

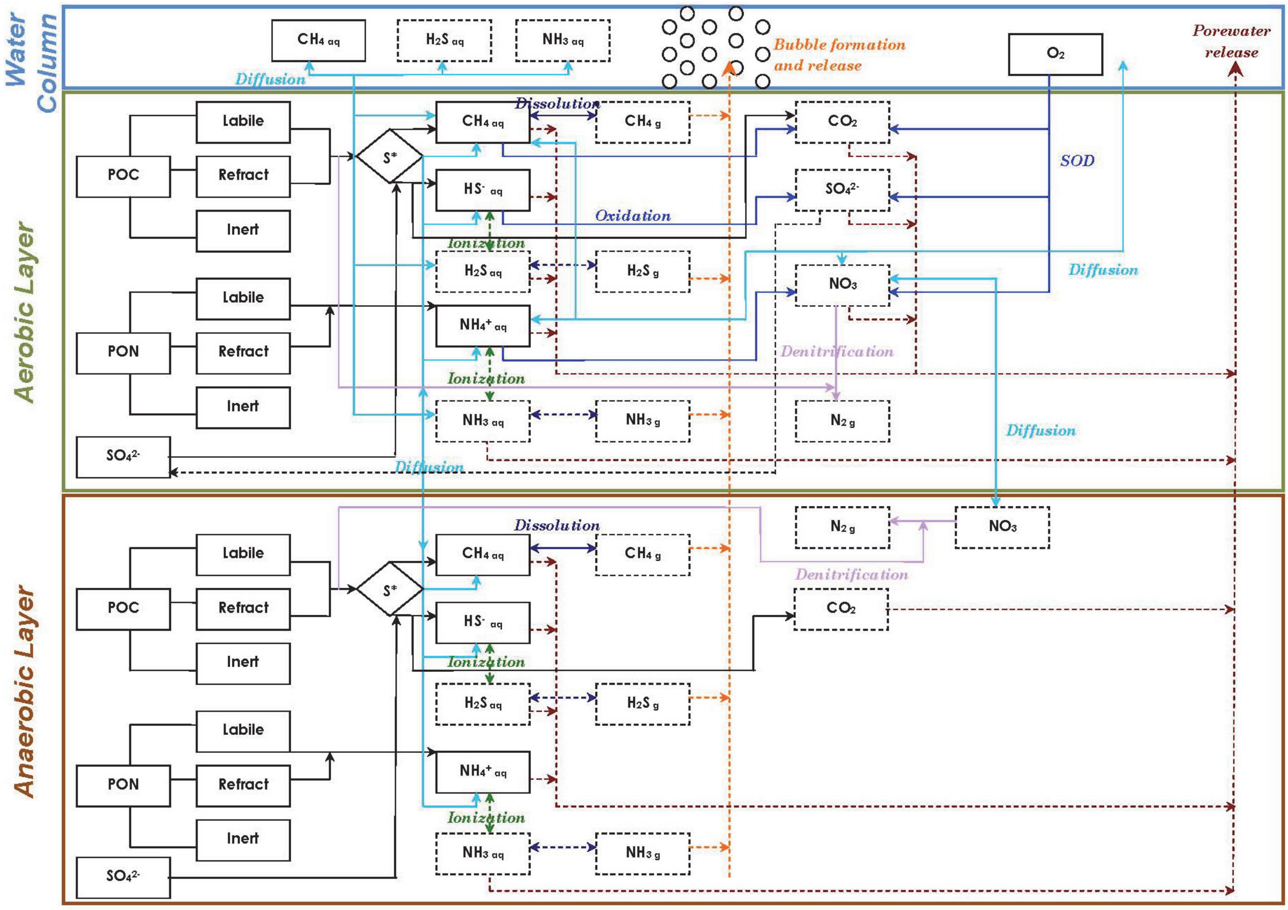


Figure 4 Sediment diagenesis framework included as part of OSPLM

4.1.2.2 Water column

The dissolved diagenetic products released through pore water and gases released through ebullition enter the overlying water column. In the water column, OSPLM links with existing CE-QUAL-W2 generic constituents to track the dissolved constituents that may consume oxygen. The movement of gasses released as bubbles from the MFT bed are also tracked through the water column until they reach the water surface where these gas bubbles burst to release gasses to the atmosphere. Gasses can also go through dissolution process while in the water column based on their solubility.

4.2 Modelling steps

In Section 2.2, the authors presented a series of steps a modeller should follow when setting up a pit lake model. These steps are now revisited using the OSPLM as a case study:

- **Define the objectives for modelling**. The objectives for modelling oil sands pit lakes are to understand the key drivers of water quality to inform pit lake design, particularly with respect to submerged tailings. In this example, the objective is to understand sediment processes and their effects on water quality in the water column.
- **Develop a conceptual model**. The conceptual model of sediment and water interactions is presented in Figure 3, and the sediment diagenesis processes are presented in Figure 4. The conceptual model was prepared through a literature review of relevant processes and through consultation with mine operators and researchers.
- **Select the appropriate model**. In this case, there was no existing model that could mechanistically model the processes of interest. Therefore, the OSPLM was developed specifically for oil sands pit lakes.

- **Establish key output metrics**. Several output metrics have been identified for the OSPLM. The model will output concentrations and fluxes of all relevant constituents, such as methane, hydrogen sulfide and ammonia, shown in (Figure 4).
- **Establish screening criteria in advance of model runs**. At the present stage of development, the model will be used for sensitivity runs. Once the predictive ability of the model has been further developed, screening criteria will be established against which simulation output can be compared.
- **Gather input data**. Data compilation will be a major undertaking for the OSPLM because there are many rates and constants that will need to be obtained. The first step will be to conduct a literature survey for available rates and constants. Then, field and laboratory studies will be completed to isolate and estimate specific rates and constants. Data for inflow quantities and chemistry, meteorology and other inputs can be gathered from the numerous baseline studies that have been completed for oil sands projects.
- **Implement quality assurance procedures**. Quality assurance procedures will be completed as specified in Section 2.2.
- **Calibrate and validate, if possible**. While there are no oil sands pit lakes as yet, there are experimental reclamation water bodies on existing oil sands leases. These water bodies may be used to calibrate part or all of the OSPLM. As oil sands pit lakes, or demonstration pit lakes, begin to fill, the model can be calibrated and validated in full.
- **Conduct an uncertainty or sensitivity analysis**. One of the main purposes for this model is to complete sensitivity analyses on sediment processes. The focus at this stage of development is experimental modelling, meaning that the mechanistic model will inform our conceptual model and vice-versa.
- **Compare results to criteria**. Once final and calibrated, the model will be used to assess pit lake performance against desired outcomes, such as maintenance of water column DO, low rate of sediment re-suspension, attainment of sulfide and ammonia guidelines, etc.
- **Continue improvement loops**. At this stage, the feedback loops are mainly occurring in the first three to five steps listed above. As the model becomes fully refined and developed, the next steps will be to focus on the validation and sensitivity analyses.

5 Summary and conclusions

Forecasting and evaluating pit lake water quality poses a challenge because of the variety of geological environments and ore deposit types that may be encountered. Furthermore, the lakes generally will not be constructed until decades after the initial mine design. For these reasons it is critical that each pit lake model be tailored to the specific conditions that influence the pit. Conditions that can strongly influence the pit model include: geochemisty, hydrogeology, hydrology, limnology, mine planning, pit backfilling, input water quality, and flow rates amongst others.

Predictive modelling is required in order to identify and implement mitigation strategies for the various stages of a mine development. Modelling allows an assessment of the potential range of water quality resulting from processes that may take years to occur. This chapter provides guidance with respect to modelling considerations. Model development starts with the setting of model objectives. Then, a conceptual model of the pit lake can be constructed that identifies key processes and inputs. A model can be selected to represent these processes, considering dimensionality and complexity of the system. If an appropriate model is not available, model development may be required to represent the processes of interest. The model must be able to report key metrics that can be screened against relevant criteria.

The outcome of a model can form the basis for water quality monitoring protocols. Monitoring data can be used to validate the results of a modelling effort. Long-term predictions can gain confidence and credibility if it is calibrated and validated, though this is not always possible with pit lakes. In the case of pit lakes that will not be constructed until well into the future, inputs to the model can be validated and refined throughout the mining period based on the results of operational monitoring, so that a robust database is available for pit lake design when it is time to fill the lake. During this period, model refinements can result in iterative loops to previous modelling steps. At all stages, quality assurance procedures can be completed to maximise confidence in model predictions.

While many water quality models are available publicly and commercially, and have been the subject of development and refinement for decades, opportunities for additional development and improvement remains available with these tools. Current and future areas of development that may be beneficial for pit lake water quality models include the coupling of hydrodynamic, water quality and geochemical models, as has been done to some extent in models such as ELCOM and OSPLM.

The case study of OSPLM discussed in this chapter provides an example of how models can be used to investigate key drivers of pit lake water quality. While preliminary, OSPLM provides a model framework for future refinements that can be completed as part of subsequent validations. As much as field and laboratory research will feed into model development, it is anticipated that the model will feed back into field and laboratory research by identifying knowledge gaps and key sensitivities.

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Development

Meeting environmental goals for pit lake restoration – factoring in the biology

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Abstract

Pit lakes may be the greatest legacies of open cut/cast mining operations, yet they are often the least considered at mine closure. Internationally, there are generally well established best practice approaches to the rehabilitation of terrestrial legacies from mining. In contrast, world-wide mine closure guidelines for pit lakes are often simplistic, with a strong focus on water quality. Water quality will generally dictate the functioning of newly created pit lakes, however ecological theory suggests pit lakes should evolve along a predictable trajectory from simple (predominantly) inorganic chemistry driven processes to eventually becoming dominated by biochemical processes. The transition towards significant biological processes developing in the pit lake can be extremely slow due to self-reinforcing chemical processes which buffer against change. Typically, the ecological community that develops will be a subset of that found in regional water bodies. The size and importance of the subset will be largely determined by the similarities in the physical and chemical environments that can be achieved in the pit lake to those of regional water bodies.

This chapter discusses important components of natural water bodies and how these are represented in pit lakes. Consideration needs to be given to which factors typically limit the development of key biotic processes within pit lake systems. These factors may include: 1) unnaturally small catchments of pit lakes which limit opportunities for organic matter and nutrients to accumulate in the lake; 2) lack of riparian zones, which are typically ignored in the terrestrial revegetation of the pit lake catchment, but play an important role in a range of processes associated with natural lakes; 3) limited littoral habitat for the establishment of complex biological communities, as shaping of the lake edge is predominantly confined to considerations of safety and stability (angle of repose); 4) lack of normal lake sediments as the pit lake bed lacks the organic matter content needed to support biological processes; and 5) water quality issues associated with extreme pH and toxicity may form positive feedback loops limiting establishment of biological communities. A brief overview of the natural development of pit lakes is presented, as are recommendations for specific considerations that may improve the rate of biotic development. Internationally, understanding of pit lake ecology is limited and mine closure planning may provide opportunities to investigate and trial restoration issues prior to relinquishment.

1 Introduction

Technological advances have allowed open cut mines to be larger in extent and depth, making them uneconomic to backfill. Therefore, more pits are likely to become pit lakes, making them an increasingly common feature of mined lands. Furthermore many mining regions or mines consist of multiple pits leading ultimately to multiple lakes creating a landscape of lakes – an engineered lake district (McCullough and van Etten, 2011). Lake districts of pit lakes can pose further problems for closure as the pit lakes might not be independently linked via surface or groundwater.

Natural aquatic habitats are also becoming increasingly diminished in their frequency, area and quality through both local and global anthropogenic activities. Concurrently, the growing activities of open cut mining are contributing pit lake aquatic habitats to post-mining landscapes. This offers opportunities during mine closure for mining companies to create a positive environmental legacy (McCullough and van Etten, 2011).

This chapter focusses on pit lakes that will ultimately form part of a region's ecosystem values. The development of biotic processes and an aquatic ecology within these lakes is considered, followed by a brief review of what is currently known and finally how better consideration of the biological fate of pit lakes during mine closure can enhance the development of these processes in a positive trajectory.

2 Key features of lakes that need to be considered in mine closure

2.1 Hydrology

Lake hydrology is essentially a balance between the volume of water in the lake, relative to the volume entering from surface runoff, groundwater and direct rainfall, and the volume leaving the lake via evaporation, transpiration, groundwater and surface discharge (Sawatsky et al., 2011). Pit lakes are no exception to this; although groundwater contributions are often the dominant component. It may take decades for the water table of deep pit lakes to rebound following cessation of dewatering and fill the pit lake. Although pit lakes may be located in, or near natural drainage lines restored upon closure, most pit lakes are deliberately isolated from these sources to reduce risk of environment impact. Nevertheless, the complicated nature of groundwater aquifers in many mined areas and the ongoing need to dewater during operations can make it difficult to accurately predict the final height of water rebound (Figure 1).

Figure 1 **An extensively 'rehabilitated' 20 year old pit lake in southwest Western Australia showing the limited catchment of some pit lakes (bounded by the tree line) and the difficulty in predicting final rebound heights. Final water height is at least 2 m below that predicted, reducing the value of much of the bankside contouring for development of a littoral and riparian margin**

2.2 Catchments

Any lake is a product of its catchment. Natural lakes connected to drainage lines often have large catchments relative to the lake surface area. However for many pit lakes, the catchment area to lake area ratio is relatively low at <4:1 (Figure 1). Surface inflows may bring high quality rainwater into the lake which can help maintain water quality against evapo-transpiration and solute inputs (Figure 2). However surface runoff, in pit lake catchments is often deliberately minimised to reduce the potential inflow of acid and metalliferous drainage (AMD) from the mine waste in the catchment. Oxidation of sulfidic minerals in exposed mining waste in the presence of water and bacteria can lead to AMD when there is limited neutralisation capacity in the catchment.

Prior to relinquishment, catchments are often shaped to geotechnically stable slopes and revegetated to the waterline. However, many pit lakes fail to attain riparian vegetation, even many years following closure (Figure 1). This is mainly due to a lack of riparian-species specific planting, unstable pit lake margins, low nutrient concentrations in the soils and rapidly changing pit lake water levels during filling (van Etten, 2011). The contribution of organic carbon (C) by terrestrial riparian and catchment vegetation was recognised many years ago as a primary causative factor in water quality improvements in AMD pit lakes (King et al., 1974). Riparian vegetation will also contribute physically to bank stabilisation, facilitating further littoral and bank vegetation establishment. One approach that has worked successfully in the southwest of Western Australia was planting of terrestrial vegetation in areas that were subsequently flooded as the pit lake filled; the dead vegetation then contributed to sediment organic C and habitat in the new lake's littoral zone.

A number of variables within physical, chemical and ecological subsets must therefore be considered when developing a pit lake for an ecological end use. These variables will begin with basic and site-specific physical considerations such as climate and void shell shape that will determine lake size, bathymetry and mixing regime, through to chemical variables such as catchment geology and other land uses that will largely determine water quality (Figure 2). Ecological variables such as the presence of catchment and riparian vegetation and diversity and abundance of primary producers (algae or aquatic plants) which form the base of food-chains for first and second order consumers such as zooplankton and fish will be dependent on the nature of these underlying and often largely pre-determined features.

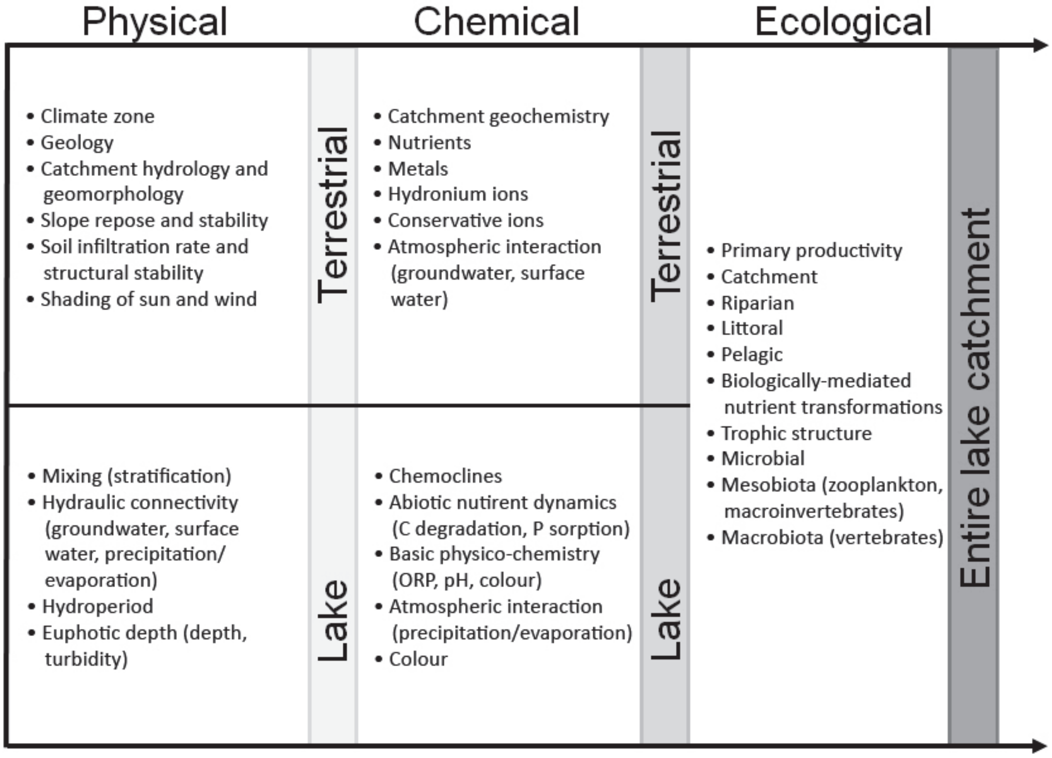

Figure 2 Catchment influences on lake development at different key stages of lake ecosystem development

2.3 Bathymetry

Mine planning attempts to minimise the removal of waste materials, such as overburden, while maximising ore recovery. As a consequence, pit voids are typically steep sided and deep relative to surface area. Pit lakes are often located high in the landscape or away from natural drainage lines. As a result, catchments are predominantly artificial and therefore often small. Where natural watercourses have been diverted to allow mining the pit lake can be reconnected to the catchment, although this creates risks of contaminated discharges. The extent of backfill is often limited due to cost and a desire to avoid burial of potential future resources, so tends to reduce the area of the pit rather than substantially altering its depth profile (Puhalovich and Coghill, 2011). The shape of pit lakes and their surrounds are often important in influencing the phytoplankton communities that occur in the lakes (Weithoff et al., 2010). Pit lakes are also often surrounded by mining waste such as overburden piles which can shelter the pit from normal wind patterns (Huber et al., 2008); reducing water column mixing within the lake. The bathymetry of pit lakes resembles that of many oligotrophic (low productivity) lakes, with steep sides and limited littoral areas relative to limnetic zones (Hakonson et al., 2009). The littoral margin is the shallow productive edge of lakes (Wetzel, 2001). It receives sufficient light for extensive plant and algae communities to grow and provide habitat and food for plankton, macroinvertebrates, fish, amphibians, waterfowl and mammals. The limnetic zone extends beyond this, where a lack of light prevents rooted plant surviving, but not necessarily all types of algae and cyanobacteria. The other important habitat area is the benthos which is the community of species living on, in or near the lake bed.

Habitat availability to biota is further complicated in pit lake ecosystems due to stratification. Stratification is encouraged by the steep sides, low surface area and low wind action, a process that can create a hypolimnion (bottom water layer) isolated from the surface. In many pit lakes, chemical oxygen demand (the low productivity of pit lakes often means that biological oxygen demand is not the principal reason) ensures that the hypolimnion is anoxic. Anoxic water bodies are unsuited to most desired lake organisms such as fin fish and crayfish. For example, in Collie, Western Australia, large freshwater crayfish (marron, *Cherax tenuimanus*) utilise the lake benthos when the lake is fully mixed but rise to depths above the hypolimnion during stratification; presumably due to anoxia. The population size of this desirable endemic fishery is therefore dependant on the size and resources (food and habitat) of the oxic littoral area of the pit lake, which is typically small in pit lakes.

2.4 Nutrient availability

Aside from any water quality issues associated with extreme pH and metal toxicity, most newly formed pit lakes are limited in available macronutrients; primarily C, nitrogen (N) and phosphorus (P), although micronutrients any also be limited. The Redfield ratio suggests that 106 moles of C, for every 16 of N and 1 of P are required for algal growth (Redfield and Ketchum, 1963). In natural lakes, C is typically readily available: through allochthonous (external) sources such as riparian vegetation input from the catchment, through natural dissolution of atmospheric CO_2 into the water (bicarbonate buffering), and from carbonates derived from the catchment and/or lake geology. Autochthonous (internal) production by algae and aquatic plants also fixes dissolved C into organic compounds in the lake. Nitrogen is also fixed from the atmosphere by some species of cyanobacteria and bacteria, and also washes in from the catchment from biological or geological sources (surface and groundwater). In natural lakes, sources of P are mainly limited to erosion of geological materials and the limited quantities in allochthonous sources of organic matter. As a result, it is typically P that limits primary productivity in natural lakes (Wetzel, 2001). In pit lake waters, the abundance of metals such as iron, manganese and aluminium ensure that P is often bound to sediment or precipitated out of the water column, further limiting its availability (Kleeberg and Grüneberg, 2005). Iron and manganese bound P is redox sensitive, released when these metals are reduced. This situation commonly occurs during stratification and development of an anoxic hypolimnion.

Nitrification is also limited or restricted under low pH (Nixdorf et al., 2001) which prevents the conversion of ammonia to nitrate/nitrite (NOx). As either NOx or ammonia are both available for algal uptake, this probably has little impact directly on algae, however is an area where pit lakes with relatively high ammonia concentrations differ from natural lakes with proportionally higher NOx. Significantly, denitrification of NOx is a source of alkalinity that is limited by NOx availability (Davison, 1987). Pit lakes have a typically low C concentration in sediments and the water column. The substrate is often almost completely mineral when the lake fills, with the only sources of C commonly being refractory coal and carbonate minerals in host geologies. Organic C accumulates very slowly in the substrates of pit lakes due to low input rates from allochthonous (poor riparian development, small lake catchment size) and autochthonous (in-lake plants and algae limited by nutrient availability) sources. Benthic algae and bacteria often occur across the lake sediment absorbing both nutrients from groundwater entering the lake and bound to sediment. Despite what appears on occasion to be relatively heavy benthic algal biomass, this growth may make little effective contribution to increasing substrate organic matter concentrations (Laskov et al., 2002). In strongly acidic pit lakes C is limited to dissolved CO_2 gas as the major C source. Heterotrophic photosynthetic bacteria also require dissolved organic C for growth (Tittel and Kamjunke, 2004). Low turbidity and dissolved organic carbon concentrations are typical in acidic waters, and results in extreme water clarity that creates ultra violet light (UV) exposure problems for a range of biota that could live in the lake. Furthermore, the UV and acidity accelerate dissolved organic C mineralisation to CO_2 which is then lost from the lake ecosystem (Schindler and Curtis, 1997), further limiting C availability. Low nutrient availability is often reflected in deep chlorophyll maxima, with algae occurring in peak abundances at depth to enable access to nutrients in the hypolimnion while protected from UV exposure.

2.5 Habitat

A major difference in the littoral area between natural oligotrophic lakes and pit lakes is that natural lakes tend to have diverse structural elements such as rocks, logs and plants (emergent and submerged) that provide habitat for organisms (Figure 3). Pit lakes have a typically poorly developed riparian zone, few plants and logs, and often sandy or muddy edges (McCullough et al., 2009). The substrate of pit lakes is also dominated by bedrock and talus and has a very low organic content (Blodau et al., 2000). Therefore the littoral regions of pit lakes are generally much poorer habitat than those found in natural lakes. In natural lakes, macroinvertebrates and decomposers (bacteria and fungi) breakdown organic matter into usable dissolved forms and a small quantity of small fragments form a denser layer in the sediment. Little is known of how these processes work in acidic pit lakes.

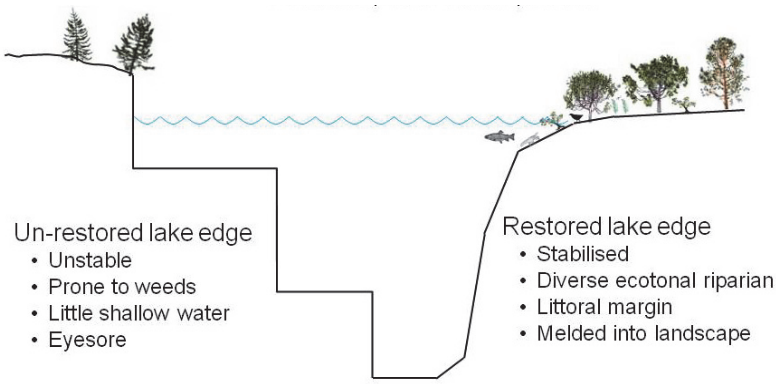

Figure 3 Development of riparian and littoral edges increases biodiversity and provides ecosystem processes to facilitate pit lake ecosystem development

2.6 Taxa

Primary production contributes to the ecological value of a pit lake in many ways. Algal primary production and allochthonous C form the basis of lake food chains providing the energy sources that are the basis of lake-ecosystem food webs (Wetzel, 2001). Primary producers can also facilitate sulfate reduction, increasing alkalinity and pH in acidic pit lakes (Nixdorf and Kapfer, 1998; Lund and McCullough, 2009), chelate metals directly causing toxicity or sorbing phosphorus (Kalin et al., 2001), and help mitigate carbon limitation (Nixdorf and Kapfer, 1998). There has been remarkably little research completed on the biota of pit lakes, with algae (benthic and planktonic) receiving the most attention (Beulker et al., 2004), with limited studies of zooplankton, macroinvertebrates (Proctor and Grigg, 2006) and very few for vertebrates.

Toxicity due to acidity and elevated metal/metalloid concentrations limits the richness of species found in pit lakes primarily to more cosmopolitan and tolerant taxa (Neil et al., 2009). Abundance is also typically low, however this appears to be primarily due to limited food resources rather than due to pH or metal toxicity (Wollmann et al., 2000). Pit lakes that are circum-neutral tend towards the diversity and abundance of macroinvertebrates in natural lakes (Proctor and Grigg, 2006; Lund and McCullough, in press), although still limited by the availability of food and habitat in pit lakes.

Terrestrial animals often use pit lakes as a source for watering, e.g. feral animals such as pigs and goats and native animals. Pit lakes can pose a significant risk to animals if the water quality is toxic or the sides of the lake have not been bunded and create a falling risk. Water birds will also use the pit lake for habitat as protection from predators, if water quality is suitable and there are sufficient food and habitat resources.

3 Natural analogues for pit lakes

What are the analogue systems for pit lakes? Firstly, pit lakes cannot be returned to pre-mining conditions, as formerly there was typically no lake/wetland. Pit lakes are characteristically large in area and deep and as such may not have any natural counterparts in the region. For example, where natural lakes are very shallow, they may still provide some value as analogues for the pit lake littoral area (McCullough et al., in press). However, there remains no reference for the limnetic or profunal zone of the pit lake. Despite the problems, it will possible to use regional aquatic systems as 'analogues' for at least specific habitats within a pit lake and use this to as a reference for what goals might be achievable (McCullough and van Etten, 2011).

4 What happens if you do nothing?

The 'do nothing' approach to pit lakes considered here, is following relinquishment and compliance with minimum regulatory requirements, such as stable slopes, fencing, etc. Geochemical weathering processes in the catchment of a pit lake can lead to poor water quality and toxicity to aquatic life (Neil et al., 2009). Affected lakes typically have limited ecological value and may affect regional water bodies through contamination of surface and groundwater sources (McCullough and Lund, 2006).

Given sufficient time many pit lakes will move from being dominated by chemical processes to biological processes. In this way, pit lakes are similar to any other area on the planet that has not had biological life on it previously, e.g. lava flows, landslides, etc., King et al (1974) describes natural restoration of pit lakes though natural, albeit slow, remediation processes such as water quality remediation by primary production and sulfate reduction. This finding has lead to an assumption that pit lakes will follow an evolution from young to mature lakes resulting in lakes with a well-developed ecosystem (Kalin and Geller, 1998). However, there are many examples of pit lakes formed soon after open cut mining technologies became commonplace that have not improved in environmental quality measures such as biodiversity and ecological function (McCullough et al., 2008, 2009). Therefore for many pit lakes, the 'do-nothing' restoration approach which assumes that primary succession will eventually lead to a mature lake is likely to take periods of time that are too long (hundreds to thousands of years) to be acceptable to regulators or the public (Schultze et al., 2009; Jones and McCullough, 2011).

5 Considerations for mine closure planning

The following are suggestions with regards to the future biology of pit lakes that can be considered during mine closure planning:

- Although it may be unfeasible to create a 'natural' bathymetry for a pit lake, biological development will be enhanced by first creating geotechnically stable slopes. The shallow littoral region of lakes is the most productive area. However, in pit lakes this area tends to be designed to meet slopes for human safety rather than the shallower slopes that would be more beneficial to biota.

- Pit lake catchments are generally minimised to reduce risks associated with offsite contamination. The ecology of pit lakes could be enhanced by maximising water flows across uncontaminated soils into the lake and thereby enhancing the potential for allochthonous C washing into the system.

- Dedicated planting of riparian vegetation to create a source of C and habitat to support biodiversity in the littoral areas. This is particularly important for attracting birds and amphibians. The use of cleared vegetation from operation areas, including tree trunks, stumps and branches in and around the littoral area may help stabilise lake banks and provide a source of slow release C and other nutrients during decomposition and also importantly animal habitat. Alternatively, amendments with complex organic materials could be made in some circumstances to accelerate this development process. Creation of a three-dimensional structure in the littoral area in particular, through use of logs, organic matter, riparian and if necessary inert materials would enhance habitat available for larger species, e.g. birds, fish and amphibians.

- In pit lakes amendment with low concentrations of P and/or N may stimulate primary production. Amendments with nutrients and organic matter are also known to stimulate a range of biological alkalinity producing processes that will work to improve water quality.

6 Conclusions

As a pit lake fills, biological activity begins in the lake; it is initially limited by physical, chemical and pH constraints. In many instances biological development will overcome the physical and chemical constraints and start to develop a pit lake aquatic ecosystem. Although little is known about pit lake ecology, our understanding of natural lakes suggests that relatively inexpensive and practical treatments applied to the pit prior to filling and during its early life should be able to improve the rate of ecological development significantly. Recognition during mine closure planning that many relinquished pit lakes will eventually develop ecosystem values would allow trials of many of the ideas presented in this chapter. A by-product of this investment is that environmental end use goals for pit lakes are recognised almost universally as the 'gold standard' and will assist companies with their plans to successfully close leases pit lakes with minimum liabilities remaining with stakeholders.

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The role and value of riparian vegetation for mine pit lakes

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Abstract

Riparian vegetation contributes to biodiversity and ecological processes of natural lakes and wetlands. This contribution can vary in importance depending on the size of the water body, e.g. high for small wetlands, low for large lakes. Formed by flooding of open cut mining voids, pit lakes are new landscape features that can show very different physical, chemical and biological characteristics and slow rates of ecological development compared to natural waterbodies. Due to high acidity, high heavy metal concentrations and low concentration in nutrients, pit lakes typically have low primary production when compared to many natural lakes. In this scenario, organic matter, mainly in form of leaves and coarse woody debris from the riparian vegetation can represent a relatively important source of food for aquatic consumers in addition to that provided by planktonic algae, and thereby potentially play an important role in the productivity of these systems. Furthermore, riparian vegetation may significantly enhance pit lake value in other ways, such as shading, bank stability, aesthetics, faunal habitat and biodiversity, principally because pit lakes generally lack these attributes. For these reasons, we argue riparian vegetation can play a more important role in pit lakes than in natural lakes. In this chapter, we explore the role of the riparian vegetation in pit lakes and why they should be considered in pit lake restoration programmes, as well as techniques to establish this vegetation.

1 Introduction

Pit lakes are formed when open pit/open cut mining has ceased and the mine void fills with water via groundwater inflow and/or surface runoff to create a lake. The number of pit lakes world-wide has increased markedly since the 1970s and is expected to further expand over coming decades as technological advances and rising commodity prices combine to improve the economic viability of open pit mining (Castendyk and Eary, 2009).

Pit lakes in general face a range of acute restoration challenges and environmental hazards, including: low or zero primary productivity and biological activity; depauperate biodiversity; poor water quality (e.g. high in acidity and heavy metals); risk of poisoning visiting animals; risk of contaminating downstream surface waters and groundwater; unstable and highly erodible slopes; and poor visual amenity (Eisler and Wiemeyer, 2004; McCullough, 2008). Shoreline contours of pit lakes rarely resemble natural contours and there are few examples of local analogues, i.e. nearby natural wetlands with similar characteristics which can be used as a model system to guide and assess the success of restoration actions; (Hobbs et al., 2009; McCullough and van Etten, 2011). This is clearly the case in arid and semi-arid lands where permanent surface water is a rare phenomenon. Pit lakes also typically have no or little development of vegetation at the shoreline or riparian zone – the important transitional area between aquatic and terrestrial environments. There are usually good reasons for this lack of riparian vegetation as pit lakes are often inhospitable sites not conducive to plant growth. This chapter addresses three aspects of riparian development around pit lakes. Firstly it explores the prospective value of riparian vegetation to pit lakes (where it can be successfully rehabilitated) from a number of different perspectives, but particularly in terms of its potential to contribute to ecological processes in pit lakes. Secondly, the chapter outlines the considerable constraints and difficulties faced in restoring pit lake margins with vegetation and other species. It finishes with coverage of potential restoration approaches and techniques which can enable this vegetation to develop at lake margins.

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1.1 Definitions and scope of review

As end products of open cut mining, pit lakes are generally deep, large and relatively new areas of permanent freshwater. Many are oligotrophic (very low levels of organic carbon, nutrients and primary productivity). Although this review focuses on these typical types of pit lakes, as this is where the major restoration challenges and environmental risks are concentrated, it will also consider other types of pit lakes from small freshwater ponds created from former gravel and clay pits to relatively shallow lakes created from dredging of sands (also known as dredge ponds). These smaller pit lakes are valuable to this review as many have been successfully restored, both in terms of their aquatic and riparian ecosystems, and consequently may reveal important insights into barriers to restoration of larger pit lakes, as well as potential solutions to overcome these barriers.

The riparian zone is defined in this chapter as the interface between aquatic and terrestrial ecosystems and is, in practice, land immediately above the general lake water level but influenced by this water through lateral flow, access (by plant roots) to lake or associated groundwater, spray and/or occasional flooding. In this way the riparian zone is a strip of vegetation surrounding a lake, often relatively narrow, which is distinctly more mesic, dense and productive than vegetation in the adjoining upland terrestrial zone (Figure 1). More often than not it is dominated by trees and/or woody shrubs. In many lakes, vegetation also develops in the shallow water at the lake's edge, both in the area which is seasonally or regularly inundated and emerging from permanent water (as aquatic macrophytes). This vegetation typically comprises tall monocots (sedges, rushes, reeds, etc.) and trees/shrubs tolerant of extended i. This vegetation zone is referred to as fringing vegetation in this chapter, and as it often contributes to the same or similar values and ecological processes as riparian vegetation, and has similar issues in terms of its establishment, it is also covered in this review where relevant and appropriate. The fringing zone is effectively the upper littoral zone – the littoral zone being the lake water and bank from the upper water level to a depth of water where net photosynthesis is no longer possible (Figure 1).

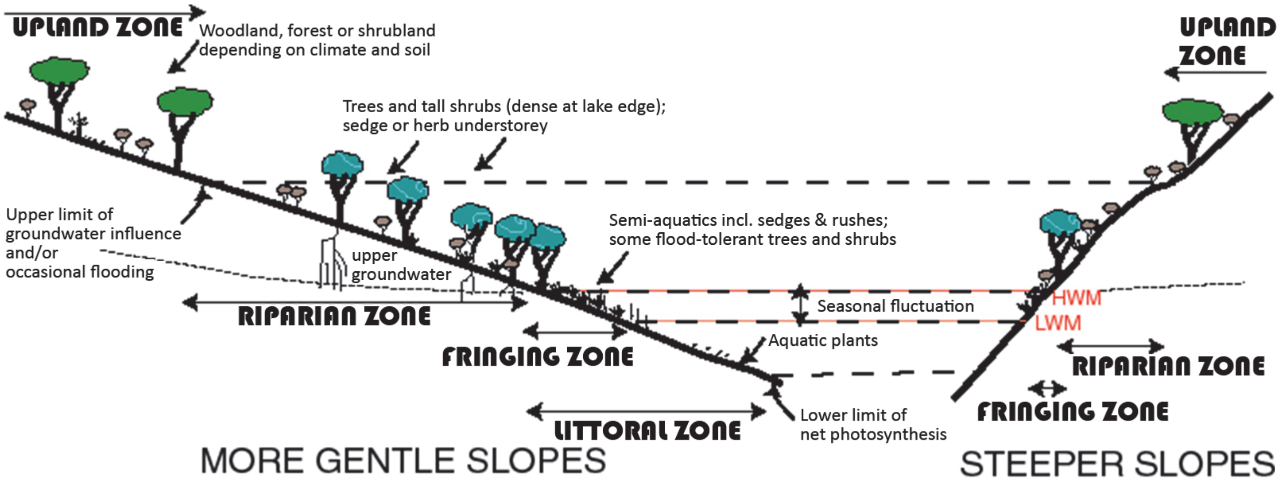


Figure 1 Generalised slope profiles delineating riparian, fringing, littoral and uplands zones at lake margins for steep and gentle slopes. Vegetation descriptions are general only and will vary from lake to lake. HWM=high water mark; LWM=low water mark

As is there a dearth of published studies on the importance and function of riparian vegetation to mine pit lakes, and references to its successful establishment are scant, mainly anecdotal or in the 'grey' literature, e.g. consultant reports, this review uses natural lakes as the closest analogue to typical pit lakes. In particular, we focus on large, deep and oligotrophic lakes where possible to draw parallels with and extrapolate to typical pit lakes. The links between riparian vegetation and lake ecosystems have received some research attention (Schindler and Scheuerell, 1992), however, most of the work on the value and importance of riparian zones to aquatic ecosystems has focussed on rivers (Naiman and Décamps, 1997). Therefore, generalisations on the value of the riparian zone to river ecosystems, as well as specific studies on these zones, are also used to compare and, where appropriate, extrapolate to pit lake environments.

However, this is primarily done to demonstrate prospective or theoretical benefits of riparian zones to mine pit lakes and need to be placed in the context of the major difficulties, general lack of success and shortfalls in expertise in restoring pit lake edges.

2 Riparian values

2.1 Biodiversity

In general, riparian habitats are rich in biodiversity and this is largely attributable to the wide range of environmental conditions they cover, both spatially and temporally, particularly in terms of soil moisture (Naiman and Décamps, 1997). They are likely to harbour species from neighbouring terrestrial and aquatic habitats, especially at their respective margins, as well as a host of species adapted to or preferring specific ecological niche(s) within the riparian zone. Consequently, they usually harbour more plant species per unit area than adjoining terrestrial and aquatic habitat (Naiman et al., 1993), although their conservation value tends to stem from the unique and often rare species that are restricted to riparian zones (Sabo et al., 2005). Relative dense vegetation, availability of perch and nest sites, and ready access to water and food, invertebrates in and above water, mean these areas are also rich in fauna, particularly birds (Malanson, 1993; Knopf and Samson, 1994). Historically, riparian zones have played an important role as refuge areas in times of prolonged dry periods, and this may become an increasingly vital function given impeding human-caused climate change (Meave and Kellman, 1994; Lake, 2011).

In rivers, disturbance created by floods and moving water is important in creating shifting mosaics of depositional and erosional patches of soil/sediment, which contributes to species diversity in riparian zones (Johnson, 1992; Naiman and Décamps, 1997). This is a less important factor in lakes, both natural and artificial, although the hydrological (flooding) regime is still important in establishing species and community zonation patterns at lake margins, and hence contributes to biodiversity.

Given pit lakes generally have no or only simple riparian vegetation, restoration of this zone, even to a rudimentary level, will very likely add new species to the ecosystem and enhance local scale biodiversity. Pit lakes, given their size, may also extend riparian habitat at the regional scale and thereby improve conservation values, especially where natural riparian ecosystems and/or their species are rare or restricted (Otahel'ová and Oťahel', 2006). Furthermore they may extend the availability of refuge areas for more mesic species of the region in general. In arid and semi-arid environments, which often have no or few aquatic habitats, establishment of riparian vegetation around pit lakes may even add to the regional species pool and attract a greater range of migratory species given the improvement in habitat complexity over unvegetated pit lakes. Ultimately, the degree to which artificial lakes, such as pit lakes, sustain or contribute to regional biodiversity depends on the number, distribution and complexity of habitat types that are restored and how similar they are to natural wetland habitats in the region (Zedler, 2000).

2.2 Organic matter, carbon and nutrient input

It is well established that riparian vegetation is an important allochthonous (external) source of organic matter for freshwater ecosystems, mostly in the form of leaf litter falling directly into water (Naiman and Décamps, 1997). Such organic matter is a direct food source for shredding invertebrates and some fish, as well as being a vital input of organic carbon and nutrients to aquatic systems. It is particularly important in streams where the tree canopy overhangs the water, and the input (as a proportion of the total carbon or nutrient budget) generally declines with increasing stream width (Conners and Naiman, 1984). Laterally transported organic matter, via runoff from surrounding vegetation in catchment or flooding within riparian zone, is of less importance, mostly less than 10% of total litter input, but may still be of significance as it is typically has higher nitrogen content than litter falling directly into water bodies (Benson and Pearson, 1993).

For lakes, organic matter input from the riparian zone is generally less than streams in both total amount and proportion of total inputs. However riparian inputs into lakes are highly variable, depending largely on the perimeter and width of the riparian zone relative to the size of lake, as well as the vegetation density and structure in this zone (Gasith and Hasler, 1976; Schindler and Scheuerell, 1992). Riparian habitat of larger, deeper lakes tend to be narrow, sometimes with patchy or no tree cover, e.g. drylands, cold climates, tundra, and hence may play a minor role in organic matter input to the lake. However, allochthonous leaf litter may still represent a valuable and proportionally high source of organic matter and carbon in oligotrophic lakes which have little to no primary production (autochthonous input of carbon). Gasith and Hasler (1976) reported that airborne leaf litter can be responsible for about 10% of total carbon budget in large oligotrophic lakes whilst generally accounting for <1% in similar-sized eutrophic lakes.

Pit lakes can be generally classified as oligotrophic systems in terms of their primary productivity, with typically low carbon and nutrient levels (Hakonson et al., 2009). They also may have very low pH where acid generating substrates are present. Hence, the successful development of riparian vegetation is potentially important in terms of increasing organic carbon and nutrient content in lakes with low base levels of these chemicals. In fact, riparian vegetation may be the key to, or at least play a role in 'kick starting' biological activity and ecological succession in oligotrophic pit lakes (Beulker et al., 2004). Increasing phytoplankton growth, even to small degree, can further increase carbon levels and, in turn, promote greater productivity, as well as more consumers of this food source (zooplankton, etc.), with cascading effects along the food chain (Hakonson et al., 2009). Both diversity and complexity of the ecosystem are likely to increase with increasing primary productivity (Brunberg et al., 2002). Although such succession may develop naturally in pit lakes, it typically occurs at exceedingly slow rates and may stall at particular steps in the succession. Therefore organic matter from riparian sources may be important in speeding up these critical ecological processes. Inputs of organic matter also come from the broader catchment via streams entering lakes as well as surface runoff from surrounding slopes. Most pit lakes are sited away from major floodplains and river systems and surface drainage is typically diverted or managed to prevent overfilling of the pit lake. However, where there is scope to consider the source of water used to fill pit lakes, it may be more sensible to use surface water higher in organics and nutrients, such as from eutrophic wetlands or vegetated streams, in preference to groundwater or local runoff, for instance. Understanding the characteristics of pit lake catchments (areas, water quality, water quantity) is an important step for not only managing water budgets/hydrology, but also for encouraging the development of pit lake ecology (Sawatsky et al., 2011).

In conclusion, the relative importance of riparian inputs of carbon and nutrients to pit lakes generally decreases with their increasing size (lake water volume) and background water carbon/nutrient levels. Larger lakes therefore are likely to require wider and denser riparian strips and or greater catchment input.

2.3 Nutrient and sediment filters

Riparian vegetation helps protect aquatic ecosystems by intercepting and trapping sediment (and pollutants bound to sediments) carried by surface water flowing from surrounding uplands (Malanson, 1993). This is a particularly important role where surrounding land use(s) result in exposed and erodible soils, e.g. agriculture, clear-cut forestry and implementing riparian buffer zones of appropriate width around rivers and lakes has become a commonplace management practice (Haycock et al., 1996; Clinton, 2011). Riparian vegetation slows down surface water flows to prevent channelling of water, allowing more time for sediments to settle out. Ground-level vegetation (grasses, sedges, low shrubs, etc.), as well as plant debris on the ground, are particularly effective in reducing flow rates and physically trapping sediment in flowing water.

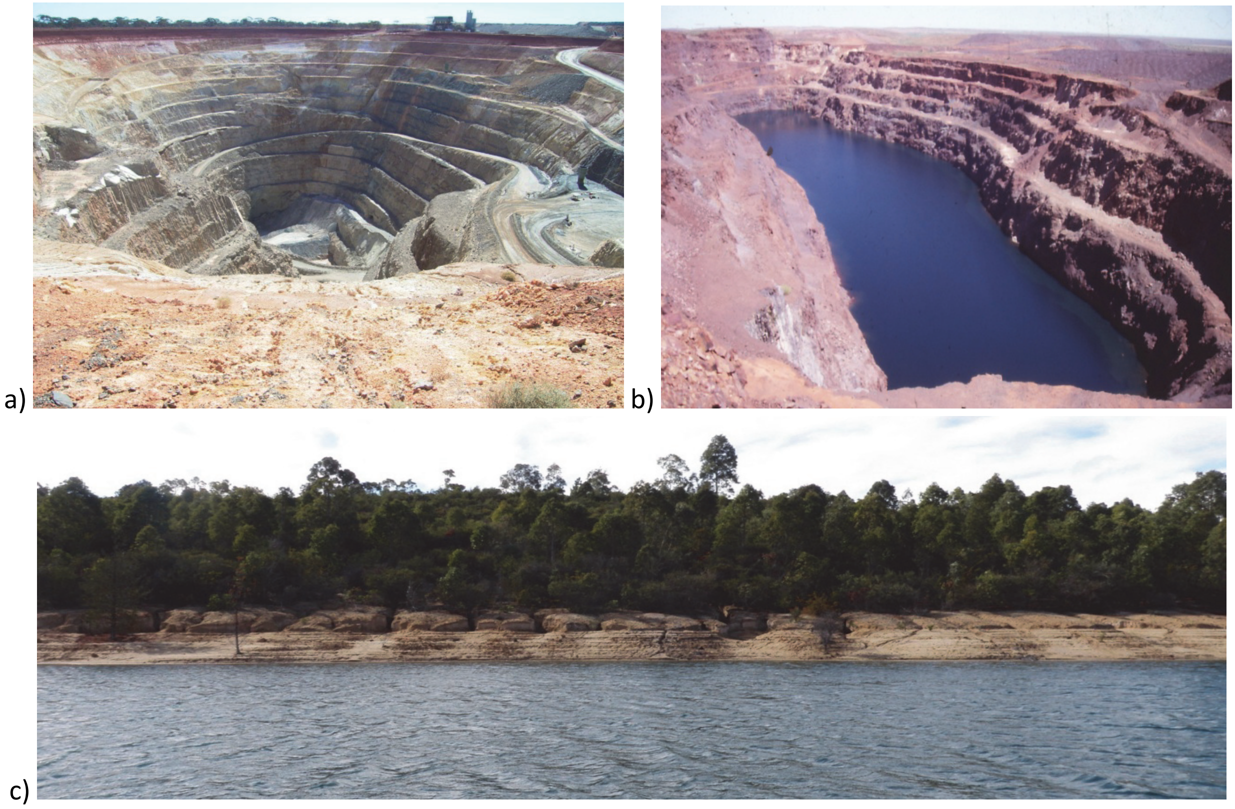
Riparian buffer strips have been shown to be very effective in reducing pollutants entering wetlands, such as pesticides and other toxic organic chemicals (Arora et al., 2010). They are also highly effective in removing nutrients; for instance, the meta-analysis of Mayer et al. (2007) showed riparian buffers, if they are sufficiently wide, remove most of the nitrogen in surface runoff entering rivers and lakes. However, this does not necessarily represent a loss of nutrients entering the wetland over the longer term; much of the nutrients trapped in riparian zone would be expected to be uptaken by plants and then at least some of this returned to the water as dead leaves and other plant debris at a later stage (Peterjohn and Correll, 1984; Mayer et al., 2007). Furthermore, the passage of nutrients through riparian vegetation is likely to change the nature of nutrients into more soluble and biologically available forms. For instance, sediment-bound phosphorus is typically trapped but then may be exported into wetland (via inflows) as soluble phosphates following decomposition of litter and other microbial processes operating in riparian zones (Vanek, 1991).

As has been argued in this chapter, addition of nutrients from surrounding uplands is likely to be important for encouraging biological activity in large, oligotrophic pit lakes. Also, sediment entering lakes from surrounding land may help establish and consolidate further plants in the riparian and littoral zones and enhance habitat diversity of benthic zones in mine pit lakes with hard-rock slopes and floors (Gammons et al., 2009), presuming some riparian vegetation can be established in the first place. Hence, filtering of sediment and nutrients by riparian vegetation may seem counter-productive in the first instance, however a longer-term perspective suggests that riparian zones are likely to be sites of sustained net nutrient and organic carbon export into lakes, and this is particularly the case for forms of these elements directly usable by aquatic biota. Furthermore, riparian vegetation around pit lakes may help prevent damage from excessive short-term inputs of chemicals, and generally regulate and even out inputs.

2.4 Aquatic habitat

As well as adding litter and other fine plant debris, riparian zones are also an important source of coarse woody debris (CDR) in rivers (Naiman and Décamps, 1997) and lakes (Schindler and Scheuerell, 1992). CDR is typically slow to decompose in water and thereby can provide long-term habitat for benthic biota, particularly fish, amphibians and aquatic invertebrates. CDR in littoral zones significantly enhances the structural complexity, biodiversity, resilience and productivity of lake ecosystems (Schindler and Scheuerell, 1992; Sass et al., 2006). Such debris at lake/river edges also helps to stabilise slopes and encourages trapping (and accumulation) of alluvial soil, propagules and fine organic matter (Montgomery et al., 1995).

Commonly the littoral zone of pit lakes is biologically barren. Therefore the role of riparian vegetation in supplying CDR is likely to be relatively important for not only providing habitat and enhancing biodiversity, but also for bank stabilisation and macrophyte colonisation of the littoral zone. Encouraging macrophytes at the edges of pit lakes will further enhance habitat complexity and biodiversity of lake edges (Persson and Eklov, 1995; Otahel'ová and Oťahel', 2006; Figure 2).



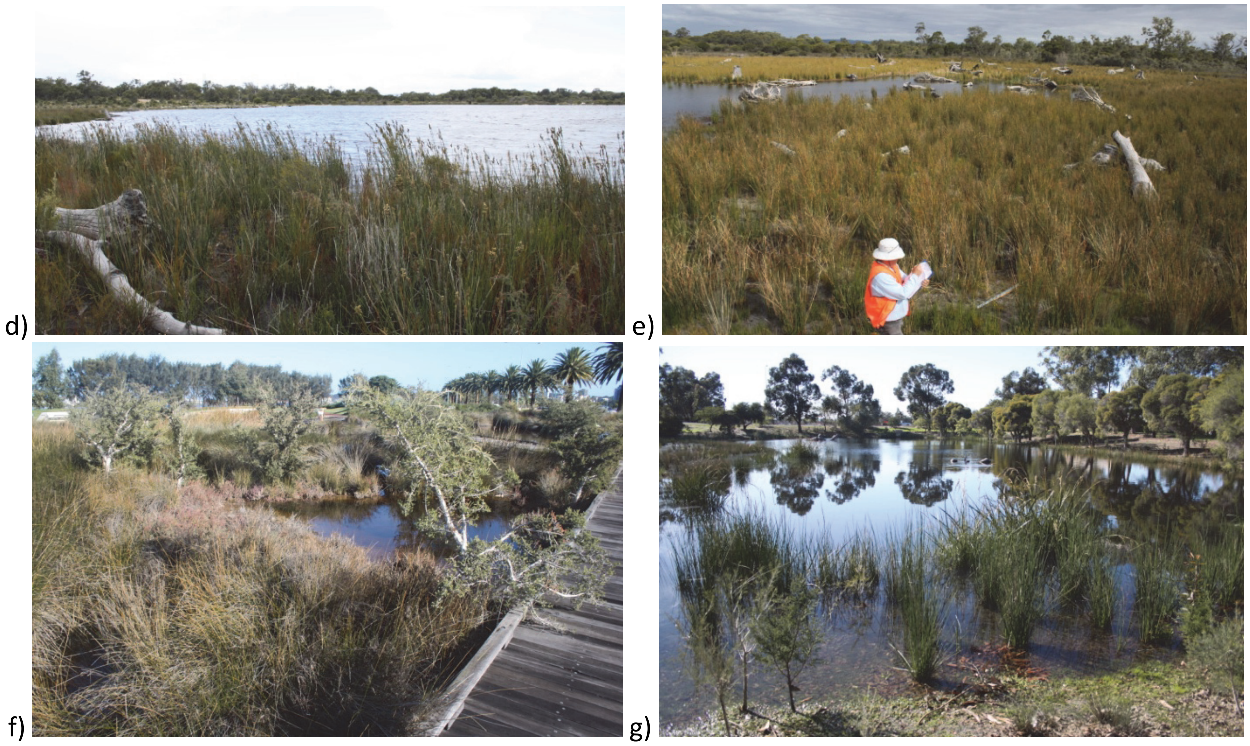


Figure 2 **Photographs of lakes with and without restored riparian zones: a) active gold mine pit at Kanowna Belle, near Kalgoorlie, Western Australia (WA), showing steep slopes and benches typical of hard-rock pits; b) pit lake with steep sites at Goldsworthy (iron ore), Pilbara Region, WA; c) edge of small pit lake in Collie coal mining district, WA, showing bare strip of vegetation in riparian zone (so called "bathtub" effect) with successful terrestrial rehabilitation above; d) and e) successful restoration of riparian and fringing vegetation (3–6 y.o.) at small pit lakes formed following sand mining at Kemerton, WA (note relatively subtle slopes and logs on ground); f) artificial wetland planted with sedges and trees some six years after establishment, Point Fraser, Perth, WA; and g) restored ox-bow lake adjacent to Canning River, Perth, WA (sedges and rushes were planted at lake edge). Photos courtesy of: a, b, e, f, g: E.J.B. van Etten; c: H. Jones; d: C.D. McCullough**

2.5 Shading and microclimatic modification

Riparian vegetation, being relatively dense, is effective in filtering sunlight and reducing air temperatures and wind speeds at lake/river edges (Chen et al., 1999). This results in less photosynthetic active radiation (PAR) and generally lower water temperatures in the upper littoral zone of wetlands. Although this would generally lead to lower primary productivity, steep microclimatic and light gradients at lake/river margins are likely to enhance biodiversity through the provision of a greater range of ecological niches (Naiman and Décamps, 1997). Furthermore, shading at the wetland edge helps to reduce temperature fluctuations (diurnal and seasonal variations) and avoid temperature extremes, which may be important for certain species or activities (e.g. breeding of fish; Balirwa, 1995). For large lakes, the riparian effect of reduced light and temperatures is unlikely to have a significant effect on overall lake productivity and any reduction would, in all likelihood, be outweighed by potential biodiversity and ecological enhancements.

2.6 Erosion control and bank stabilisation

Another vital role of riparian vegetation is to stabilise banks of wetlands (Beeson and Doyle, 1995). The roots of plants are highly effective in binding soil/sediment and thereby help prevent it being eroded by moving water. Dense and multi-layered vegetation consisting of multiple growth forms (tree, shrubs, herbs, rhizomatous plants, etc.) is more likely to develop greater and deeper root mass and density, thereby offering greater protection, than more simple vegetation structure. Although this stabilisation role is logically more important in rivers and streams, especially in sections of flowing water, it is still important in large lakes where the fetch is sufficient to generate waves and surface water currents of some force

(Hofmann et al., 2008). Dense riparian vegetation however effectively dampens wind and wave energy and thereby may reduce the impact of wind-generated waves at lake margins. The benefits of riparian vegetation to the stability of pit lake margins is therefore likely to be more important in larger lakes, although the substrate type and degree of slope are likely to be more significant factors. Pits with hard-rock surfaces, a common scenario, will be considerably more resistant to erosion than pit edges comprising of sand, mud, silt, etc. Where sediment dominates at the lake edge, and this applies to where it is added for restoration purposes, as well natural accumulation of sediment, slope is probably the most important factor determining erosion from wave action, although riparian vegetation can still render stability even when banks are relatively steep.

2.7 Aesthetics

With the exception perhaps of cold climates, natural lakes almost always have riparian vegetation of some degree, even in degraded or highly modified systems, and it is generally recognised that such vegetation improves scenic values (Brown and Daniel, 1991). A vegetated riparian zone at a pit lake margin is likely to look more natural than one without vegetation and is therefore more likely to be acceptable to the general public and regulators. Although ultimately subjective, riparian vegetation is likely to dramatically improve the visual amenity of pit lakes over that of bare areas (Figure 2c). Scenic value is particularly important where pit lakes are planned to be used for recreation (Gammons et al., 2009).

2.8 Safety and access control

Given many pit lakes are hazardous sites (poor water quality, toxic chemicals, steep and unstable slopes), it is often necessary to keep people, livestock and wildlife away. Riparian vegetation, where dense and multi-layered, has proven to be effective in deterring access to waterways and may work in similar fashion for pit lakes, although this should be integrated with other access control measures such as fencing, etc., especially given livestock are likely to target riparian areas for food and shelter.

3 Restoration challenges at pit lake margins and their solutions

Although values and benefits of riparian vegetation as outlined above are likely to be realised if restoration is successful, it should be recognised that pit lakes are generally harsh and unique sites in terms of their bio-physical environment, and present a number of difficult restoration challenges. These include the following.

3.1 Steep slopes

Steep slopes are a challenge to restore for a number of reasons: soil erosion, subsidence, landslips, etc. The nature of much open pit mining, particularly involving hard rock, means that steep slopes may be unavoidable with remedial action to fill pits and reform slopes likely to be prohibitively expensive. However, there may be scope to create more gentle slopes in the zone where the final water level of pit lakes is anticipated through such measures as battening-down edges, partial backfill, and/or using existing benches as high water mark (Gammons et al., 2009) (Figure 3). More gentle slopes also effectively increase the potential width of the riparian zone (Figure 1) and are more resistant to erosion by water.

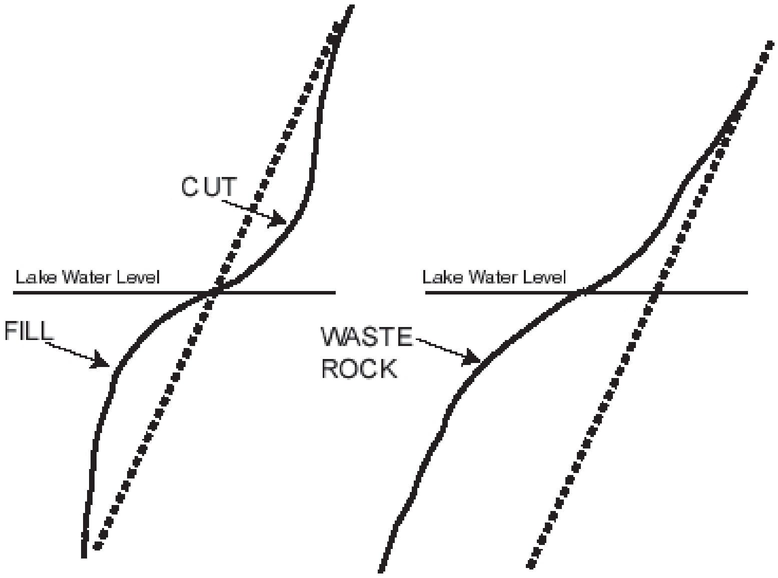


Figure 3 **Slopes profiles of steep pit faces showing before (dotted line) and after (solid line) remedial treatment to reduce slope angle. Treatment on left is 'cut-and-fill' where rock material extracted from slope is used to create bench below. Treatment on the right is using waste rock to build bund or bench. Predicted average lake water levels are shown. Figures are for illustrative purposes and are not necessary to scale**

3.2 Hard rock surfaces

Mining of rock inevitably results in hard, compacted surfaces on pit lake slopes and floors. This represent a challenge for revegetation of the riparian zone given few plant species have roots which can penetrate rocky ground. Natural development of soil through rock weathering is a very slow process with much of this soil likely to be eroded away before plants can establish, especially on steeper slopes. Therefore soil development may need to be quickened through blasting, drilling, landscaping and/or addition of looser material, e.g. overburden, crushed waste rock or topsoil (see Section 5.4) where available and affordable. The absence or lack of substrate/soil represents one of the main barriers to plant establishment around pit lake margins.

3.3 Water level fluctuations

It is difficult to establish and maintain riparian vegetation where the pit lake water levels fluctuate in an irregular, stochastic or dramatic fashion. Riparian and fringing vegetation patterns are strongly linked to hydrology, particularly flooding frequency and seasonal timing, and, in fact, a predictable, regular fluctuation is likely to result in zonation of different species and communities at pit lake margins (Malanson, 1993). Dramatic shifts in flooding patterns are likely to compromise already existing vegetation patterns as plants are unable to adapt or migrate quickly enough to the new flooding regime. General water levels of pit lakes can be predicted and effectively managed through study of water budget, control of surface inflows and provision of overflow channels, etc., with annual fluctuations due to seasonal differences in groundwater levels and/or rainfall input likely to be acceptable if not excessive in degree.

3.4 Wave action

As outlined above, the common phenomenon of wind-generated waves in large lakes promotes soil erosion within riparian zones. Solutions to mitigate or reduce this impact include landscaping of more subtle slopes, development of robust and resilient riparian vegetation and armouring slopes with rock, logs and other debris. Other approaches involve reducing the fetch and wind speeds through innovative land forming, such as creating islands and inlets, ridges and dunes.

3.5 Poor water quality

Where pit lake water quality problems are severe, such as heavy metals and acute acidity, direct toxic effect on plants are possible, especially for fringing and aquatic plants in direct contact with water for prolonged periods (Gammons et al., 2009). In these circumstances, restoration may need to be postponed until water quality improves through some intervention, or species selection needs to be biased towards species more tolerant of toxic chemicals. Tolerant plants which can also sequester heavy metal ions are particularly desirable as they may reduce overall toxicity levels and thereby encourage other plants over time (Baker and Whiting, 2002).

4 Case studies

4.1 Hard rock mining, Rocky Mountains of North America

The Rocky Mountains is rich in mineral resources, particularly metals such as copper, gold, lead, silver, molybdenum and zinc, and as a consequence has numerous open pits, many of which have been abandoned to become pit lakes, although rates of filling with water are comparatively slow; many are still filling. Some of these pit lakes have severe water pollution issues.

For example, the Berkeley Pit Lake, located in Butte, Montana is a large (~1.3 km^2) and deep (250–300 m) pit lake containing water of pH ~2.5 due to oxidation of pyrite and other sulfides, and is consequently high in heavy metals. It is the largest EPA 'superfund' site in the USA and infamous for the death of a large population of migratory lesser snow geese (*Chen caerulescens caerulescens*) which landed on the lake in 1995. It has no detectable organic carbon available to support biological activity and the steep-sided, hard rock slopes has prevented development of riparian vegetation to date. Also a 'superfund' site, the Yerington mine site in Nevada (ex-copper mine) has a large pit lake with similar but not as severe water pollution problems as Berkeley. This lake, in contrast, has developed some riparian and littoral habitat on one side, with studies recently commissioned to assess its viability, ecosystem function and role as bird habitat.

Shevenell (2000) reported that most of the 10 ex-gold mine pit lakes she examined in Nevada had slopes which were too steep for development of riparian vegetation, despite generally having good water quality (i.e. neutral pH, low in As). There were a few exceptions with one pit lake in particular having healthy riparian vegetation and was used for recreational fishing and boating. She concluded that lack of riparian zone was limiting wildlife and recreational potential in Nevada pit lakes.

Hakonson et al. (2009) studied the bathymetry of an unnamed pit lake in this region and found that, due to very steep slopes at the shoreline, only small areas of littoral and riparian zone were produced. The total amount of littoral zone habitat comprised only 4% of the lake surface area and 0.4% of its volume.

4.2 Sand mining of coastal dune systems, southwest Australia

Mining of sands for heavy minerals, silica and construction is commonplace on the extensive coastal sand plains south and north of Perth, Western Australia. Due to relatively shallow aquifers under much of these dune systems, mining is often done by dredging which results in a series of relatively small and shallow pit lakes (also called dredge ponds) which are basically surface expression of local groundwater systems. Evaluation of rehabilitation on the slopes and margins of dredge ponds in the Kemerton area, some 120 km south of Perth, demonstrated that spreading topsoil over landscaped slopes was the most successful method for re-establishing species-rich vegetation in riparian and fringing zones, but not uplands (areas uninfluenced by groundwater) which were often devoid of native plants. This was believed due to topsoil being sourced from wetland margins and seasonally waterlogged 'damplands' and hence contained seed of species adapted to or preferring wetter sites (van Etten et al., in press; b). The most successful restoration in terms of resemblance to native local vegetation was riparian zones with subtle slopes (Figure 2). Wind-dispersed seed is likely to have contributed to dense cover of sedges in fringing zones. Availability of topsoil and 'soft' substrate (sand), as well ease of land forming to create gentle slopes, are likely to be main reasons for this success.

4.3 Former gravel pits, UK

Large numbers of ponds and small lakes have been created throughout the United Kingdom and Europe following extraction of gravel, clay and sand for the building industry. The Aldermaston Gravel Pits, in Berkshire, UK, are a typical example. Here seemingly spontaneous colonisation of emergent semi-aquatics such as Carex, Phragmites and Typha are evident. The shoreline has dense tree cover of Salix and Alder, and these lakes and ponds have become important habitat for birds including rare species and others of conservation significance (Dobson et al., 1997). Many people mistake them for natural lakes.

4.4 Martha Lake, New Zealand

Plans for the creation and rehabilitation of a large pit lake form an integral component of the mine closure plan for Martha Mine, a gold and silver mine near the town of Waihi, NZ. The goal here is to create a recreational lake to be used by local community. Plans include the provision of berms around the edge of the lake primarily for safety reasons, but also to develop a wide littoral zone for revegetation with semi-aquatic plants. Lake levels are to be controlled using outlets, and little fluctuation in water levels is expected. River water is to be pumped into the lake in early years to accelerate filling; this water is relatively rich in nutrients with models predicting the lake will become eutrophic and reasonably productive. This demonstrates the importance of catchment hydrology and runoff in contributing to water quantity and quality (Sawatsky et al., 2011). Hydroseeding has been used to revegetate upper slopes ahead of pit filling; however, this has not been successful on acid forming slopes.

4.5 East Pit Lake, Wabamum, Alberta

This pit lake was created following surface mining of coal. Extensive landscaping and contouring occurred after mining to create shallow lake beds (average depth just over 3 m) with relatively gentle slopes. Large number of trees, shrubs and grasses were planted on slopes and aquatic species planted in shallow water. Logs and branches were also deposited into the lake (Gammons et al., 2009). The end result has been a healthy ecosystem with diverse assemblages of fish, aquatic invertebrates and aquatic plants (Sumer et al., 1995). It is now a popular recreational fishery.

4.6 Coal mine pit voids, Collie, Western Australia

Collie is the main coal mining district in Western Australia and numerous pit lakes have developed in abandoned mine voids. Most of these are relatively large and deep and suffer acute water quality problems (high acidity and metals, little biological activity, etc.). Rehabilitation of slopes above lake using a combination of top soil, seeding and planting has been relatively successful in restoring native forest of the area, but riparian and fringing zones are often unvegetated (Figure 2c). Restoration of these zones has been recommended as one solution to add organic carbon and nutrients to these lakes (McCullough et al., 2009).

5 Restoration planning and techniques

5.1 General guidelines

The review of literature and case studies demonstrate the difficulty of restoring pit lake riparian zones, but also that success is possible in some circumstances. There are many published guides and manuals on river and lake restoration, as well as those for creating artificial wetlands, which are likely to be helpful to establish appropriate techniques to revegetate riparian zones around pit lakes (Meney, 1999; Brierley and Fryirs, 2008; Romanowski, 2009). Restoration ecologists working to establish riparian and fringing vegetation in new wetlands or restore degraded riparian zones face some of the same constraints and issues as those working to revegetate pit lake margins.

5.2 Setting goals

Setting appropriate and clear restoration objectives and goals is the first and probably the most important step in planning any restoration project as it establishes or guides all other key decisions and steps (Tongway and Ludwig, 2011). These goals need to be realistic, e.g. cognisant of the biophysical constraints and degree of modification inherent at the site, and include clear targets with timelines. For riparian vegetation around pit lakes, restoration goals can vary from the functional (e.g. nutrient inputs to lake), structural (e.g. certain vegetation cover), diversity (e.g. % of species returned) and/or geomorphic (e.g. degree of slope stabilisation). No matter what goal(s) are chosen, it is usual practice to establish a reference or analogue system relevant to the goals as a way to assess progress and degree of success in restoration (McCullough and van Etten, 2011). For pit lakes, these can be based on characteristics of natural wetlands in the surrounding area (van Etten et al., in press; a) or some hypothetical ecosystem where no similar natural wetland exists (Brewer and Menzel, 2009).

5.3 Species selection

Ultimately the selection of species for a restoration project should reflect the chosen goals and the underlying site characteristics/constraints. Understanding the patterns and processes operating in natural wetlands nearby can help elucidate appropriate plant species for restoration of pit lake riparian zones (van Etten et al., in press; a). Otherwise, local guides to wetland flora are likely to be valuable. More specifically, species chosen need to have morphological and physiological adaptations to cope with biophysical conditions of the riparian zone, e.g. widely fluctuating soil moisture, some degree of water logging and anoxic conditions, shifting sediments, etc. Also reproductively, many plants in the fringing and riparian zones spread vegetatively (rhizomes, resprouting, etc.) and these traits allow relatively rapid colonisation of intermittently flooded sediments (Naiman and Décamps, 1997). Seeds of species in these zones also often display hydrochory (adaptations to dispersal by water movement, such as the ability to float).

5.4 Site treatments

The roles of site treatments are to improve rates of survivorship and growth of restored species and to generally reverse degradation processes. In addition to treatments outlined above to deal with specific constraints imposed by pit lakes, usual post-mining treatments such as ripping (to reduce compaction), weed control, surface roughing (to improve water infiltration) and fertilisation (to encourage initial plant growth) should be considered. Fertilising usually needs to be carefully practised close to aquatic systems, but would be generally permissible adjacent to most pit lakes given their typical oligotrophic status.

5.5 Habitat construction

In addition to providing or encouraging appropriate environmental conditions for plant species, post-mining landscaping and other specific site treatments can also accelerate the development of habitat conditions to support fauna. Logs placed at or above high water mark can create sites for faunal shelter, basking, perching, movement, etc., whilst fringing vegetation in general is good frog habitat. Habitat complexity can be enhanced in the fringing and sub-littoral zones through adding submerged rock, logs, etc., these artificial reefs are likely to improve fish and amphibian breeding and diversity over the long-term (Gammons et al., 2009).

Artificial floating islands have been successfully constructed out of floating materials (either natural or plastic) lined with heavy sediment and seeded/planted (Gammons et al., 2009). These islands effectively increase the surface area of vegetation in lakes and hence may improve nutrient assimilation, pollution filtering and habitat creation over that of having riparian vegetation alone. They have proven to be successful in improving water quality in artificial wetlands (Stewart et al., 2008).

5.6 Methods for plant establishment

Provided suitable substrate is available or can be developed for plant growth, the next step in restoration is vegetation establishment, with several techniques available. The usual debate over planting versus seeding extends to the restoration of riparian and fringing zones. Planting (of nursery-raised seedlings) has advantages in these environments as plants can be specifically conditioned to expected environmental conditions of revegetation site and are already established (resulting in higher rates of survivorship; Figure 2). Seeding is comparatively cheaper, but can be difficult to achieve at lake margins as seed can be washed away. This applies to directly applied (sown) seed as well as to topsoil application and hydroseeding (seed embedded in mulch); the solution therefore may be to apply seed (in whatever form) whilst water levels are low so that plants are established to some degree before onset of flooding.

Topsoiling has been successfully used to restore many post-mining landscapes including margins of dredge ponds following sand mining (van Etten et al., in press; b), as well as degraded riparian zones in general (Nishihiro et al., 2006). In practice, topsoil needs to relatively fresh (to maintain viable seed) and applied with sufficient thickness to provide an acceptable density and diversity of plants. Additionally, topsoil needs to be sourced from similar environments as the site it is applied onto to ensure species are adapted to the site (van Etten et al., in press; b). For these reasons, it is unlikely sufficient volumes of suitable topsoil will be available to restore riparian zones of pit lakes unless initial mining is concentrated on wetland margins.

It is difficult to establish plants via seed or planting on steep slopes due to erosion and subsidence. Matting made of biodegradable fibre (jute, coir, hessian, etc.) has been widely used to stabilise slopes whilst providing protection for plants and seeds, as well providing effective weed control (Meney, 1999). It can also be used in intermittently flooded zones. A similar approach is to propagate plants in sandbags and then use these sandbags to stabilise lake margins and slopes. Brushing (placing whole branches on ground) can also be used to reduce erosion and encourage sediment deposition, whilst also potentially providing a seed source.

An alternative approach to planting nursery-raised seedlings is to transplant whole plants or parts of plants adapted for vegetative reproduction (rhizomes, rootstock with adventitious buds, tubers, etc.) if a suitable donor site is available. This method is likely to suit many fringing and riparian species which favour vegetative reproduction, e.g. many sedges, rushes, reeds, etc.

Encouraging natural regeneration is probably the cheapest and easiest restoration technique of all, but requires getting the habitat conditions right (slope, substrate and hydrology in the case of pit lake margins) and having a seed source within seed dispersal range, such as nearby wetlands. Many sedge and rush species (such as *Carex* and *Juncus* spp.) are known to naturally recolonise denuded wetland margins via wind dispersed seed (van der Valk et al., 1999). However, it is quite possible that weeds will also proliferate via wind-borne seed and riparian areas are usually highly suited to exotic species given abundant resources, etc. (Meney, 1999).

6 Conclusions and recommendations

This review has highlighted the hypothetical potential for riparian and fringing vegetation to improve the water quality, visual amenity, biodiversity, productivity, stability and safety of mine pit lakes. Much of this potential however stems from the general low base levels of pit lakes with respect to these factors, e.g. deficiencies in nutrients and carbon; low levels of biological activity and diversity; little to no riparian habitat compared to other types of lakes. In this way, development of riparian vegetation is likely have a relatively important role even though their actual inputs in organic matter, nutrient, etc., are likely to be modest and slow to accumulate. Despite this, the potential for these inputs to initiate or accelerate key autogenic processes (phytoplankton growth and autochthonous production, ecological succession, habitat building, etc.) shouldn't be underestimated. Much of the potential value of riparian vegetation outlined in this chapter is however conjectural as it is based on extrapolation from studies of natural wetlands and general principles – therefore it is strongly recommended that more experimental work (from mesocosms to whole lakes) be conducted to test ideas and hypotheses generated in this chapter regarding the value of riparian vegetation to mine pit lakes. More fundamentally, research is urgently required to find effective and affordable techniques to overcome the biophysical barriers preventing the establishment and growth of plants around pit lakes as this currently seems to be an insurmountable hurdle in some situations, e.g. hard-rock mines with steep faces.

Riparian zones are not the only source of organic carbon and nutrients inputs into pit lakes, and it is important to characterise the pit lake catchment in terms of inputs via surface, stream and ground-water. Furthermore, water balance studies are vital to predict water levels and fluctuations as this will inform the position and type of riparian vegetation which can develop. Slopes ideally should be made gentle around these predicted lake water level(s). Major or irregular water level fluctuations or drifts should be avoided.

Lastly, it must be emphasised that to successfully establish riparian vegetation around pit lakes, several critical issues need to be resolved and key decisions need to made early in the mine planning process; in particular, things like water level(s), slope profile, habitat enhancement, topsoil source and storage need to decided during the planning process. It is therefore vital for pit lake design and riparian zone rehabilitation to become key elements of mine closure plans, and that these plans are integrated into overall mine site plans which are finalised and approved by regulators before commencement of mining.

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Filling and management of pit lakes with diverted river and mine water — German experiences

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Abstract

Dependent upon climatic and hydrologic conditions, the duration of filling of pit lakes may range from years to many decades following mine closure. There are three main reasons to prefer fast filling for pit lakes: (i) reduction of slope erosion and landslide frequency, (ii) abatement of acidification, and (iii) shorter waiting time for beneficial end-use of the post-mining landscape including the pit lakes. These reasons have driven the use of river and active mine dewatering water for filling of pit lakes in former lignite strip mines in Germany over the last 35 years. River water has been the most important water source for filling pit lakes created after 1990. From 1990 to 2010, ca. 2.317 10^9 m^3 of river water and ca. 763 10^6 m^3 of water from dewatering operations of active mines was diverted into mine voids to create pit lakes in eastern Germany.

Fast filling allowed for steeper slopes of the mine voids before lake filling, saving money by shaping slopes of shallower inclination. Acidification was prevented or neutralised as well. Diversion of river water was also successfully applied as a strategy to prevent acidification of already filled pit lakes although, in some cases, additional chemical neutralisation was still necessary.

The most relevant processes are introduced and the German experiences in using river water and mine water for filling and management of pit lakes are presented. Examples from other countries are also presented briefly and summarising conclusions are drawn.

1 Introduction

For the purposes of this chapter, German pit lakes are residual lakes in former surface lignite mines. Lignite has been an important contributor to the production of heat and electricity in Germany (25.2% in 2008; Statistisches Bundesamt, 2010). A similar contribution is expected for the next few decades. Since all lignite mines in Germany extend below groundwater level, pit lakes form after mine closure in the residual mine voids. Full backfilling with overburden is not possible.

Lignite has been mined in three larger and some additional smaller mining districts in Germany. Mines are currently operated in four of the districts: Rhenish district, district of Helmstedt, central German district and Lusatian district. In the other districts, mining ceased during the last three decades. The mined lignite is of tertiary age. The lignite seams are embedded and overlain by unconsolidated rock like gravel, sand, loam and clay. However, the geological conditions vary among the districts and also within the single districts. For details on the geology of the three main German lignite mining districts, see Seifert et al. (1993) for the Lusatian district, Eissmann (2002) for the central German district, and Briechle et al. (1998) for the Rhenish district.

Pit lakes exist in all of the German lignite mining districts, in summary about 575 today (Nixdorf et al., 2001). The majority (about 370) of pit lakes are located in the central German and in the Lusatian district. About 120 new lakes formed in these two districts during the last 20 years (Krüger et al., 2002). The experiences reported in this chapter mainly originate from the central German and the Lusatian district.

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Fast filling of pit lakes with water is desired for mainly three reasons:

- Fast filling stabilises the side walls of the mine voids.
- Fast filling is an approach to acidification abatement.
- Fast filling allows for early beneficial end use of the post mining landscape including the pit lakes and new socio-economic development after mine closure.

Natural filling of pit lakes by groundwater rebound may require decades or even more than 100 years in Germany. In addition to the geological conditions, the climate strongly influences the duration of filling of a pit lake. Except for the Rhenish district, evaporation from a lake surface (about 750 mm yr^{-1}) is higher than precipitation in all other German lignite mining districts. The central German district and the Lusatian district are located in the regions of lowest precipitation in Germany (500–600 mm yr^{-1}). Therefore, diversion of river water and the use of water of mines still in operation (referred to as mine water in the following) became the most important strategies for filling pit lakes in Germany during the last about 35 years.

There are also a number of reasons for a permanent diversion of river water into a pit lake: (a) a mine occupied part of the course of a river and the river is diverted back into its natural bed after mine closure, (b) the pit lake shall be used as a reservoir or for flood protection, (c) river water may be necessary to maintain a minimum water level or minimum water quality in the lake; and, (d) the pit lake can be used as treatment facility to improve the water quality of the river.

The third option, i.e. the flushing of pit lakes with river water to maintain the water quality of the lakes, is the second issue which will be discussed in addition to the fast filling of pit lakes. The aim of this chapter is to describe the processes most relevant for the filling and flushing of pit lakes with river water and mine water, to present examples and the lessons learned in Germany, and to discuss briefly options for the application of fast filling and flushing with river water and mine water relevant to other countries.

2 Relevant processes

The most important processes are when filling or flushing pit lakes with river water or mine water (Schultze et al., 2011a):

- dilution of existing pit lake water in a purely physical sense, i.e. without chemical reaction
- displacement of existing pit lake water resulting in outflows into groundwater or into rivers downstream
- import of chemicals into the lake (including alkalinity and acidity)
- chemical reactions in the lake water (including sedimentation of resulting precipitates)
- interaction with the bottom and walls of the mine void (including landslides and erosion)
- interaction with the lake sediment
- primary production in the lake and microbial alkalinity generation.

Concentrations of almost all substances are usually higher in existing mine water (1,500–5,800 mg L^{-1} total dissolved substances (TDS) on average, depending on mined minerals and local conditions; Banks et al., 1997; Nordstrom and Alpers, 1999) than in river water (50–1,300 mg L^{-1} TDS on average, depending on climate, regional geology and human impact) (Meybeck, 2005). Therefore, filling and flushing with river water typically results in dilution initially. Moreover, dilution also contributes to neutralisation – 1 mL of 10^{-3} N hydrochloric acid has a pH of 3. The pH can be elevated to 4 by adding 9 mL of pure water. However, full neutralisation to pH 7 requires 9,999 L of pure water. That is, the contribution of dilution to neutralisation is theoretically considerable but rather limited in practical use.

In the case of fast filling with river or mine water, none or only little groundwater is able to enter the pit lakes while water is flowing from the lake into the dewatered aquifers (Figure 1). This is a major difference between filling of pit lakes exclusively by groundwater rebound and filling by river and/or mine pit dewatering water (Figure 1). The water loss from the lake to groundwater is lost from the lakes but helps faster groundwater rebound. The first consequence of the flow of lake water into the dewatered aquifers is that transport of substances from refilling aquifers into the filling lake is minimised. For example, erosive transport of particles at springs forming on pit void side walls, or washout of small particles from the refilling aquifers leading to instability of the pit wall slopes is minimised. This is a substantial advantage regarding safety and helps avoiding landslides. A second advantage for slope stability is that the pressure of the lake water against the pit walls compensates for the pressure of the groundwater. The latter alone may cause destabilisation of the slopes and landslides.

Figure 1 Interaction between pit lake and groundwater without (left), and with fast filling by diversion of river water or mine water (right), in addition to groundwater rebound. Long dash (–) water level and flow during mining, short dash (-) water level and flow during filling of pit lake, solid (—) water level and flow after establishing a new long-term hydrological balance (after Schultze et al., 2011a, simplified)

A further benefit of rapid filling is that products of pyrite oxidation are transported only slowly into the filling lake. That is, any acidity which has to be neutralised during fast filling of the pit lake is smaller. In addition, more time is available for natural attenuation of acidity in the groundwater which was found to be particularly relevant in older overburden dumps of German lignite mines (Hoth et al., 2005; Storch et al., 2007). Smaller inflow rates of acidity into the pit lakes also allow for proportionally greater contribution of slow in situ processes to the abatement of acidification, e.g. sulfate reduction. Koschorreck and Tittel (2007) reported mean neutralisation rates of 182.5 meq m^{-2} yr^{-1} for neutral lakes of relatively low productivity and 1,878 m^{-2} yr^{-1} for lakes of high productivity. Another slow neutralisation process is weathering of silicates (e.g. feldspars, clay minerals) which may become relevant over long periods. However, when flushing pit lakes, the effluent water should have a quality that does not damage the receiving ecosystem of the downstream stretch of the river and that fulfils legal requirements.

The import of chemicals with river water and mine water has two opposite aspects. The import of alkalinity, in particular bicarbonate, is one of the main reasons for diversion of river/mine water to rapid fill pit voids. In the case of diversion of river water, the import of aquatic organisms may accelerate developing pit lake colonisation and the establishment of a more diverse aquatic biotic community. On the other hand, river water and mine water may contain several elevated chemicals which may be undesired in pit lakes such as phosphorus, organic trace pollutants and/or toxic metals. Therefore, prior treatment may be necessary for river/mine water or, in situ treatment of the pit lake water.

The reaction of river/mine water bicarbonate with pit lake acidity is the most important chemical reaction removing lake acidification. It is accompanied by the precipitation of dissolved iron and aluminium as the main contributors to acidity in former lignite mines. In former metal mines, other metals may also have to be removed from the lake water. The success of metal removal may be limited since some metals require pH above 8 (e.g. copper, nickel, zinc) which is usually not reached without specific addition of alkaline chemicals. Co-precipitation with iron and aluminium are important mechanisms of the removal of substances from the lake water during neutralisation. Typically co-precipitated substances are phosphorus and trace metals. A similar mechanism of removal is flocculation of particles and microorganisms by iron and aluminium.

During pit lake filling, the mine void bottom and pit walls are subject of intense elution and, in the case of unconsolidated rock, of erosion resulting from pit wall runoff and wave action. Because of the rising water table, the entire pit walls are affected by erosion. The thickness of the eroded surface layer depends on the rising rate of the water table, the geomechanical properties of the pit walls and the exposure to runoff and wave action. The erosion causes an intense elution of all soluble substances (Abel et al., 2000). The pit walls and mine void bottom typically show the most intense oxidation rates of pyrite and other sulfides since they are dewatered and exposed to the atmosphere for a long time (Grützmacher et al., 2001). In hard rock environments, mining operations such as blasting may increase the number and the size of pores, fissures and fractures allowing more intense interaction between rock, oxygen and water. Therefore, mine void bottom and pit walls are often the main sources of acidity for the pit lakes during filling. In the long-term, products of pyrite oxidation stored in overburden dumps and ongoing pyrite oxidation there become the most important sources of acidity for pit lakes. Even worse events compared to erosion are landslides. They may cause the total reversal of the neutralisation successes of several months as reported by Gröschke et al. (2002). A number of landslides resulted in a drop of pH from approximately 5 to about 4 accompanied by an increase of acidity by about 0.1 mmol L^{-1} and of the sulfate concentration from approximately 600 mg L^{-1} to temporarily 800 mg L^{-1} in Lake Gräbendorf (volume (V): 93×10^6 m^3, Lusatian mining district) in late summer of 1997 (Gröschke et al., 2002).

The filling and neutralisation of pit lakes is accompanied by the formation of high amounts of precipitates of iron and aluminium, resulting in temporarily high sedimentation rates. The interaction between lake water and lake sediment may be limited due to this fast accumulation of sediment. The interaction between lake and groundwater varies in space and time as the lignite mines are usually in contact with more than one aquifer. The lowest aquifer of the filling lake often has a higher hydraulic head than the lake during filling since this aquifer has never been fully dewatered. This causes permanent inflow into the lake from this aquifer across the forming lake sediment. Upper aquifers may be still unsaturated with water at the same time and receive water from the filling pit lake. However, stable biogeochemical conditions in the sediment are important to prevent the remobilisation of undesired substances, e.g. by reductive dissolution of ferric iron precipitates.

The potential role of microbial sulfate reduction as a source of alkalinity was previously discussed. Primary production is a considerable source of organic material which contributes organic carbon as a substrate for sulfate reduction in the lakes’ sediment. However, Totsche et al. (2006) demonstrated that artificial eutrophication, through stimulation of primary production, is limited by phosphorus fixation to iron minerals in the lake sediment and cannot be considered an effective approach for pit lake neutralisation. Accordingly, the contribution of primary production to the neutralisation in the case of fast filling with river water or mine water has to be expected as rather small. In the case of ongoing lake flushing with river water, the contribution of primary production becomes more relevant over longer terms.

3 Filling and flushing of pit lakes with river water and mine water in Germany

The first German pit lake filled with river water was Lake Senftenberg (V: 98×10^6 m^3, Lusatian district). Its filling with water from river Schwarze Elster lasted from 1967 to 1972. The lake is still flushed by diversion of part of the river water. The Muldereservoir (V: 110×10^6 m^3, central German district) was the second pit lake filled with river water (1975–1976). The entire Mulde River still flows through the lake. From 1990 to 2010, diversion of river water contributed about 64.4% (ca. 2.317×10^9 m^3) of the pit lake volume filled in that period. About 763×10^6 m^3 of mine water were used for filling of pit lakes, corresponding to 21.2% of the pit lake volume filled in that period. Figure 2 shows the amounts of river water and mine water used in the Lusatian district and in the central German district over individual years. Fast filling and flushing of pit lakes with river water and/or mine water has also become the main strategy for the abatement of acidification of pit lakes in Germany in the last 20 years. The large future pit lakes in the Rhenish mining district (Lake Garzweiler, V: 1.18×10^9 m^3; Lake Hambach, V: 5.3×10^9 m^3) will also be filled with river water including water from the Rhine River.

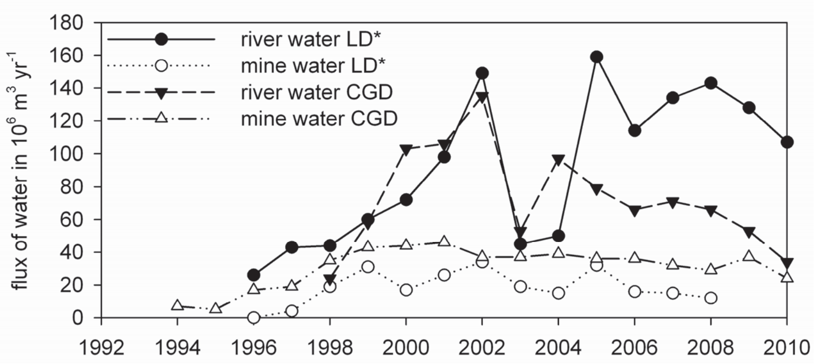

Figure 2 **Fluxes of river water and mine water diverted into pit lakes in the Lusatian district (LD) and in the central German district (CGD) since 1990. (*The data for river water from the Lusatian district for 2009 and 2010 also contain the amount of mine water used in the respective river catchment area)**

The filling of the pit lakes was planned based on predictions of water balance and water quality for all individual pit lakes. First estimates were based on the local hydrogeology and limnological knowledge from existing pit lakes. These estimates were followed up by elaborated predictions with models. The predictions have been updated based on collected field data as filling and lake development proceeded in order to adapt filling and management to real development.

3.1 Primary filling with river water

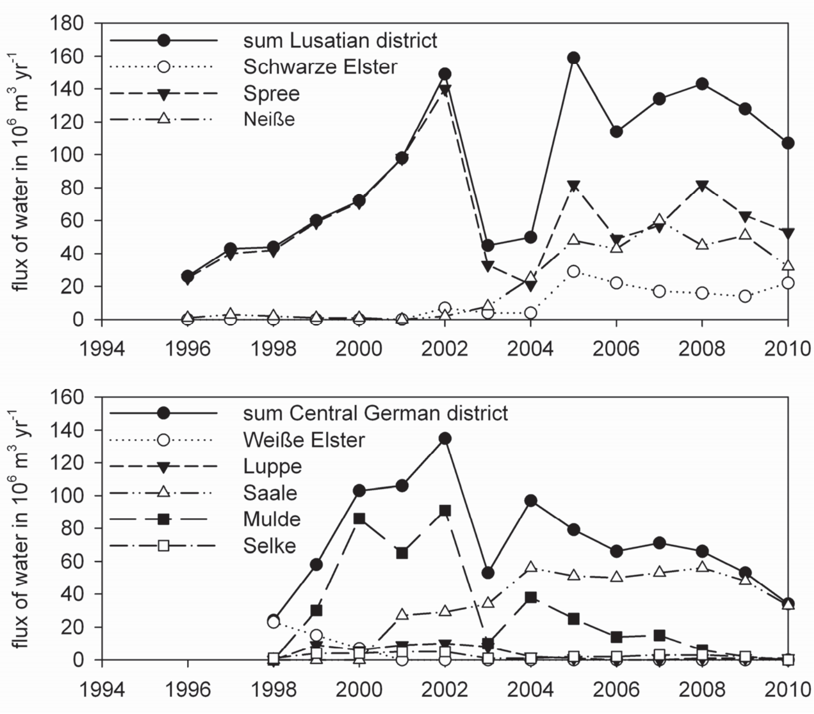

Figure 3 **Fluxes of river water diverted into pit lakes in the Lusatian and central German districts since 1990. (The data from the Lusatian district for 2009 and 2010 also contain the amount of mine water used in the respective river catchment area)**

Since 1990, 36 pit lakes received river water for filling. That is 30% of the pit lakes to be filled after 1990. These lakes comprise 3,490 × 10^6 m^3 after complete filling, representing 77.5% of the final volume of pit lakes to be filled since 1990. Figure 3 shows the contribution of the different rivers in the Lusatian district and in the central German district to the filling of pit lakes.

Although the first diversion of river water was done in the Lusatian district, the most detailed study on the consequences of filling pit lakes with river water was conducted at Lake Goitsche (V: 213 × 10^6 m^3) in the central German district (Duffek and Langner, 2002; Schultze et al., 2002; Boehrer et al., 2003; Trettin et al., 2007; Schultze et al., 2011a). Table 1 summarises changes in Lake Goitsche water quality during its regular filling from May 1999 to July 2002. The flood event of August 2002 (Klemm et al., 2005) is not shown in Table 1 since it is not typical for the use of river water for filling pit lakes in Germany. Lake Goitsche consists of three basins. At the bottom of the basins, small water bodies (referred to as precursor lakes in the following) formed before the diversion of river water began. The precursor lakes were fed by precipitation, local surface runoff and groundwater. Their water levels were kept stable by dewatering operations.

Table 1 Filling of Lake Goitsche from May 1999 to July 2002. Acid neutralisation capacity (ANC), analysed by titration with 0.1N HCl to pH 4.3; Base neutralisation capacity (BNC), analysed by titration with 0.1N NaOH to pH 8.2; TP – total phosphorus. * Amount of river water diverted from Mulde River which has a mean flow rate of 64 m^3 s^{-1} (period 1961–2007)

	Water Level (m.a.s.l.)	Volume (10^6 m^3)	pH	ANC (mmol L^{-1})	BNC (mmol L^{-1})	TP (µg L^{-1})
Lake Goitsche						
April 1999						
Basin Muehlbeck	53.5	1.7	3.2	0.0	4.3	<6
Basin Niemegk	40.0	4.0	2.9	0.0	9.6	290
Basin Doebern	35.0	1.2	7.6	1.1	0.1	<6
July 2002						
Entire lake	71.5	166	7.7	0.7	0.04	<6
River Mulde May 1999 – July 2002	-	140*	6.6–7.6	1.2–1.5	0.02–0.16	19–135

Because of the poor water quality in the rivers in eastern Germany in the first half of the 1990s, in particular their high phosphorus concentrations (>100 µg L^{-1}), eutrophication was suspected to be an important issue in the filling pit lakes. However, as indicated by the low phosphorus concentration in July 2002 (Table 1), expected eutrophication did not occur in Lake Goitsche. Instead, phosphorus was removed rapidly from pit lake water without causing eutrophication (Duffek and Langner, 2002; Herzsprung et al., 2010). The same loss of phosphorus was found for the other lakes filled with river water (Lessmann et al., 2003; Schultze et al., 2005) because of high lake sediment and pore water iron concentrations (Kleeberg and Grüneberg, 2003; Kleeberg et al., 2008; Herzsprung et al., 2010). Additionally, the inflow of groundwater is a permanent source of iron for pit lakes over a long-term. The risk of contamination with pathogens by river water was also not found to be relevant (Pusch et al., 2005; Wolf, 2005).

The rapid filling of the lakes Wallendorf (V: 38 × 10^6 m^3) and Raßnitz (V: 66 × 10^6 m^3, central German district) demonstrated the stabilising effect of filling with river water on meromixis (Schultze and Boehrer, 2008). The meromixis in Lake Goitsche was probably also a result of the filling with river water (Boehrer et al., 2003).

In the early 1990s, the potential use of diverting floods to fill pits was discussed. The outcome of this discussion was that the use of floods for filling pit lakes would be not sufficient in Germany. Firstly, the occurrence of flood events is unpredictable. Secondly, the lignite mined in Germany is embedded in unconsolidated rock. Enormous constructions were necessary to protect the side walls against flood waves flowing into empty voids. Therefore, limited but constant, diversion rates in the range of a few cubic metres per second were found to be a better option. However, the diversion of river water for filling pit lakes always requires the consideration of already existing water use downstream and the ecological needs of the river; including seasonal variability of flow rate and the frequency and magnitude of floods. Therefore, the diversion of river water had to be reduced or even interrupted during periods of low river flow.

Environmental authorities required further interruptions during flood events in rivers considerably contaminated with hazardous substances. The flushing of the catchment area caused remobilisation of contaminated sediments often leading to exceptionally high concentrations of these chemicals in the phase of rising flow rates (Baborowski et al., 2004).

3.2 Primary filling with mine water

Figure 4 shows the southern part of the central German lignite mining district. The majority of the pit lakes which formed in that region during the last 20 years were filled with mine water. No river water was used since it was needed in other parts of the central German district and enough mine water was available from the two mines which are still in operation.

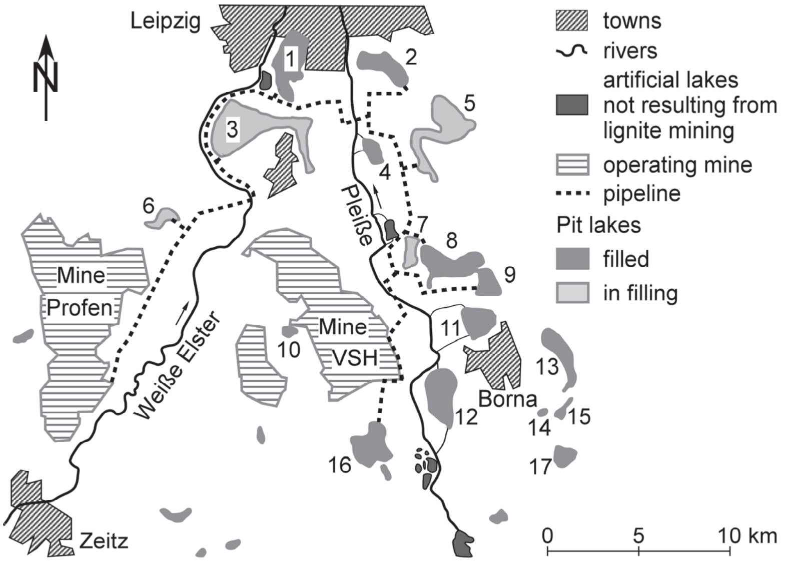

Figure 4 **Distribution system for mine water in the south of Leipzig (central German Mining district). VSH – Vereinigtes Schleenhain; Names of the lakes: 1-Cospuden (V: 109 × 10^6 m^3), 2-Markkleeberg (V: 60 × 10^6 m^3), 3-Zwenkau (V: 176 × 10^6 m^3), 4-Stöhna (V: 11 × 10^6 m^3), 5-Störmthal (V: 157 × 10^6 m^3), 6-Werben (V: 9 × 10^6 m^3), 7-Kahnsdorf (V: 22 × 10^6 m^3), 8-Hain (V: 73 × 10^6 m^3), 9-Haubitz (V: 25 × 10^6 m^3), 10-Großstolpen (V: 0.3 × 10^6 m^3), 11-Witznitz (V: 53 × 10^6 m^3), 12-Borna (V: 97 × 10^6 m^3), 13-Bockwitz (V: 19 × 10^6 m^3), 14-Hauptwasserhaltung (V: 1.1 × 10^6 m^3), 15-Südkippe (V: 1.6 × 10^6 m^3), 16-Haselbach (V: 24 × 10^6 m^3), 17-Harthsee (V: 5.4 × 10^6 m^3) (from Schultze et al., 2011b)**

Four main aspects stimulated consideration of mine water as a source of water for filling pit lakes in the central German lignite mining district in the first half of the 1990s:

1. The water quality of the river water was very poor, with high concentrations of biological and chemical oxygen demand, phosphorus and (at least in winter) ammonia as waste water treatment was in an early stage of implementation. The experience from a well monitored pit lake filling with river water, e.g. like that of Lake Goitsche, was not yet available. Therefore, treatment of the river water was discussed to ensure an adequate water quality of the new pit lakes suiting the requirements of the planned use, mainly recreation.
2. Treatment facilities for the mine water of the still operating mines were required by the regional authorities in order to improve the water quality of the rivers. In particular, the iron load of the mine water (<10 mg L^{-1}) impacted the rivers with oxygen consumption and turbidity.
3. The iron concentration of the mine water of the operating mines was low (<10 mg L^{-1}) compared to the acid waters occurring in the abandoned mine voids (>200 mg L^{-1} of iron). The water from the operating mines was net-alkaline as it was mainly natural groundwater originating from aquifers which were not influenced by mining before. Estimates indicated that the bicarbonate of the mine water would be enough to neutralise the majority of the pit lakes to be filled.

4. The use of the mine water provided an economic benefit for the ones responsible for the filling of the pit lakes as well as for the operators of the active mines. Construction and operation of treatment facilities could be saved by both parties. Therefore, the pipeline system shown in Figure 4 was constructed (ca. 60 km).

Mine water quality from the two operating mines used for filling pit lakes in the south of Leipzig differed at the beginning. The bicarbonate concentration of the water from Profen Mine was higher (6.2 mmol L^{-1} HCO_3^- on average in 1998) than of the water from Vereinigtes Schleenhain Mine (VSH; 0.46 mmol L^{-1} HCO_3^- on average in 2000). Over time, the contribution of water from mining affected areas and overburden dumps increased for both mines causing a gradual decrease of the bicarbonate concentration in the mine water. The resulting bicarbonate concentrations were 4.8 mmol L^{-1} HCO_3^- for Profen Mine and 0.02 mmol L^{-1} HCO_3^- and pH 4.0 for VSH Mine on average in 2009. Due to the decrease in water quality, the use of the water from VSH Mine for filling pit lakes was stopped in 2010, and a treatment plant for this mine water was implemented. The water of Profen Mine is still a valuable source for filling and neutralising pit lakes.

The first pit lake filled with mine water was Lake Cospuden. In 1993, i.e. the year before filling with mine water began, several small precursor lakes had formed at the bottom of the mine void. Half of the precursor lakes were acidic, half of them neutral. The filling of Lake Cospuden started in 1994 with water from the neighbouring Zwenkau Mine which was in operation until 1999. The majority of water for filling came from Zwenkau Mine (Table 2) since the construction of the pipeline from Profen Mine took some time. However, water from Profen Mine also contributed substantially to the filling of Lake Cospuden and in particular to its neutralisation (Table 2). The quality of water from Zwenkau Mine varied widely from neutral to acidic depending on the sites within Zwenkau Mine where the water came from. The Profen Mine provided well-buffered neutral water from 1998 to 2000.

Table 2 Filling of Lake Cospuden. Q – amount of mine water for filling from 1994 to June 30, 2000; ANC – acid neutralisation capacity, analysed by titration with 0.1N HCl to pH 4.3; BNC – base neutralisation capacity, analysed by titration with 0.1N NaOH to pH 8.2; water quality data are median values (minimum-maximum)

Water	Q (10^6 m^3)	pH	ANC (mmol L^{-1})	BNC (mmol L^{-1})
Zwenkau Mine	42.15	6.6 (2.4–8.5)	2.0 (0.0–3.5)	0.57 (0.1–6.1)
Profen Mine	31.86	7.3 (7.0–7.8)	5.9 (3.2–6.5)	0.8 (0.5–3.5)
Lake Cospuden				
1993	-	4.9 (3.1–8.1)	0.38 (0–3.75)	1.64 (0.1–59.3)
June 2000	-	7.6	1.6	0.25

When filling of Lake Cospuden was completed in summer 2000, an excellent water quality was achieved fully suiting the requirements of the planned end use for recreation, e.g. swimming, scuba diving, and sailing. Because of its location at the margin of the city of Leipzig (ca. 0.5 million inhabitants), Lake Cospuden became a popular recreation site. Basically, the filling with mine water resulted in substantial removal of acidity in all lakes filled with mine water in addition to Lake Cospuden in the south of Leipzig since 1990: Markkleeberg, Zwenkau, Störmthal, Werben, Großstolpen, Kahnsdorf, Hain, Haubitz and Haselbach.

In some pit lakes the neutralisation capacity of the used mine water was not high enough to overcome the acidity already present in the mine voids and entering the rising pit lakes by groundwater, interflow, local runoff and erosion. The lakes Hain and Haubitz had to be treated with lime; 8,614 t for Lake Hain, 1,390 t for Lake Haubitz. Lake Haselbach is the only exception since cessation of filling by water from the VSH Mine and still receives water from this mine to maintain the water level. Nevertheless, Lake Haselbach was still treated with limestone (314 t) to maintain an acceptable pH buffering capacity. More details on the filling of pit lakes in the south of Leipzig can be found in Schultze et al. (2011b).

In some cases, dewatering wells had to be operated around filling pit voids even during pit lake filling to avoid local destabilisation of the side walls by high groundwater inflow rates. For example, at part of the eastern side walls of Lake Goitsche, dewatering wells were necessary due to the high local groundwater level. The water from such dewatering operations was generally diverted into the rising pit lakes but was not treated since it was usually not acidic and the amount of water was generally small compared to the amount of filling water from other sources such as river water or mine water from other mines.

In the Lusatian district, mine dewatering water has to be treated with lime because of its acidity before it is used for filling pit lakes. For example, the water treated in the treatment plant Rainitza is used for filling Lake Ilse (V: 135 × 10^6 m^3). The general water scarcity in the Lusatian district requires the use of all sources.

3.3 Flushing with river water

The motivation for intentional flushing of pit lakes was to achieve stabilisation of the water level, therefore avoiding erosion and landslides, and the management of the water quality. Inflow of acidic groundwater continues often after filling and primary neutralisation of pit lakes. This import of acidity causes a decrease in pH if the rate of import of alkalinity is smaller than that of acidity. Such a new acidification is referred to "re-acidification" since an initially neutralised pit lake becomes acidic again. The main sources of alkalinity import to be considered are: surface inflows, groundwater, biogeochemical alkalinity generation inside the pit lake including its sediment and elution of side walls and shore material. The major sources of acidity are the same ones as relevant for the filling of pit lakes. The re-acidification process may take some time because of the stock of alkalinity of the lake water from primary neutralisation and because of the time required for full groundwater rebound. In general, substantial changes in the hydrological regime of a pit lake may cause re-acidification if relevant sources of acidity are present in the catchment of the pit lake.

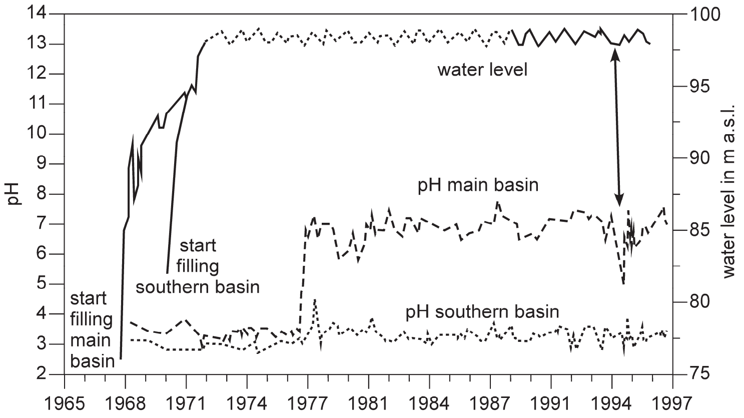

Figure 5 Development of water level and pH in Lake Senftenberg (Lusatian lignite mining district, Germany; adapted from Werner, 1999)

Figure 5 shows the development of the pH in the two basins of Lake Senftenberg. This lake is the first example in Germany for neutralisation by diversion of river water and also for lake flushing as the main measure for sustaining neutral conditions (Werner et al., 2001). Lake Senftenberg consists of two basins separated by an island which results from an overburden dump. The diversion of water from the Schwarze Elster River neutralised only the main basin since shallow areas at the ends of the island with dense macrophyte stands hindered water exchange between the two basins. In 1995, the inflow pipeline had to be closed for inspection and repair. This temporary absence of river water inflow caused an exceptionally long lake water level reduction and intermediate re-acidification (signed by the arrow in Figure 5). This episode underlines the importance of the flushing for the water quality of Lake Senftenberg.

For the future, the flushing of a chain of currently filled pit lakes is planned in the Lusatian lignite mining district. This chain of pit lakes comprises from east to west the lakes Spreetal (V: 97 × 10^6 m^3), Sabrodt

(V: 27 × 10^6 m^3), Bergen (V: 3 × 10^6 m^3), Bluno (V: 64 × 10^6 m^3), Neuwiese (V: 56 × 10^6 m^3), Partwitz (V: 133 × 10^6 m^3), and Sedlitz (V: 212 × 10^6 m^3). The water for flushing will be diverted from the Spree River in the east. The Schwarze Elster River will receive the outflow in the west.

Beyond acidification, other aspects of water quality may be managed by flushing of pit lakes with river water, e.g. the concentration of sulfate in the pit lakes or in the receiving downstream waters. High sulfate concentrations cause corrosion of concrete along contaminated rivers and leads to expenses for purification of water for industrial purposes and water supply (drinking water threshold for sulfate in the European Union: 240 mg L^{-1}). Additionally, sensitive aquatic species may be detrimentally affected even to death in waters downstream of pit lakes. Due to these diverse reasons and the expected risks of re-acidification, a sophisticated, model-based water management system was implemented for the Lusatian lignite mining district (Schlaeger et al., 2003; Koch et al., 2005). This system combines currently filling of pit lakes with river water and mine water and lake flushing with river water. Flushing will be the future main strategy to sustain acceptable water quality in the pit lakes as well as in the rivers. The management system includes the water exchange among the rivers and their catchments: about 30 × 10^6 m^3 yr^{-1} between Neiße and Spree and about 60 × 10^6 m^3 yr^{-1} between Spree and Schwarze Elster (Luckner, 2006). In order to manage potential future phases of water scarcity in the mentioned rivers caused by climate change, diversion of water from the larger rivers Elbe and Oder is under discussion (Koch et al., 2009).

Flushing also occurs where the lakes are used for flood protection or as reservoirs. The lakes Zwenkau, Stöhna, Witznitz and Borna (all central German district, see Figure 4) are used for flood protection. They replace the retention capacity of mined areas in the former flood plains. Substantial stretches of Weiße Elster and Pleiße Rivers have artificial river beds where mining occurred in the former flood plains. Because of the natural water scarcity in Lusatia and the importance of the Spree River for the water supply for Berlin, construction of reservoirs and the use of pit lakes as reservoirs has been an important issue for many decades (Kaden et al., 1985; Grünewald, 2001; Koch et al., 2009). The pit lakes used as reservoirs in the catchment area of the Spree River are: Bärwalde (V: 173 × 10^6 m^3), Burghammer (V: 35 × 10^6 m^3), Dreiweibern (V: 35 × 10^6 m^3), Lohsa I (V: 5.8 × 10^6 m^3) and Lohsa II (V: 97 × 10^6 m^3). Additionally, the pit lakes Senftenberg and Knappenrode (V: 7.8 × 10^6 m^3) are used as reservoirs in the catchment of the Schwarze Elster River.

As mentioned previously, the entire Mulde River permanently flows through the Muldereservoir. The Muldereservoir has beneficial consequences for Elbe River and the North Sea (Zerling et al., 2001; Klemm et al., 2005). The upper catchment of Mulde River was subject of metal mining and metallurgy for about 800 years. Substantial fractions of the resulting load of heavy metals and arsenic of Mulde River are trapped in the Muldereservoir. The comparison between the total load of Elbe River into the North Sea and the load trapped in the sediment of the Muldereservoir shows the importance of this pit lake for the river system downstream (average values from 1993 to 1997, trapped load as t yr^{-1} and as percent (%) of the total load of Elbe River into the North Sea; Zerling et al., 2001): As 21.6 t yr^{-1} = 27.0%, Cr 14.6 t yr^{-1} = 20.6%, Cd 5 t yr^{-1} = 90.3%, Pb 43 t yr^{-1} = 50.8%, Zn 243 t yr^{-1} = 15.8%, Cu 26.4 t yr^{-1} = 22.8%.

4 Application in other countries

Filling of pit lakes with river water is known from the Czech Republic (Sixta, 1998; Svoboda et al., 2008), from Spain (Arnold et al., 2002; Delgado, 2005) and from Australia (Lund and McCullough, 2008; Salmon et al., 2008). In Spain and in the Czech Republic, the main goal of the diversion of river water for the filling of pit lakes is the stabilisation of the side walls and the early use of the pit lakes. Due to the geological conditions, acidification is not likely in almost all Czech pit lakes in former lignite mines in North Bohemia (Svoboda et al., 2008). However, the available amount of water is limited requiring an integrated river basin management for the two main rivers of the region, rivers Ohre and Bilina (Svoboda et al., 2008). The results of the water quality development of the pit lakes in the Czech Republic appear satisfying and have met the expectations so far (Prikryl, 2010). Filling of pit lakes in former coal mines in northwest Spain is underway yet. In the case of the Lake Meirama, the mine was operating at the bottom of a river valley. The river was diverted around the active mine. After filling the pit lake, the river will be connected to the lake (Delgado, 2005).

Lake Kepwari (V: 24×10^6 m^3, Collie region of Western Australia) was filled with river water over three winters until 2005. The pH increased from 4.3 (2002) to 4.8 (2005), but decreased afterwards to 4.5 in 2009 (Salmon et al., 2008; McCullough et al., 2010). A second goal was the protection of a downstream reservoir from high salt concentrations in the seasonal river from first-flush events at the beginning of the wet season (McCullough et al., 2010). The high salt content in the first flush of rivers after the dry season results from agricultural land use and occurs in many regions of Australia (e.g. Jolly et al. 2001). Saline river water was diverted three times into Lake Chicken Creek 4 (surface area (A): 21.6 ha, maximum depth (z_{max}): 41 m, Collie region) increasing the pH from 2.6 to 5.7 and chloride concentration from 980 to 2,540 mg L^{-1}. Without river water, the pH and chloride concentration decreased to 4.0 and 1,410 mg L^{-1} in 2009, respectively (McCullough et al., 2010). Lake Stockton (A: 15.4 ha, z_{max}: 47 m, Collie region) was temporarily flushed with mine water resulting in a temporal reduction of acidity and increase of pH (McCullough et al., 2010). These are examples for transferability of experiences among mining regions. The described development is comparable to the findings in Germany, regarding both the beneficial use of river and mine water as well as the phenomenon of re-acidification.

Kalin et al. (2001) reported the filling of the B-Zone pit lake (A: 24 ha, z_{max}: 54 m) with water from the neighbouring natural Lake Wollastone in winter 1991/1992. The excellent water quality of the pristine Lake Wollaston resulted in good water quality in the B-Zone pit lake too. The pit lake water quality even improved over time (1992–1998) as indicated by changes in the plankton community (Kalin et al., 2001).

A very special case of filling a pit lake with surface water is the Island Copper Mine pit lake on Vancouver Island, Canada (V: 241×10^6 m^3, A: 1.73 km^2, z_{max}: 350 m; Pelletier et al., 2009). The lake was filled mainly with sea water. Only the top layer was filled with freshwater making the lake meromictic. The intention was to establish a system for storage and treatment of acid rock drainage (ARD). Low level contaminated ARD was diverted into the top layer whereas the more heavily contaminated ARD was diverted to a depth of 220 m below the lake surface. Flushing of the top layer by diversion of fresh and brackish water is essential for the stability of the meromixis. Otherwise, the density of the top layer would increase gradually. For more details see Fisher and Lawrence (2006) and Pelletier et al. (2009).

The South Pit Lake in Tennessee (550 m long, 146 m wide, 61 m deep; Wyatt et al., 2006) is another special case. The pit lake is flushed permanently by the North Potato Creek (mean flow 31 m^3 min^{-1}, mean pH 5, 0.5 meq L^{-1} acidity, and 10 mg L^{-1} iron at the treatment site) as part of the treatment strategy for the stream water. The North Potato Creek is contaminated with heavy metals since it drains a substantial part of Tennessee Copper Basin where mining took place in the past. The intention was to use the lake as disposal site for sludge resulting from the lime based treatment. Because the lake is meromictic, its monimolimnion also serves as source for iron rich water used to improve the flocculation in the treatment system. Although not the focus of the treatment system, the flushed surface layer of the South Pit Lake became pH neutral within a few weeks after implementation of the treatment system (Wyatt et al., 2006).

Probably, not all cases of filling and flushing of pit lakes with river water or mine water are known to the authors. However, the mentioned examples demonstrate that these strategies for filling and management of pit lakes are not an exclusively German issue.

5 Conclusions

Fast filling of pit lakes with river water and mine water and flushing with river water have proved to be very useful strategies of pit lake creation and management in Germany. Pit walls were stabilised and acidification could be prevented, or, at least, reduced. These strategies were also applied in other countries.

The basic prerequisite for the use of river water and mine water for filling and management of pit lakes is the availability of water. Water scarcity may be a limiting factor. That is, the applicability of filling and flushing of pit lakes with river water and mine water strongly depends on the climate and the intensity of the use of water downstream the pit lakes. In the case of limited water availability, the use of floods may be evaluated different from the practices in Germany. Floods may be the only options for the filling of pit lakes under certain conditions. However, the ecological needs of the river system downstream the pit lakes have to be kept in mind, including the variability of the flow rate under such conditions.

The water quality of the used river water and mine water has to suit the requirements of the planned use of the pit lakes. Otherwise, treatment of the river water, the mine water or the pit lake is necessary. The pit lakes can also be used as reactors under certain conditions. For example, the removal of moderate concentrations of metals from water may be cheaper by frequent fertilisation of a pit lake than in typical mine water treatment facilities. The concentrations of copper and zinc have been kept below the permitted limits in the top layer of the Island Copper Mine pit lake by year-round fertilisation with nitrogen and phosphorus (Pelletier et al., 2009). Although the main goal in this case is the pit lake, the example indicates that this approach may be used as a treatment for contaminated river water or mine water at other sites. The Island Copper Mine pit lake is also a good example for the maintenance of meromixis by the superficial inflow of fresh water. Sustaining meromixis is an important aim in pit lakes which have been used as disposal sites for waste materials from mining or other sources.

Any case of using pit lakes for flood protection and water storage is essentially flushing the lakes with river water; although the management of the water quality of the pit lake is usually not the main goal. An optimum may result if all potential aspects are considered when planning and managing such pit lakes.

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Bacterial sulfate reduction based ecotechnology for remediation of acidic pit lakes

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Abstract

Pit lakes are globally increasing in size and number due to rising scale and frequency of open cut mining practices. Pit lakes can have good or poor water quality which is mainly governed by the nature of ore type mined, host and country geology, hydrology and climate.

Pit lakes affected by the generation of acidic and metalliferous drainage (AMD) are often problematic pit lakes in mine closure as AMD may lead to high concentrations of acidity, sulfate and metals. In line with the current sustainable mine closure approaches world-wide, acidic pit lakes may need to be remediated effectively to address any environmental legacy. Growing water scarcity through increased water demand and climate change in many regions is also increasing the attraction of exploitation of pit lakes as possible water resources. Nevertheless, the poor water quality in acidic pit lakes needs to be treated before this vast resource can be partially or fully realised.

A wide range of treatment technologies based on two main principles (chemical neutralisation and biological neutralisation) are now available to ameliorate acidic and metal contaminated waters. Some of the technologies that have been trialled at field scale with varying degree of success are addition of alkaline reagents such as lime, external flooding with good quality water, stimulation of bacterial sulfate reduction through organic matter addition and stimulation of algal primary production through nutrient addition. Among the various technologies available, biological based solutions, i.e. ecotechnologies appear to be more appropriate for remediation of acidic pit lakes as there may be often ongoing catchment or in-lake acidity generation.

This chapter focusses on bacterial sulfate reduction based ecotechnology for in situ acidic pit lake remediation. Bacterial sulfate reduction involves using sulfate reducing bacteria to reduce sulfate to sulfide using organic carbon source which leads to acidity, sulfate and metal removal in a single process. The chapter provides insights on the potential use of bacterial sulfate reduction for remediation of acidic pit lakes highlighting the technology's strengths and limitations. The chapter also emphasises the important aspects such as appropriate organic carbon sources, acid load management around the catchment and limnological factors that needs to be considered for an effective treatment using sulfate reducing bacteria (SRB) based ecotechnology. Finally, major factors that need to be considered are also outlined on how to implement the SRB-based ecotechnology for effective acidic pit lake treatment.

1 Introduction

Pit lakes may form from abandoned open cut mine voids as they fill with groundwater and/or surface inflows. Pit lake water can be contaminated due to AMD generation in and around the lake, depending on the host and country geological and mineralogical characteristics (McCullough, 2008). AMD is characterised by high acidity, sulfate and metal concentrations mainly due to biogeochemical oxidation of iron sulfides (Johnson, 2003; Kalin et al., 2006). Pit lakes with elevated acidity, sulfate and metal concentrations have little use and can be a potential source of ecological risk if there are nearby aquatic and terrestrial ecosystems. However, the enormous quantities of water in pit lakes can present a variety of beneficial end uses if the acidity and metals in the water can be successfully treated (McCullough and Lund, 2006). Pit lakes can be a significant water resource during and post mining, especially in dry regions where the need for water is ever increasing (Kumar et al., 2009). Moreover, the recent awareness world-wide among the public and regulatory authorities increasingly encourages the development of feasible frameworks for sustainable mine closure including addressing the water quality problems associated with the acidic pit lakes (Jones and McCullough, 2011).

Acidic pit lakes are relatively new aquatic systems and information about their possible succession via natural remediation processes towards neutral water is limited. Even though the pit lakes can undergo natural attenuation process, such remediation will be governed by several interlinked parameters such as presence of limited incoming acidity, high acid neutralising capacity and adequate organic material to support bacterial reductive processes. There are few reports of acidic pit lakes self-neutralising after 5–25 years (Schultze et al., 2010). Neutralisation in these lakes occurred due to the strong influence of natural processes such as flushing of acidic waters by through-flow of ground and surface waters, alkaline inputs from naturally neutral groundwater and surface water (Schultze, 2011) and bacterial sulfate reduction (Schultze et al., 2010).

World-wide there has been increasing research interests to develop viable treatment technologies to deal with the AMD problems in the mining industry (Johnson and Hallberg, 2005; Kaksonen and Puhakka, 2007; Wielinga, 2009). AMD treatment in the mining industry is not new and several treatment technologies are available based on physico-chemical and biological principles which range in status quo from experimental to fully developed stages. Nevertheless, none of the technologies used until today have proved to completely solve the AMD related environmental problems especially for acidic pit lakes (McCullough, 2008). Although there are several remediation technologies available for AMD treatment in flowing (lotic) discharges (Mitsch and Wise, 1998; Johnson and Hallberg, 2005), AMD treatment for wetland and lake (lentic) systems is entirely different (McCullough, 2008). The main differences here are substantial volumes, different sediment chemical composition and distinctive water chemistry due to the effects of lake stratification and regional climate such as evapo-concentration (Blodau et al., 1998; Castro and Moore, 2000; McCullough, 2008). Nevertheless, in recent years there has been increased international research interest for exploring effective and innovative technologies for pit lake remediation (Geller et al., 2009; McCullough and Lund, in press).

Treatment technologies for acidic pit lakes should focus on delivering long-term solutions rather than short and temporary solutions as there are often ongoing sources of acidity generation; either inside the lake or in its greater catchment (Peine et al., 2000). Among the major treatment technologies for pit lakes the widely used ones until now with varying degrees of success (Nixdorf et al., 2010) are: 1) chemical neutralisation such as liming; 2) neutralisation by external flooding of pits with neutral or alkaline water (e.g. river diversion); 3) inorganic nutrient addition to stimulate primary productivity for phytoremediation; and 4) addition of organic materials to stimulate SRB activity for bioremediation.

Chemical neutralisation methods have limitations such as high costs and an ongoing need for chemical dosing as there is often continuous acidity influx or generation in the acidic pit lakes (Ronicke et al., 2010; Wendt-Potthoff et al., 2010). Neutralisation of acidic pit lakes or prevention of iron sulfide oxidation in mine pits through river diversion will only be feasible in regions where there are rivers nearby and contain sufficient alkalinity and divertable water volumes. Conversely, in situ ecotechnologies of enhancing primary production and bacterial sulfate reduction mainly aim at increasing the natural in-lake alkalinity generation capacity. Among the various technologies the most sustainable option may be to enhance the rates of naturally occurring neutralisation through bacterial sulfate reduction which may also facilitate establishment of a functioning aquatic ecosystem by providing nutrients and appropriate habitat in the longer term (McCullough, 2008; Geller et al., 2009; Wendt-Potthoff et al., 2010). This chapter focusses on bacterial sulfate reduction as an ecotechnology for in situ treatment of acidic pit lakes.

2 Sulfate reducing bacteria

SRB are a ubiquitous, extremely diverse group of facultative and obligate anaerobes commonly found in anoxic environments. They mainly obtain energy for their survival and growth through dissimilatory sulfate reduction. Depending on the nutritional requirements, SRB can be classified in two classes; namely, heterotrophic SRB that use organic materials as electron donors; and autotrophic SRB which alternatively use CO_2 and H_2 (Nagpal et al., 2000; Liamleam and Annachhatre, 2007). SRB are known to utilise a wide variety of low molecular weight organic compounds such as lactate, pyruvate, acetate, butyrate, propionate, succinate, sugars and amino acids. Research in the last decade has also demonstrated that SRB can also use short and long chain alkanes and long chain alkenes as carbon source for growth (Aeckersberg et al., 1998; Grossi et al., 2007; Kniemeyer et al., 2007).

Ever since Tuttle et al. (1969) highlighted the SRB's potential for AMD treatment, there has been numerous studies exploring this ecotechnology as a possible solution for AMD related environmental problems. Despite the early recommendation of SRB for AMD remediation, until recently most SRB were considered to be inactive or least effective in systems at a pH of <5 (Johnson, 2003; Willow and Cohen, 2003). However, many recent studies on AMD and pit lake bioremediation have demonstrated that sulfidogenesis at low pH <4 is feasible and has potential (Kimura et al., 2006; Koschorreck et al., 2007; Becerra et al., 2009; McCullough and Lund, in press).

SRB have the potential to treat acidic, sulfate and metal contaminated water by reducing sulfate to sulfide under anaerobic conditions in the presence of an external electron donor such as labile organic carbon (Blodau et al., 1998; Kusel, 2003). Sulfides generated can form FeS in the presence of reduced iron and burial of pyrite (FeS_2) is highly beneficial for alkalinity generation and breaking the acidity generating cycles (Castro and Moore, 2000). Sulfides produced by SRB activity also form sparingly soluble metal precipitate complexes such as ZnS, CuS, PbS, etc. A major advantage of SRB ecotechnology is therefore that elevated acidity, sulfate and metals in the water column can be removed in a single process.

3 Organic matter addition for acidic pit lake bioremediation

Acidic pit lakes are geologically young and generally oligotrophic; characterised by very low nutrients, especially organic carbon which hinders the establishment of a functioning aquatic ecosystem. Poor allochthonous (McCullough et al., 2009; Van Etten, 2011) and autochthonous (Peine and Peiffer, 1998) organic carbon generation in acidic pit lakes also typically limits rates of naturally occurring bacterial sulfate reduction in pit lake sediments. Low organic matter concentrations in pit lakes is mainly due to limited primary productivity as there is often not enough free phosphorus available for algal primary productivity. Though phosphorus is highly soluble in low pH environments, P is removed from the water column in acidic pit lakes as it co-precipitates with iron and aluminium (Kapfer, 1998; Kleeberg and Grüneberg, 2005). Acidic pit lakes are generally not nitrogen limited, however nitrogen is predominantly present as ammonia mainly due to limited nitrification at low pH (Nixdorf et al., 2001). Consequently, in acidic pit lakes bacterial sulfate reduction is limited by low organic carbon concentrations since many pit lakes often contain high sulfate and iron concentrations. Organic matter can be externally supplemented to initiate the bioremediation processes. Despite low organic carbon concentration in acidic pit lakes, bacterial sulfate reduction may still occur, albeit at a very slow rate (Fortin et al., 2002; Schultze et al., 2010). Organic substrates therefore must be amended to the acidic pit lakes to increase the bacterial sulfate reduction rate by achieving reducing conditions suitable for dissimilatory sulfate reduction to occur and also to serve as either direct or indirect source of electron donors for SRB (Wendt-Potthoff and Neu, 1998; Castro et al., 1999).

A variety of simple organic compounds such as acetate, lactate, ethanol and glucose have been tested as carbon source for increasing the SRB activity (Frömmichen et al., 2003, 2004; Meier et al., 2004). Among these compounds, ethanol has been reported to be the most effective carbon source (Koschorreck, 2008). Numerous natural organic materials have also been used as carbon sources for SRB activity; including sewage sludge, leaf mulch, wood chips, animal manure, compost, sawdust (Waybrant et al., 1998; Sahinkaya, 2009; Kumar et al., 2011; McCullough and Lund, in press), wine waste (Costa et al., 2009), mushroom compost (Dvorak et al., 1992), whey (Christensen et al., 1996), ryegrass (Harris and Ragusa, 2001) and green waste (Greben et al., 2009; McCullough and Lund, in press). SRB are known for their inability to use complex and refractory organic substrates such as starch, cellulose, proteins, and fats. Instead, SRB are dependent on other microbial communities that degrade these complex substrates and ferment them to compounds that can be used as substrates (Figueroa et al., 2004; Muyzer and Stams, 2008).

SRB-based bioremediation can therefore often be simply initiated by addition of organic materials. However, selection of the most appropriate organic material plays a prime role in determining the success of the treatment. The organic material chosen should meet the following criteria: bulk availability, low cost, material reactivity (e.g. as a labile source of nutrients) and material longevity. Additional benefits of organic material may include serving as a source of bacterial inoculum and functioning as a physical barrier to prevent lake water mixing (McCullough and Lund, in press). However, more than the simple bulk availability, direct substrate costs and transport costs also need to be considered before selecting the appropriate organic amendments for pit lake bioremediation (Table 1). The high initial cost of pure organic substrates may not be a very cost effective option for SRB ecotechnology and hence the natural organic substrates may often be a more attractive alternative as they can be available in bulk quantities at reasonable prices; even in many remote mining regions (Kumar et al., in press).

Table 1 Organic materials commonly used and their effectiveness for bioremediation by stimulation of SRB. Organic material effectiveness scale for SRB activity: 1 (low or none), 2 (moderate), 3 (good), 4 (very good), 5 (excellent)

Organic Materials	Cost	Availability	Organic Material Reactivity	Organic Material Longevity	Additional Benefits		Total
					Inoculum	Mixing Barrier	
Sugarcane waste	3	1	5	2	2	2	15
Agricultural waste	4	1	4	5	2	5	21
Sawmill waste	3	1	2	5	1	5	17
Abattoir waste	2	1	5	3	5	2	18
Sewage sludge (1° treated)	5	5	4	3	3	3	**23**
Compost	3	2	3	3	2	3	16
Biosolids (2° treated)	5	2	2	2	2	2	15
Cleared vegetation	5	5	3	5	3	5	**26**
Garden waste	5	5	3	5	3	5	**26**

Source: Kumar et al. (in press).

Municipal sewage and green waste appears to be very suitable as they are easily available in large quantities; often even from the nearby mining service towns (McCullough and Lund, in press). Use of sewage for acidic pit lake bioremediation may further offset costs associated with municipal sewage treatment and disposal. Another advantage of municipal sewage over other carbon sources is that it also acts as SRB inoculum, thus improving the initial rate of bioremediation following addition. Sewage also has a high biochemical oxygen demand (BOD) to quickly produce anoxic conditions (Sahinkaya, 2009). However, the use of municipal sewage for acidic pit lake bioremediation may also involve some risk as the material may contain elevated levels of metals and several organic pollutants like herbicides, pesticides, hydrocarbons, etc. Sewage may only be able to be used where the water quality in pit lake is very poor and the addition of sewage will only marginally increase solute concentrations. An example for this is the pit lakes in Collinsville, Australia (McCullough et al., 2008).

4 SRB ecotechnology strength and limitations — case studies

Like any technology, SRB-based ecotechnology has strengths and limitations which are highlighted in this section with two case studies. The case studies highlight that for SRB-based ecotechnology to be highly effective for pit lake remediation it may require optimum temperatures for SRB growth and activity. Warmer climates may be more favourable for high bacterial activity when compared to colder regions especially those where lakes are susceptible to freezing during winter, thereby slowing the bioremediation processes. Furthermore, SRB-based remediative processes can be halted, or even reversed, by high inputs of oxidants and ferrous iron from groundwater inflow.

4.1 Case study 1 — Collinsville, Queensland, Australia

Collinsville is a small inland coal mining town located approximately 70 km from the coast of North Queensland, Australia. Collinsville has a semi-arid monsoonal tropical climate dominated by moderately low and sporadic summer (December to April) rainfall (708 mm/annum) (Figure 1a) with a very high annual evaporation rate (1,860 mm/annum) (McCullough and Lund, in press). Regional geology mainly comprises of highly weathered hard rocks and soils with very low organic matter. There are around 20 pit lakes in Collinsville and all the pit lakes in the region are highly acidic (*ca*. pH 2) with elevated sulfate and metal/metalloid concentrations. Garrick Area East (GAE) pit lake due to good accessibility and proximity to the Collinsville wastewater treatment plant and green waste dump (<0.5 km) which served as source of organic materials, was experimentally manipulated for a SRB-based bioremediation trial. GAE has a maximum depth of 13.8 m, surface area of 5.9×10^4 m^2 and a volume of 4.7×10^5 m^3. GAE water is extremely acidic (pH 2.1, titratable acidity ~7 g/L $CaCO_3$) and contains very high sulfate (~12 g/L) and metals (Al 0.2 g/L, Fe 1 g/L, Mn 0.07 g/L, S 2.6 g/L). The experiment performed followed a before-after-control-impact (BACI) design where GAE and control pit lakes were monitored for water physico-chemical changes both before (~1 year) and after organic materials dosing. For this, GAE was partitioned into two (Figure 1b), a 7×10^4 m^3 treatment lake; Garrick East West (GEW), and a 4×10^5 m^3 control lake; Garrick East East (GEE). Bioremediation was initiated in GEW by adding municipal sewage (wastewater 3,200 t, solid sludge 60 t) and green waste (980 t). Water physico-chemistry was then monitored afterwards for 12 months. Initial results showed that treatment increased GEW hypolimnion pH, but after 12 months the pH increase had halted and pH returned to pre-treatment levels (Figures 2a and 2b). However, later monitoring results revealed that bioremediation reversals were only temporary events and pH increases in GEW started again once cyclonic rainfall events had passed. Cyclonic rainfall events seemed to affect the bioremediation by inducing lake mixing and increasing the acidity inputs from the un-rehabilitated catchment (Figure 1a). Control lakes' water quality (pH 2.4 and oxidation-reduction-potential (ORP) 530 mV) remained largely unchanged throughout the study period (Figures 2a and 2c). Significantly, ORP in GEW remained low (~100 mV) despite the reduced pH recorded after rainfall events (Figure 2d). This indicates the SRB-based remediation's resilience and once anoxic conditions persist, pH increases can occur again. After three years of bioremediation, GEW hypolimnion water pH and ORP were 4 and 10 mV, respectively.

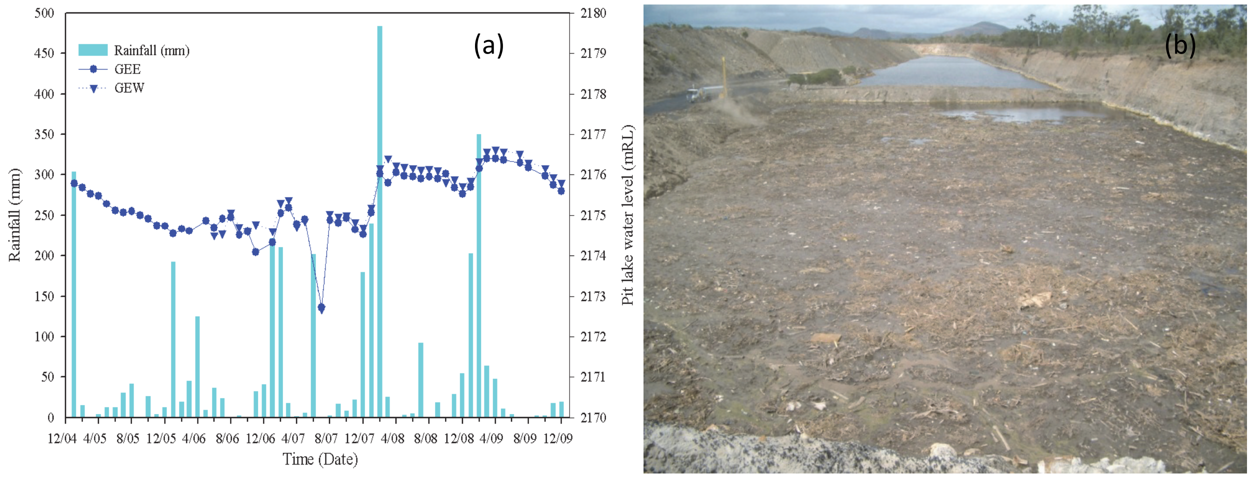

Figure 1 **(a) Collinsville rainfall data during the field trial period and pit lake water levels on the secondary axis, and (b) View of partitioned GAE pit lake, the treatment lake GEW (closest) and control lake GEE (farthest). GEE – control lake, GEW – treatment lake**

This long-term field study demonstrated that municipal sewage and green waste has potential to treat acidic pit lakes despite GAE's extremely acidic water quality. Warm climes along with a mixture of organic waste material types (readily available and recalcitrant carbon sources) seem to be favourable for sustained high pit lake bioremediation rates. However, environmental factors that affect acidic pit lakes bioremediation rates warrant more long-term trials to gain better understanding about their influence on geochemical and microbiological processes.

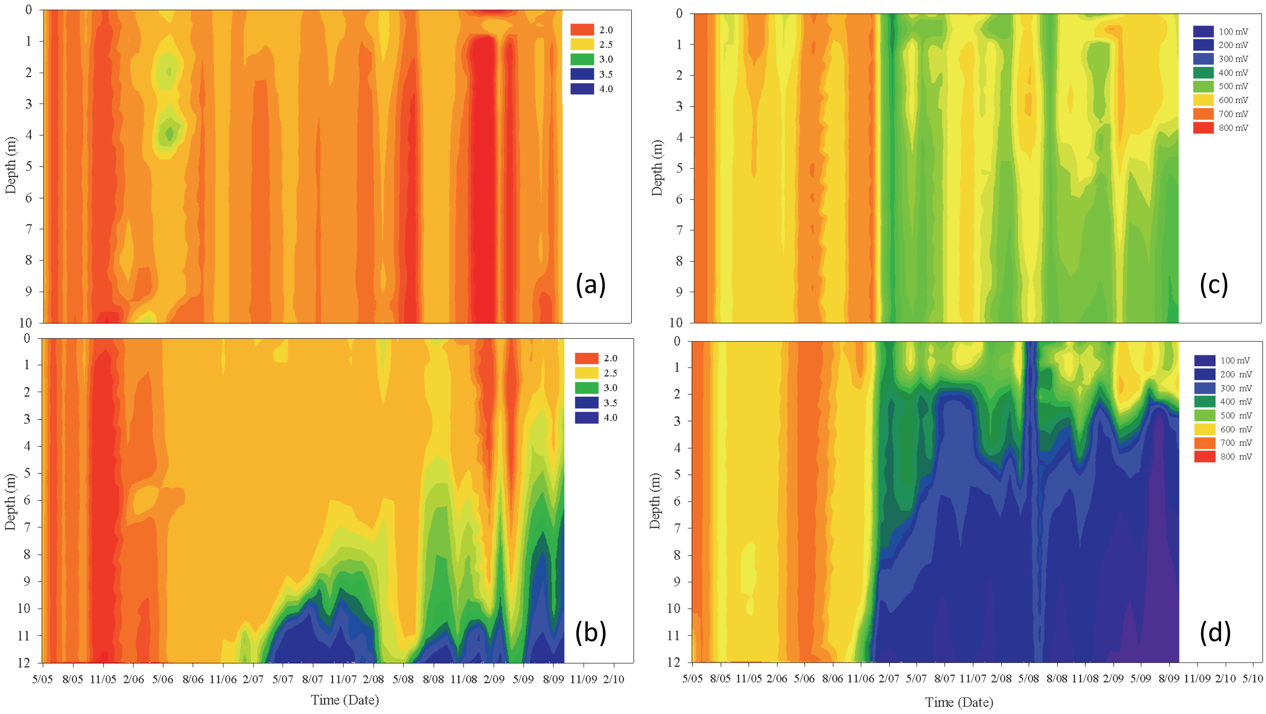

Figure 2 **(a) pH profile of GEE with time, (b) pH profile of GEW with time, (c) ORP profile of GEE with time, (d) ORP profile of GEW with time. The dark vertical line indicates addition of organic matter. GEE – control lake, GEW – treatment lake**

4.2 Case study 2 — Lusatia mining district, Germany

Mining Lake 111 in the Lusatia mining district in Germany has been the site for long-term SRB-based ecotechnology trials. Mining Lake 111 formed after cessation of mining in 1956 and was filled with groundwater in 1969 (Karakas et al., 2003). The pit lake has a mean depth of 4.2 m, maximum depth of 10.2 m and surface area of 1.1 x 10^5 m^2 (Herzsprung et al., 1998). The pit lake is highly acidic with pH 2.6 and also contains high solute concentrations such as sulfate 1.3 g/L, Al 0.04 g/L, Fe 0.15 g/L, Mn 0.008 g/L and very low nutrient concentrations (Herzsprung et al., 1998; Frömmichen et al., 2003).

Frömmichen et al. (2004) carried out initial laboratory microcosm studies to test the SRB ecotechnology feasibility and found that carbokalk and straw as organic substrates stimulated SRB activity and neutralised acidic pit lake water and the underlying sediments. Based on the laboratory microcosm study results, a suite of different field enclosure trials with capacity ranging from 26 to 4,500 m^3 using carbokalk and straw both individually and in combination were then trialled (Wendt-Potthoff et al., 2002; Geller et al., 2009). Water quality and sediment processes were monitored in the enclosure trials for five years and demonstrated that, the rate of neutralisation was significantly less than that recorded in laboratory studies. Their results highlighted that in the field studies the top layer of the sediment formed a reactive zone which was anoxic but remained acidic and the water column's physico-chemical characteristics were also largely unchanged. A detailed sediment geochemical analysis revealed that the uppermost sediment layers accumulated an acidic layer characterised by ferric precipitates as a result of oxidation of ferrous iron contributed from groundwater (Geller et al., 2009). Contributions of ferrous iron which can be oxidised to ferric iron poses a hindrance towards SRB-based ecotechnology which requires an anoxic water column and sediment for effective propagation of alkalinity generating processes and the sediment layers should be neutral without any access of oxidants to the sulfides generated (Castro and Moore, 2000; Geller et al., 2009). Geller et al. (2009) concluded that it is necessary to minimise the oxidant access to the reactive sediment layer and water column and/or at least the sediment layers must be neutral and anoxic to prevent re-oxidation of sulfides formed during bioremediation. Other authors have also reported that contributions of ferrous iron from groundwater can lead to a secondary cycling of iron (ferrolysis) which can negate the SRB-based processes by physically separating the reactive sediment zone from the water column (Peine et al., 2000; Blodau, 2004).

5 Important factors for successful SRB-based ecotechnology implementation

A successful SRB-based ecotechnology requires an interaction of several factors such as presence of labile organic carbon, lake stratification, appropriate bacterial communities, anoxic conditions and minimal acidity contributions from the catchment especially from surface runoff. This section highlights some of the most important factors that need to be considered for a successful SRB-based ecotechnology for acidic pit lake treatment.

5.1 Organic carbon – quality and quantity and dosing regimen

Until recently, most of the research has explored various organic materials as electron donors for SRB-based ecotechnology for acidic pit lake treatment but there are only few studies that have tested the effects of organic materials in combinations and in different doses on process efficiency. Further, the majority of these studies have only been reported from laboratory scale microcosms (Castro et al., 1999; Frömmichen et al., 2004; Becerra et al., 2009; McCullough and Lund, in press). Simple up-scaling of laboratory experimental results to field scale often reduces the process efficiency significantly (McCullough et al., 2008; Geller et al., 2009). The influence of natural conditions in the field, particularly rates of organic material degradation and bioavailability of nutrients, are difficult to simulate in the laboratory. These rate differences must be taken into account when up-scaling the process.

A recent study highlighted the importance of appropriate dosing regimen and matching organic carbon quality and quantity for an effective use of SRB-based ecotechnology (Kumar et al., 2011). The study found that a dosing regimen where the total organic materials are all dosed at once rather than prolonged dosing was key to initiating the bioremediation processes (Figures 3a, 3b and 3c). This study also found that stored sewage retained high total organic carbon but had a very low labile organic carbon (LOC). The stored sewage failed to evoke any bioremediation processes for acidic water neutralisation. However, once LOC (ethanol and lactic acid) in different concentration was added to the microcosms containing old sewage, the water quality improved vastly with the lowest concentration (3 g/L) of LOC (Figures 3d, 3e and 3f). It is important to note that even though LOC was required to initiate the bioremediation processes too much of it can also slow the SRB-based bioremediation processes by increasing the acidity (Koschorreck et al., 2002).

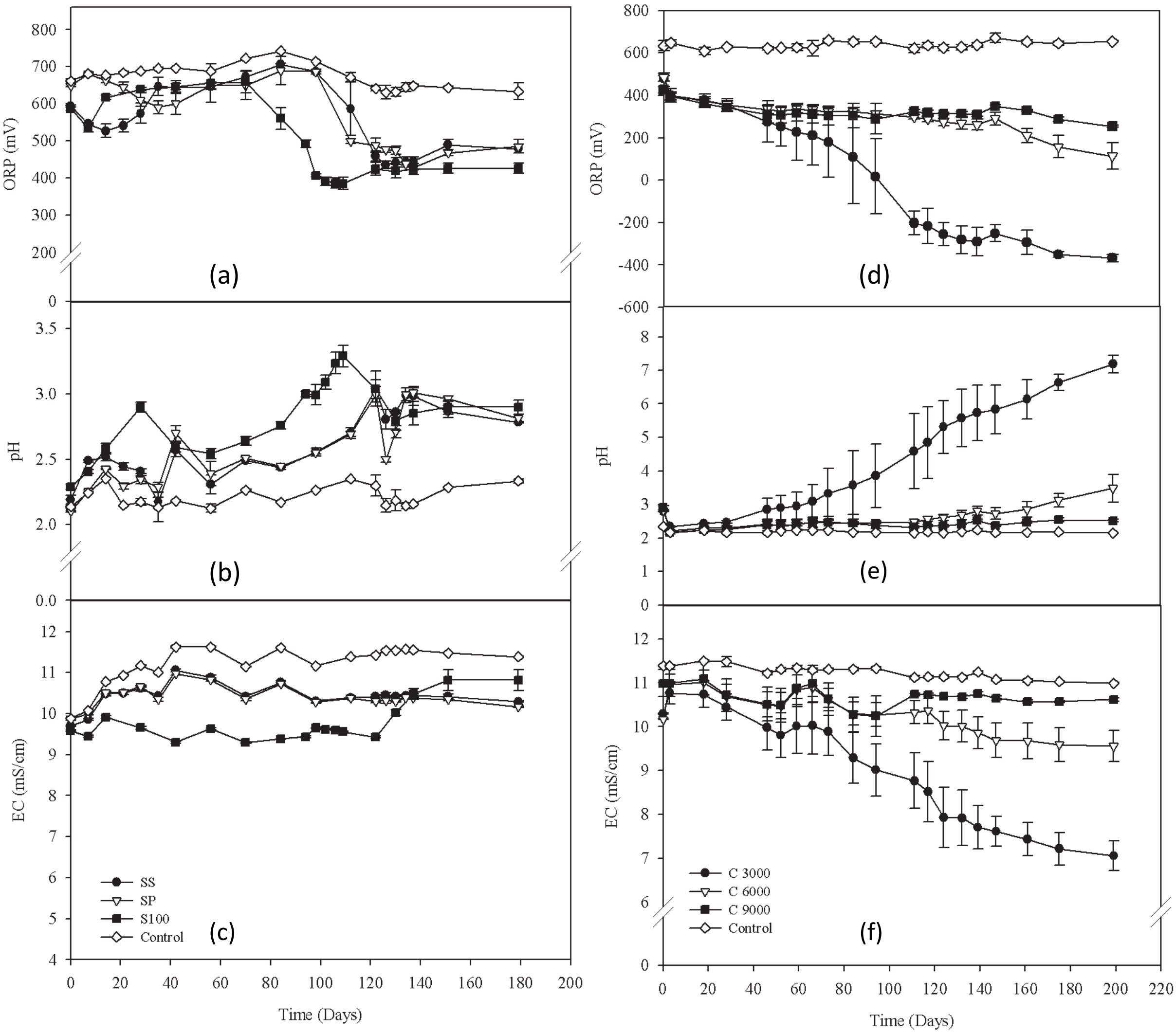

Figure 3 **Changes in (a) ORP, (b) pH and (c) electrical conductivity (EC) with time with different concentrations of sewage; and changes in (d) ORP, (e) pH and (f) EC with time with different concentrations of LOC. Source: Kumar et al. (2011)**

5.2 Effective catchment rehabilitation

The pit lake catchment plays a significant role in defining the success of SRB-based ecotechnology. Inappropriately managed catchment drainage can impact the overall outcome of the bioremediation process. It is important to know about any acid generating areas around the pit lakes, so that these areas can be engineered to divert/treat the flow of acidic waters into the pit. Further, quantification of any alkaline materials around the pit is also useful as it will provide information on the potential contribution of alkaline substances into the pit lake by runoff/sediment erosion.

Following mine closure, pit lakes are generally abandoned by simple bunding and/or fencing for safety. The pit lake catchment may be left un-rehabilitated and can contain minerals which can have high acidity generating potential. The SRB-based ecotechnology also has to offset this incoming acidity which can slow or even halt bioremediation if undersized to handle the acid load. SRB processes in the pit lake may be severely affected by catchment acid drainage which may directly contribute not only acidity but also providing further sources of oxidants such as ferric iron (McCullough et al., 2008; Geller et al., 2009). Ferric iron can chemically oxidise sulfides generated during the bioremediation process which further increases acidity (Peine et al., 2000; Rohwerder et al., 2003; Dopson et al., 2007). Figure 4 shows an example of poorly managed acidic drainage into a pit lake in Collinsville, Australia.

Figure 4 Examples of un-rehabilitated catchment and its effect on acidic pit lake bioremediation. Note the high concentrations of iron (left) and sulfur (right) containing water drainage into the pit lake

5.3 Environmental and limnological factors

Environmental factors such as regional climate are one of the most important aspects that can influence the SRB-based ecotechnology. For instance, regional weather plays a significant role in defining crucial limnological characteristics such as the lake stratification and water mixing regime. A stratified water column is necessary for anoxic conditions to develop which are favourable for bacterial sulfate reduction following organic matter amendments in acidic pit lakes (Castro and Moore, 2000; Geller et al., 2009). Bioremediation rates may be affected by intense wind and rainfall events which can induce lake mixing and introduce chemical oxidants which can inhibit the bioremediation processes (McCullough et al., 2008). Further in regions with extended cold weather, conditions may not be highly favourable for an effective propagation of SRB-based ecotechnology (Blodau, 2006).

Shallow acidic pit lakes may not be suitable for using SRB-based ecotechnology as these lakes may be highly prone to mixing events either due to strong winds or seasonal weather changes. Stratified water column is important since the sulfides generated during the bioremediation process needs to be protected from exposure to oxygen to avoid re-oxidation for the treatment process to be successful and this will likely to be a significant issue in shallow pit lakes.

5.4 Acidic pit lakes with low sulfate and iron concentrations

Bacterial sulfate reduction as a bioremediation strategy for pit lake neutralisation may not be appropriate for lakes affected by only moderate AMD generation and with very low concentrations of iron and sulfate (Figure 5). An example of such acidic pit lakes are in the coal mining region of Collie, southwest of Western Australia (Lund and McCullough, 2008). These oligotrophic to ultra-oligotrophic pit lakes lack sufficient sulfate concentrations for alkalinity generation through the bacterial sulfate reduction (Lund et al., 2006). A remedy by supplementing sulfate in addition to organic carbon is unlikely to provide a viable solution to realise SRB bioremediation in acidic pit lakes with low iron and sulfate concentrations.

Figure 5 **Examples of aluminium buffered acidic pit lakes in Collie, Western Australia with low iron and sulfate concentrations**

6 Key considerations for implementing SRB-based ecotechnology for acidic pit lake bioremediation

Acidic pit lakes can be remediated by SRB activity using bulk organic carbon addition, however, the process needs to be carefully planned and designed for realisation of full potential of the treatment. Following are some major points that should be considered.

- Regional climate – Adequate information on regional weather like rainfall or cyclonic influences and evaporation rates will be crucial to design the acidic pit lake treatment.
- Pit lake physical characteristics – Gathering information on pit lake catchment size and shape, wind fetch, surface runoff rates, groundwater influences and lake stratification. Effectively treating and managing acidity contributions from catchment drainage.
- Pit lake chemical characteristics – Long-term data on lake water quality, information on the changes in water chemistry over different seasons.
- Organic materials – Characterisation of organic materials for nutrients, metals/metalloids and any potential additional benefits such as source of SRB inoculum and lake water column mixing barrier.
- Process optimisation – Laboratory optimisation of process influencing parameters like carbon quality, quantity, influence of pit lake water pH and acidity.
- Pilot-scale field studies – Based on the laboratory optimised parameters, further field trials to study the influence of environmental and limnological effects on the bioremediation process which could not be simulated in laboratory conditions.
- Final field implementation – Dosing organic materials and monitoring treatment and reference pit lakes after organic material amendment. Additional organic dosing if required, for instance, following increased load of incoming acidity due to heavy rainfall event.

7 Conclusions

Acidic pit lakes formations are likely to continue with the increasing scale of modern open cut mining activities (Kumar et al., 2009). There has been an increasing consideration of preventive measures restricting the development of acidic pit lakes, e.g. backfilling with waste materials. However, there are also many existing acidic pit lakes as legacies of open cut mining which have evolved very little both chemically and biologically over the past decades. This failure to self-remediate invokes a need for precautionary approaches such as treating the pit lakes to achieve water quality improvements. Although there is no dearth of treatment technologies being marketed as solutions, none of them are seen as effective long-term and cost-effective solutions to the majority of acidic pit lake situations. Among these, ecotechnologies appear to be most appropriate strategies for sustainable water quality improvement. SRB-based ecotechnology has the potential to deal with a wide range of water quality issues in acidic pit lakes especially for those with greater depth and high iron and sulfate concentrations. The progress made to develop ecotechnologies for pit lake water quality remediation during recent decades, especially the bacterial sulfate reduction sustained by a source of organic matter addition, appears to be very encouraging. The current knowledge on SRB-based ecotechnology suggests that pit lakes can be remediated this way when appropriate organic carbon source is used, warm temperatures prevail, there is an absence of oxidants and ferrous iron contributions from groundwater, long periods of lake stratification are favoured and there is management of incoming acidity from the surrounding catchment.

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Closure

Regulator guidance and legislation relevant to pit lakes

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Abstract

Open cut mining that develops pit lakes is common internationally, but regulatory guidance specific for pit lake formation and development is sparse in the international context. Instead, approaches toward pit lake development have generally been made by considering every mine site as unique. As a result, current international practice is that development of pit lakes should, and are generally managed on a case-by-case basis. There are a wide range of broad but non-specific forms of regulatory direction and processes such as water quality guidelines to allow for an initial decision-making strategy on whether it is desirable for pit lakes to form and as to what potential end uses may be. However, most of the regulatory guidance focusses heavily on risk as the sole pit lake end point at mine closure. Development of clear social or environmental end use goals in pit lakes uses may provide either provide benefit or to even offset some of the risk.

Once an end use goal is established and comfortably articulated as fitting with broader company sustainability strategies, it will assist in the development of general conceptual plans for a mine pit lake at lease relinquishment. It will also serve to inform regulators of a well-developed concept for going beyond current broad guidelines for pit lake formation and management to better achieve corporate goals of sustainability and social licence-to-mine.

The timescale for the evolution of lakes as end uses may be in the order of hundreds of years. In order to be successful, presenting a well-developed pit void closure plan to regulators and stakeholders should ideally be the conclusion of many years of a well-developed strategy of testing, refinement and stakeholder engagement of an end use development proposal.

1 Introduction

Open cut operations by mining companies operate internationally in countries with varying governmental regulations and guidance for mine closure. The purpose of this chapter is to assess the current state of regulations, guidelines and current operating practices that address the closure expectations and practical realities of mine pit lakes remaining at the completion of open pit mining. We contacted a wide range of people working in the field of managing pit lakes both within Australia and internationally. These people were consultants, regulators, operators working on existing mines and researchers working in the field.

1.1 Regulation forms

There are real legal differences between Guidelines, Codes of Practice, ministerial conditions and regulation in countries that have a common (British) law basis for their legislation (Jones, 2008). These can be roughly outlined as shown in Table 1. Historically new technical issues in the mining industry are initially addressed by guidelines which may then be superseded by regulations if the industry's response is considered ineffective. Guidelines are also often used by governments as *de facto* regulations. In Australia, ministerial conditions issued as part of the approval process for establishing a mine are becoming more detailed in their closure requirements over time reflecting an increased concern by government regarding mine closure.

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Table 1 Forms of pit lake closure "regulation"

Regulation	Detail
Guidelines	Intended as guidance. Following the advice in a guideline is not compulsory nor is it normally a legal requirement as guidelines should not normally be incorporated into legislation.
Codes of practice	Give advice and/or directions on how to comply with the law. Generally speaking, failure to follow an approved Code of Practice is considered a breach of the relevant regulation.
Regulations	Approved by government and part of the law of the land. Can be general or detailed and explicitly state what needs to be done and lists penalties for non-compliance.
Ministerial conditions	Usually site specific and are attached to a specific mining tenement or licence. Failure to meet the conditions can result in the loss of that tenement or licence.

An important point is that all of the above are liable to change. This is important for three reasons:

1. Both guidelines and legislation can result in unintended consequences.
2. Simply meeting today's standards may not be sufficient to meet future community requirements and expectations.
3. Technology changes for the mining industry.

Legislation can either be directed at processes (prescriptive) or towards outcomes (enabling). Prescriptive legislation may dictate how the pit lake can be built, while enabling legislation defines the outcome the pit lake must attain, without constraining the means by which those criteria can be met.

Generally speaking, prescriptive legislation is a poor method of addressing the long-term environmental requirements of waste landforms because it is imposed across all mine sites, irrespective of site specific conditions and discourages the development of an optimal solution for any particular mine. An example of this is if water quality guidelines for environmental protection are specifically applied to protection of pit lake water ecosystems.

Enabling legislation is more likely to result in acceptable post-mining landforms by setting outcomes for the new landforms, including the pit void lake, without constraining the designers. This approach requires the mining company to consider the site specific conditions and arrive at a design much closer to the optimum for that site than the application of a set, one-size-fits-all design.

It is common for more than one regulatory authority to have responsibility for the environmental aspects of mine closure and in many cases a formal Memorandum of Understanding has been drawn up by the responsible authorities to define their respective regulatory processes and responsibilities. Counter to most terrestrial restoration requirement and approaches, there appears to be no consideration to development of multiple pit lakes as landscapes, e.g. as lake districts outside of these individual pit void lake assessments (McCullough and Van Etten, 2011). The general approach of all jurisdictions to this issue is very similar, namely to assess each open pit void and its lake in isolation on a case-by-case basis as part of the general closure requirements. For example, in Western Australia the Environmental Protection Authority (EPA) has used the process of Conditional Ministerial Approval under the *Environmental Protection Act* to recommend to the Minister closure conditions for individual mines.

Some ministerial conditions that relate to water in open pit voids are prescriptive, such as Condition 7.1 for the Windarlind W2 pit (Ministerial Statement No. 802, published on 18 August 2009).

> *"Subject to conditions 7-4 and 7-5, the proponent shall ensure that grazing and predation do not cause an increased impact on flora and fauna in the vicinity of the mine, by backfilling the Windarlind W2 Pit void to a level that will prevent the formation of permanent surface water on cessation of pit dewatering."*

Other ministerial conditions are more enabling, such as Condition 11-2 for the Southdown Magnetite Proposal (Ministerial Statement No. 816, published on 25 November 2009).

> *"The proponent shall ensure that after mine closure the final pit void:*
>
> 1. *does not cause significant groundwater contamination; and,*
> 2. *does not cause material or significant environmental harm to native fauna."*

It should be noted that the Windarlind W2 pit ministerial conditions (conditions 7-4 and 7-5) do provide for alternative solutions, should backfilling be found non-viable. However, it was unspecified and likely undetermined as to which specific animal species are considered at risk from these pit lake developments, if any. Equally there is typically no consideration of pit lakes providing any benefit to local wildlife.

2 Hydrogeology

2.1 Australia

The Western Australian Government has published a detailed water-related resources and guidelines for mining in Western Australia that are of close relevance to pit lake creation. "Mine Void Water Issues" (Johnson and Wright, 2003) presents a then current overview of pit lakes in Western Australia and discusses the management of water remaining in pit voids after mine closure.

The Western Australian government's Department of Mines and Petroleum (DMP) and the Office of the Environmental Protection Authority (EPA) have recently jointly prepared *Draft Guidelines for Preparing Mine Closure Plans* (DMP/EPA, 2011). These guidelines are unusual in that they explicitly provide guidance on pit lake issues. Pit lakes with poor water quality are recommended to be isolated from the environment (including fencing and bunding as required), pit lakes with saline water/developing salinisation are addressed as potential contamination and ongoing abstraction of regional water resources or for watering feral goats (Dunson, 1974; Burke, 1990). Pit lakes with good water quality are also addressed as potential risks for feral predators, grazers and stock animal watering which could impact upon nearby vegetation and disease vector, e.g. mosquito habitat reservoirs.

Figure 1 Over-grazing of rehabilitation vegetation around a pit lake in Western Australia by feral goats (Photo courtesy of H. Jones)

These two guidelines demonstrate a strong and internationally universal theme by Government to protect the beneficial use of existing water resources; be they ground or surface waters. In Australia, this appears to be the main driver for increasing prescription that mining operations in some regions backfill the final void to a level above the potential ground water recovery when mining ceases. Although such guidance highlights backfill as the most risk-free alternative to pit lakes, typically little guidance is available for partial backfill scenarios, or certain waste types (e.g. AMD materials), for maintenance of certain hydrogeological conditions, for specific wildlife habitat types or approaches to be used in different climatic zones.

2.2 North America

Canada and USA have a considerable interest in abandoned mines; particularly mines that have discharges of low pH water that potentially contain chemistries considered toxic such as elevated concentrations of cadmium, selenium and mercury. In all of these cases the focus is on discharges from the mines into the surrounding environment and little concern was expressed regarding situations where the water in the mine remained in the mine area.

The USA and Canada have a similar approach to mine reclamation in that the legislation is found in multiple legislative acts that govern mining (making it sometimes a complicated regulatory framework) (Garcia, 2008). Legal requirements for mines proposing to form pit lakes in the US are linked to a number of federal laws governing mining activities and any activity that could harm the environment. A significant difference, however, is that the US has further specific legislation for coal mining activities that would influence those specific pit lake types (Williams, 2009).

When pit lakes are proposed by in mining plans, both state and federal regulatory agencies in the US generally require detailed geochemical modelling of projected water quality as well as hydrological and hydrogeological modelling of water quantity and pit filling rates and final water heights (Vandenberg, 2011). Sometimes these are required as part of their mining proposals (often by federal mining licence permitting regulators), sometimes they are required as part of closure plans (often at state level). This modelling may extend for decades or longer into the future to assure long-term water quality; the longer it extends the less reliable the model will become due to internal (e.g. inaccuracies in model parameter determination such as groundwater transport rates) and external factors (e.g. change in pre-empted environmental conditions such as through climate change) (Miller et al., 1996). Regulatory agencies also typically require monitoring of both water quality and quantity as pit lakes fill to validate modelling projections. In the event that water quality of a pit lake does not meet relevant water quality standards, it may be necessary to implement a water treatment programme to assure that surface and groundwater are protected. Implementation of required water treatment programmes will generally require detailed design studies, construction of treatment facilities, and planning for potentially perpetual operation and disposal of associated waste products. The requirement for ongoing operation of water treatment systems following mine closure and lease relinquishment is the reason for interest in passive (sometimes erroneously called walk-away solutions) (Neculita et al., 2007) to mine water quality using a variety of ecotechnological approaches (Wren et al., 2011; Kumar et al., 2011).

State laws in the US are unclear as to whether pit lakes as final mining landforms are acceptable or not. Instead, state laws generally rely on other relevant laws regarding ground and surface water quality, and their proposed end use by wildlife and/or humans to determine whether a pit lake would be acceptable or not. Provincial and state regulations and often company expectations are often to returning mining landscapes to some level of productive use, hazard reduction and stable landforms (Tuttle and Sisson, 1998; Government of Alberta, 2009; Williams, 2009; DMP/EPA, 2011). Consequently, it is unlikely that a pit lake with predicted poor water quality would be permitted in the US without an approved plan for remediation at closure, e.g. perpetual external or in situ water treatment, water diversion, backfilling, etc.

One example of a large open pit lake being managed by both federal and state authorities in the USA is the Berkeley Pit in Butte, Montana (Frank, 2000). This has been the centre of extensive underground and open pit mining operations since the 1870s (Gammons, 2011) with open pit mining beginning in 1955. Operations were suspended in 1982 and after the pumps were shut down, groundwater levels started to rise immediately to about 396 m by the end of 1982 and to 914 m by the end of 2000. The chemistry of the bulk of the water included a pH of 2.5, specific conductance of 8,600 $\mu S\ cm^{-1}$ with dissolved copper and zinc concentrations of 190 and 620 mg/L respectively.

A maximum level to which water will be allowed to reach has been set by the US Environmental Protection Agency and the Montana Department of Environmental Quality. The aim is to maintain the Berkeley Pit as a “Terminal Pit” thereby ensuring that the water in the pit is hydraulically contained (hydraulic sink, Commander et al., 1994). Such hydraulic control mechanisms can also make use of pit lakes in other regions of net evaporation as sacrificial pit lakes that protect the broader environment around the pit lake from surface and groundwater transport of toxicants from the pit lake (McCullough and Lund, 2006). However, prescriptive regulation may form an obstacle to this type of closure design due to explicit failure to meet pit lake closure water requirements. If operating as designed, lake will evapo-concentrate acidity and metals to while providing local hydraulic drawdown. This means the lake will eventually fail to meet some water quality criteria, e.g. for environmental protection.

Pit lakes most often become a relinquishment issue if surface or groundwater quality is threatened or if the quality of the pit lake itself poses an environmental risk (Younger, 2002; Doupé and Lymbery, 2005). Nevertheless, there are no US laws that specifically prohibit pit lakes as a possible relinquishment option at closure; with the proviso that relevant ground and surface water quality regulations are still met.

Although regulation in the US is similar to Canada, different mineral ownership laws and a greater percentage of federal lands managed within individual states makes the regulatory environment of many mining situations potentially different to both Canada and Australia which have both federal and provincial/state Government systems, a well developed mining industry and a high standard of living and similar mineral ownership laws.

The Canadian Federal Government published the Environmental Code of Practice for Metal Mines (Environment Canada, 2009) which outlined the broad requirements for mine operation and closure. However, this publication did not specifically address the question of water potentially remaining in open pit voids at closure. Under the Canadian constitution, mining is a provincial responsibility. The federal Government has responsibility for the three territories, but is slowly devolving this to the territories. Several of the provincial guidelines, other regulations and published policies have more detailed reference to open pits, but again there is little detail on pit lakes specifically.

In direct contact provincial regulators all expressed a preference for dealing with all mine closure details on a case by case basis; albeit subject to broad water quality and public safety standards being maintained. For example, Saskatchewan's *Guidelines for Northern Mine Decommissioning and Reclamation* (Saskatchewan Ministry of the Environment, 2008), required pits lakes at mine closure to have water quality similar to what is found in local waterbodies. Water quality in deeper zones within flooded pits could be of poorer quality if these zones become isolated through the formation of a chemocline. However, stability of chemoclines had to be established (presumably through modelling (Boehrer and Schultze, 2006)) before closure.

The Alberta Government established an End Pit Lake Working Group which published *Guidelines for Lake Development at Coal Mine Operations in Mountain Foothills of the Northern East Slopes* (End-Pit Lake Working Group, 2004). While this document addressed the question of open pit voids after closure it was restricted in its application to surface coal mine operations in the Northern East Slopes Region of Alberta. It recommends broad physical, hydrological, chemical and biological criteria for end pit lakes, but cautions that site-specific conditions must also be taken into account. The End Pit Lake Working Group also stated that these guidelines stressed the importance of the continued use of adaptive management principles in the establishment of end pit lakes.

Given the Canadian climate, which almost always results in an excess of precipitation over evaporation, the concerns of the Canadian authorities are on the potential for contaminated water to escape from the mine site and affect local water quality. In most parts of Canada, pit lakes are not a choice, they are inevitable. Backfilling of end pit lakes can be considered in the case of strip mines (i.e. surface coal mines and oil sands), but it is not financially viable in many typical deep, hard rock mining pits. In the case of some of the end pits left after coal mining, they are to ensure that the quality of water remaining in the pit does not adversely affect local aquatic biota, in particular fish caught by the local community.

The public safety aspect of flooded open pits is addressed in Ontario by a specific regulation which requires that at least one sloped entrance shall be left or created to allow a reasonable exit point should inadvertent access occur (Ontario Government, 2007).

More recently, the Canadian oil sands industry's Cumulative Environmental Management Association (CEMA) has developed an end-pit lake committee with representatives from most major oil sand resource companies. CEMA's mandate is to produce guidelines and management strategies that will enable operators to achieve acceptable water quality for end pit lakes in the Athabasca oil sands region (Charette, 2011). The industry's first pit lake (of up to 26) is expected to be developed as a full-scale lake in 2012 and is expected to take 10 years to develop as an ecosystem.

Following initial lake development, intensive monitoring and adaptive design methods are recognised as being particularly important to make the right changes to design and management plans for these future pit lakes.

2.3 Europe

The European community (EU) undertook a research and development project with a consortium of partners from February 2001 to January 2004. The overall goal of the *Environmental Regulation of Mine Waters in the European Union* (ERMITE) project was to provide integrated policy guidelines for developing European legislation and practice in relation to water management in the mining sector (Amezaga and Younger, 2004). The extensive report produced did not specifically address the issue of water in mine voids except where those voids have resulted in water being released from the void and impacting on water resources in the surrounding environment. The considerable majority of the information collected focusses on old abandoned mine workings, mainly underground operations and on operations where there is a high level of pollution already existing.

The overriding concern for ERMITE is to prevent pollution resulting from mining and the concept of pit lakes is not specifically addressed. Significantly different to both Australian and North American approaches, however, there has been collective consideration for development of multiple pit void lakes across a region as a 'lake district'. For example, in the former East German lignite mining region of Lusatia, lakes are considered not only from their independent individual contribution to human and wildlife utility, but also on their collective contribution to landscape aesthetics and sustainability opportunities as a novel landscape that can be engineered to meet the needs and desires of local communities regulatory authorities and also regulators (Nixdorf et al., 2005).

Figure 2 Large pit lakes, as will flood this large open cut pit in Czech Republic (a), and multiple pit lakes, such as this one in Highland Valley, British Columbia, Canada (b), can alter the environmental and social dynamics of a region to that of a novel, but socially and ecologically valid pit "lake district" (Photo courtesy of C.D. McCullough)

2.4 South Africa

South Africa has a well developed series of guidelines published by the Department of Water Affairs and Forestry (DWAF, 2008).

Of these guidelines three have specific application to closure of open pits, namely G4, *Impact Prediction* and G5, *Water Management Aspects for Mine Closure*. These are best practice guidelines dealing with general water management strategies, techniques and tools, which could be applied across multiple sections. They are also explicitly considered under A5, *Water Management for Surface Mines*. The guidelines have been developed as part of the implementation of an integrated water resource management concept brought into being under the National Water Act 1998. The emphasis is on using risk assessments on a case-by-case basis to address the management of water in all phases of mining so as to minimise water pollution, preserve water resources and maximise the reuse of water that has been affected by mining. The guidelines appear to have been drafted to specifically complement each other and not as ad hoc responses to specific issues. There is strong recognition that each mine is unique and will therefore require a site specific closure plan.

The guidelines enable mining companies to comply with South African law by indemnifying them from any post-closure responsibilities. Instead, liabilities are directed to appointed third parties to be responsible for implementing any post-closure monitoring and maintenance programmes. This post-closure phase is required to continue until the residual impact of the mine has reached acceptable levels and no further ongoing maintenance work is required. Nevertheless, apart from these broad closure considerations, the South African guidelines do not specifically address the case of pit lakes, except where that water has the potential to contaminate the surrounding environment or a potential to be reused.

3 Pit lakes as post-mining landforms

3.1 Australia

Similar requirements exist in all states in Australia to provide mechanisms to prevent public access to mines that have been closed. The specific detail of the requirement varies from state to state, with some states allowing fencing around the open pit and others requiring a substantial bund.

Public safety of abandoned open pits in Western Australia is addressed by the Mines Safety and Inspection Act (1994) and the Mines Safety and Inspection Regulations (1995). In part the resulting regulations reflect a case of a member of the public successfully suing the WA local and state Governments for approximately A$1.8 million in damages following an injury at an abandoned open pit lake (Jones, 1996). The Western Australian Mines Safety and Inspection Regulations (1995) contain regulations that apply to the geotechnical considerations that must be adequately considered during the abandonment of an open pit excavation. The Department of Industry and Resources (DOIR) (now Department of Minerals and Petroleum (DMP)) publication *Safety Bund Walls Around Abandoned Open Pit Mines* (1997) requires that before open pits can be legally abandoned, that all long-term drainage, stability, and public access issues are adequately considered and controlled. Environmental requirements for abandoned mines are also specified by the license conditions imposed by the Department of Environment and Conservation (DEC) during the mining project approval process. The DOIR guideline recognises that all excavated pit walls have potential for failure and requires mine slopes to be designed to a standard which evaluates the consequence of failure and the inherent uncertainty in the geotechnical model used as the basis for the pit wall design.

3.2 North America

Public safety around open pits is commonly addressed by fencing and/or bunding of pit edges and a geotechnical assessment of the pit wall stability. In some provinces and states the regulations specify the type and location of fences and/or bunds, but in most cases this is not done. All Canadian provinces rely on the recommendations of the professional geotechnical assessment for achieving safety in the stability of the open pit walls at closure.

Quebec's *Guidelines for Preparing a Mining Site Rehabilitation Plan and General Mining Site Rehabilitation Requirements* nominate factor of safety numbers for waste rock dumps and tailings storage facilities at closure but do not nominate any such requirements for open pits. However, the guideline's appendix on stability criteria contains several statements which could also be applied to open pit walls. In particular, a requirement that stability calculations be based on all long-term conditions affecting structures. They are also required to take anticipated static and dynamic loads and gradual alterations in construction material properties into consideration.

3.3 Europe

Many of the nations in Europe have a requirement to prevent public access by fencing off all open pits at closure, but the responsibility for constructing and maintaining the fences is often not clear, as many of the mine sites are the responsibility of local Government authorities, rather than the national Government. Due to population pressures in historical mining regions, many abandoned open pits in Europe have now become recreation areas (Pearman, 2009); either organically or with oversight and design. With the development of lakes for boating, water bird sanctuaries and fun parks the public is increasingly encouraged to visit these abandoned mine sites at an intensity not seen in other historical mining sites with pit lakes.

4 Acid and metalliferous drainage

Mine metal drainage is known variously as acid mine drainage (AMD), acid rock drainage (ARD), mine metalliferous drainage (MMD) and acidic and metalliferous drainage (AMD). AMD was documented as long ago as Roman times. The process normally requires three basic drivers, sulfide minerals that are able to oxidise in the prevailing conditions at the mine, oxygen and water to enable the acid forming reactions to be initiated and water also so that the acid can be transported from its place of formation. Some common observations of AMD (Costa and Duarte, 2005) provide pointers to the nature of the oxidative process:

- AMD may be delayed in development – onset may occur some significant time after mining operations begin, and AMD is commonly a greater problem after mining ceases than during the life of the mine.
- Once AMD is initiated, acid production may increase exponentially – there is a tendency for the quantity and/or concentration of AMD to escalate and appear to become out of control.
- Once AMD is established, a return to former anoxic conditions may not halt its progress.

However, the AMD-generation process can be mitigated by:

- Minimising the excavation of rocks containing the sulfide minerals.
- Minimising contact between sulfidic minerals and water and oxygen.
- Minimising transportation by water.
- Neutralising any acidic discharges.

4.1 Regulations

AMD is often a significant concern for the international mining community, particularly the threat elevated concentrations of metals/metalloids can pose to ecosystems living downstream from AMD pollution sources (McCullough, 2008).

4.2 International

The Global Acid Rock Drainage Guide (GARD Guide) from the International Network for Acid Prevention (INAP) consolidated relevant information and summarised technical and management practices for industry and stakeholder use. This guide provides a structured system to indentify proven techniques for characterisation, prediction, monitoring, treatment, prevention and management of ARD (Verburg et al., 2009).

4.2.1 Australia

The Australian Commonwealth and State Governments do not have specific regulations to AMD. However, the Commonwealth has published a series of guidelines in its *Leading Practice Sustainable Development Programme for the Mining Industry including Managing Acid and Metalliferous Drainage* (September 2007) which is regarded by Australian regulators as best practice and is sometimes quoted as de facto regulation.

The Western Australian DMP and EPA has also recently released draft *Mine Closure Guidelines* (DMP/EPA, 2011) which explicitly consider AMD as both acidic and neutral/alkaline discharge environmental hazards, recommending 6 or even 12 month kinetic leach tests to fully ascertain risk.

4.2.2 North America

The most detailed information and guidelines relating to the development of acid in mine waste materials, sampling and testing procedures and the mitigation of potential mine metal drainage is contained in the Mine Environment Neutral Drainage (MEND) programme, a joint initiative of governments and industry.

This series of guidelines are increasingly being accepted by regulators as the most reliable source of information concerning sampling and analysis, prediction, prevention, control, treatment and monitoring of acid generated as a result of mining.

4.2.3 Europe

The European Parliament in 2006 issued a Directive (2006/21/EC) on the management of waste from extractive industries and in 2009 supported aspects of this Directive with a commission decision "*completing the technical requirements for waste characterisation laid down by Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from extractive industries*". This decision is now in the process of being incorporated into law by the Members of the European Community.

The commission decision on waste characterisation is a high level document that sets out broad requirements for characterising waste resulting from extractive industries (which includes mining). Its key requirement is that waste characterisation addresses five aspects, namely background information, geological background of deposit to be exploited, nature of the waste and its intended handling, geotechnical behaviour of the waste, and the geochemical characteristics and behaviour of the waste.

Environmental Regulation of Mine Waters in the European Union (EU) (ERMITE) (Amezaga and Younger, 2004) provides integrated policy guidelines for developing European legislation and practice in relation to water management in the mining sector, which was funded by the European Commission 5th Framework Programme. ERMITE addresses the various regional and national conditions in EU Member States and some Eastern Europe countries involved in the enlargement process by integrating different disciplines: water resources, mining, ecology, economy, law, institutions and policy.

4.2.4 Government surety

Performance bonds as government surety can be expressed as letters as credit or similar financial arrangements, or even cash commitments. They are intended to guarantee to government finances to cover the cost of mine closure should the operating company be unable to meet its closure obligations, are becoming common in many mining jurisdictions. These surety arrangements are normally established prior to mine permit approval and held on behalf of a government pending appropriate rehabilitation and final relinquishment of mining leases.

Bonds are still typically insufficient relative to accepted standards of rehabilitation and cannot be considered as an incentive for pit lake development to meet standards where social and environmental end uses may be met. Performance bonds therefore internationally present little direct incentive to a company's relinquishment performance. Furthermore, when performance bonds occur in regulatory environments with few specific guidelines for relinquishment of mine leases with pit lakes as they often do internationally, bonds provide little incentive to develop pit lakes for relinquishment outside of the generic legislation already described. Even if bonds are taken, these bonds may be released prior to achievement of satisfactory pit lake relinquishment standards. For example, when a regulatory agency believes that in the event of rehabilitation performance failure, the country/state can legally recoup enough monies to rehabilitate the site appropriately through other means.

5 Social aspects

Mine closure regulations for many jurisdictions do not specify legislative requirements for stakeholder consultation during mine closure. However, there has been increasing pressure from regulators and the public for the mining industry to engage with stakeholders in a documented process throughout the life of a mine as a social licence to mine (Nelson and Scoble, 2005). The goal of closure is typically to minimise future environmental impacts and to reduce future financial risk to the company's shareholders. Financial institutions such as the International Finance Corporation (IFC) have emphasised the importance of closure for socially conscious and fiscally safe banking purposes and there are broad programmes that financial institutions can adopt to manage the environmental and social risk of mine closure (Garcia, 2008).

It is generally assumed that pit lakes will follow an evolution from newly filled pit lakes with more environmental and social risks to mature lakes with better water quality and a well-developed ecosystem (Kalin and Geller, 1998). Although long-term issues may not be considerations in shorter timeframes that many regulatory authorities and pit lake closure regulations may be primarily interested in, these longer time frames still represent a significant issue for mine closure in a broader sense through the long-term sustainability of regional communities and environments. Consequently, without confident predictability, regulators may consider pit lakes to significant health and safety risks for regional human and wildlife communities, for many hundreds of years following cessation of mining operations (Doupé and Lymbery, 2005). As such, the environmental and social liability that pit lakes represent to communities and the environment is often considered a significant legacy of the regional geography after lease relinquishment (McCullough et al., 2009a).

Notwithstanding the lack of specific regulations, key national and international mine closure guidelines recognise that sustainable mine closure requires effective stakeholder engagement. Stakeholder engagement is an inclusive process, which involves people potentially affected by the mine closure and those with an interest in its rehabilitation or future use. It requires closure information to be distributed to stakeholders in a timely and coordinated manner, and allow adequate time to respond to stakeholder requests (ANZMEC/MCA, 2000). This involves bringing together the views and knowledge of various stakeholders to achieve beneficial outcomes for the operating company and the local community (ICMM, 2008). The objective of stakeholder engagement during mine closure is to enable all stakeholders to have their interests considered before the mine is closed. Early and open company interactions with staff, shareholders and community will also assist regulators to make decisions for pit lake closure with minimum practicable risk of potential controversy.

Although many pit lakes exist and have been developed along these trains of thought, because of the non-scientific nature of many end use development processes, publication of most pit lake developments for social or environmental beneficial end uses occur predominantly within the non-scientific literature in a case-study format with little general guidance offered (Walls, 2004). Instead, factors governing the decision to develop pit lakes are either to reduce or remove impact to meet regulatory performance requirements, or to go further and develop them into a tangible environmental or social benefit. As such, factors to be considered when determining the nature of a final pit lake fall largely into either regulatory requirements or development incentives. An exception is the Western Australian "Draft guidelines for preparing mine closure plans" (DMP/EPA, 2011) which explicitly request mine closure planners for operations realising pit lakes to consider beneficial end uses in their closure plans where water quality is likely to be good.

6 Development incentives for pit lakes

There may be little regulatory or financial pressure to develop an end use benefit from a pit lake. Indeed, many mining companies, researchers and regulators themselves currently perceive regulation to often be more an impediment than an incentive to their own development of social and environmental end uses from pit lakes. Nevertheless, although there may be genuine risks associated with some end uses (Doupé and Lymbery, 2005), pit lakes are being increasingly recognised as opportunities and not just liabilities for potentially gaining benefit to their local community and environments (McCullough et al., 2009a) and particularly in arid environments (Kumar et al., 2009).

Internationally, public perception of pit lakes at abandoned, disused, or unreclaimed hard rock and coal mine sites is typically negative (MMSD, 2002; Hammond, 2010) and may even expose mining operations to more risk than relevant regulations do. Public concerns about pit lakes tend to centre on pit water quality and the possible impacts to nearby water bodies, wildlife, and sometimes even public safety (Williams, 2009). As a result, many mining companies have developed sustainable development policies that likely provide for greater protection from negative effects of pit lakes; and also for greater restoration opportunities than simple regulation does alone. These restoration attempts seek alternative reclamation options particularly for development of pit lakes that have good quality water and could enhance opportunities for sustainable development of the mining operation. In some cases, overly prescriptive regulations that are sometimes not relevant to the case-by-case situation of many pit lake closure scenarios may discourage beneficial end uses developments by directing company focus wholly upon risk. In these cases companies are encouraged to comply with meeting detailed regulatory directions rather than broadly and narratively defined closure objectives which they – together with researchers, consultants and project stakeholders – may have been better able to define.

Figure 3 **Misapplied, regulation can be a major obstacle to development of innovative mine water treatment and closure scenarios. Controversially for state regulators, but with strong community support, this passive treatment field experiment in North Queensland used raw sewage as a carbon source (McCullough et al., 2008) (Photo courtesy of C.D. McCullough)**

Although the target of a post-mining landscape is generally to restore the affected areas to the environment of the previous landscape (Lögters and Dworschak, 2004), this is not often practicable due to high expenses for earthworks and backfill, extended non-operational times to relinquishment, or simply that, due to the abstractive nature of mining, mined resources (waste rock, etc.) are no longer available. Consequently achieving a planned landscape of equal or even greater social and environmental value by instead using the pit lake may be one way in which the mine operation can positively contribute to a region's sustainability and meet biodiversity goals.

7 Conclusions and recommendations

Regulatory requirements governing available pit lake end use options differ between and even within different countries as a result of both different regulatory regimes and also due to the many different potential risks that pit lakes may represent to that particular region. For example, as many mines occur in remote, low rainfall regions (e.g. the Pilbara but also similar arid regions of the US and China), inappropriately managed pit lakes may represent a significant risk to the local human and environmental water resources (Brown, 2003). Where communities reside nearby, pit lakes may also present risks for recreational swimmers where there is a risk of drowning with the limited shallow margin typically afforded by them or falls from high walls that have not been battered down (Hinwood et al., 2010). This is the case even in remote areas where pit lakes are often swum in as organic recreational opportunities (Hinwood et al., 2010). In agricultural areas pit lakes such as the Pilbara may lead to poisoning and drowning of stock and wild life where there is a risk of falls from the pit high walls. In environmentally sensitive areas, mixing of local water resources with contaminated pit waters may lead to loss of biodiversity or ecosystem function (McCullough and Lund, 2006). Particularly in drier regions, pit lakes may also be an ecological liability through supporting populations of feral animals. Consequently, significant rehabilitation may be required to turn a pit lake landscape from an industrial site to an acceptable public amenity or wild life habitat (Krüger et al., 2002).

Figure 4 Mine rehabilitation regulation and closure requirements have lagged behind that for terrestrial post-mining landforms; what is no longer acceptable for above ground landforms, (top) unrehabilitated waste dumps is also becoming unacceptable to pit lakes at closure as well (bottom) unrehabilitated lake edges and poor water quality (Photos courtesy of J. May, C.D. McCullough)

A select few countries and regions do clearly regulate end uses for pit lakes. This end use choice is usually determined by existing local economic, social or environmental interests. For example, end use amenity is broadly regulated in the Lower Lusatian Lignite mining area of Germany on the basis of regional planning targets for land use for economic, environmental and social (recreation) concerns (Dähnert et al., 2004). Nevertheless, these overall strategies may be inflexible for other end uses, including more local-scale interests (Kruger et al., 2002). For instance, social amenity end uses are less commonly specified as end uses for pit lakes as these end uses are typically novel for the area.

In most countries, mining companies are given no prior advice of acceptable end use options by governing bodies. Rather, mining companies interested in developing an end use approach regulatory authorities with their preferred option and then these agencies make judgements as to whether this end use is acceptable. Nevertheless, most developed countries and states are consistent in their requirement for mining companies to plan and/or rehabilitate to minimise or prevent entirely any potential deleterious effects of the pit lake water body on regional ground and surface resources (Miller, 2002). Special regard is also especially given to protecting regional human and ecological communities from negative effects of the pit lake. For example, in Australasia, closure guidelines are based on (ANZECC/ARMCANZ, 2000) criteria (generally for a combination of, ecological and/or drinking water and recreation requirements). Such guidelines generally emphasise either a demonstration of null-negative effects of the lake, or a requirement for active management to a specific point of compliance where issues from the pit lake remain, such as poor water quality (Kuipers, 2002).

Nevertheless, where such regulatory guidelines that are normally only relevant for protection of natural systems such as natural lakes are applied to pit lakes, end use opportunities may be rendered unavailable as inappropriately high environmental and social values are placed on these artificial systems. This has occurred internationally where the water quality of a Minnesota, USA, pit lake was not permitted by state regulations to be degraded by aquaculture below that permissible in a natural lake (Axler et al., 1996, 1998).

Significantly, lack of knowledge of state-of-the-art rehabilitation strategies and capabilities, such as remediation techniques, by regulators may also produce a strong deterrent for companies wishing to engage in end use development activities; whether they be for social use or as wildlife habitat (McCullough et al., 2009b). Although it is expected that liability caused by a pit lake will be incurred until the lake is relinquished to state/federal authorities, in some of these cases mining companies have needed to incur themselves an increased risk of liability during development of a specific end use in order for beneficial end use development to be approved by regulators.

There are a wide range of general guidelines and recommended processes to allow for an initial decision-making strategy on whether it is desirable for pit lakes to form in empty mining voids in Pilbara operations. However, specific regulatory guidance specific for developing and closing pit lakes is sparse. Instead, approaches toward pit lake development have generally been made by considering every mine site as unique. As a result, current international practice has indicated through publications and interviews that development of pit lakes should, and is generally managed on a case-by-case basis. We agree and support this approach to pit lake planning and approval.

A significant guiding principle that is generally missing from regulatory statement and documents is the need to identify what target form of wetland (the restoration goal) these water bodies could and should take. Once this goal is established and comfortably articulated as fitting with broader company sustainability and biodiversity strategies, it will assist in the development of general conceptual plans for each mine sites that may form pit lakes at closure and abandonment. The next step must then be to evaluate as a gap analysis information and understanding for mine closure against this closure goal; as it is for other mining land forms lakes. Filling remaining knowledge gaps is therefore suggested as a critical focus of the pit lake development planning and process. The use of regional water bodies as reference systems to direct potential development trajectories in pit voids and also as restoration goals for developing pit void wetlands is essential. Presenting a well-developed pit lake closure plan to regulators and stakeholders would then be a near-final stage of refinement of the pit lake and broader mine closure and abandonment process.

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Monitoring the water quality of pit lakes

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Abstract

This chapter reviews some of the important chemical and physical properties of pit lakes that should be monitored during and after flooding. At a minimum, seasonal depth profiles should be collected that show changes in water temperature, salinity (specific conductance), pH, turbidity (total suspended solids), and redox state (ORP/Eh). Based on the pit lake profile, water samples should then be collected at enough depths to adequately characterise different lake layers. Besides the usual list of major and trace solutes, suggested analytes include dissolved Fe(II)/Fe(III), nutrients and dissolved organic carbon, and dissolved gases (including O_2*,* CO_2*,* H_2S*, and ammonia). Secchi depths or Photosynthetically-Active Radiation (PAR) sensors give useful information on sunlight penetration. With new benchtop instrumentation, stable isotope analysis of water (both O and H) is very inexpensive. Such data can be used to gain insights into lake stratification, sources of water filling the lake, and the extent of evaporation of different layers in the lake. Stable isotopes of dissolved inorganic carbon, also inexpensive, can be used to track sources of alkalinity, as well as biological reactions such as respiration and photosynthesis. Isotopic analysis of dissolved sulfate may be used to better understand sources of sulfate loading to a lake (e.g. oxidation of sulfide minerals versus dissolution of sulfate minerals), mechanisms of pyrite oxidation (e.g. by* O_2 *or by* Fe^{3+}*), and redox reactions involving bacterial sulfate reduction.*

The well-known Berkeley Pit lake, in Butte, Montana, is used as an example of how pit lake monitoring can inform management decisions. A monthly water-level monitoring and semi-annual water quality monitoring programme for the Berkeley Pit was implemented by the state and federal regulatory agencies as a tool to determine when in-perpetuity treatment of the lake system will begin, and to track changes within the lake and surrounding flooded underground mines which may or may not affect treatment. Additionally, the monitoring data are being used to optimise an ongoing resource recovery project that is extracting copper from the lake.

1 Introduction – why monitor water quality?

Lakes formed by flooding of abandoned open pit mines can have a very wide range of water chemistries, depending on factors such as local geology, climate, pit morphometry, rate of filling and the type of water used to fill the lake (Eary, 1999). Although progress has been made, the science of predicting the future water quality of pit lakes is still in its infancy. For this reason, determining the chemical characteristics of a given pit lake must rely on direct observation, i.e. monitoring.

Water quality monitoring plays a critical role in many aspects of pit lake management. Long-term monitoring of pit lakes is often required by state, provincial, or federal agencies to ensure that changes in water quality do not pose a threat to human and/or aquatic health. Possible threats include unusually high or low pH, elevated concentrations of metals or metalloids, elevated concentrations of cyanide, thiocyanate, or other anthropogenic compounds, high partial pressures of dissolved gas (e.g. CO_2, H_2S), and the presence of pathogens. Increased attention is being paid to the possibility that mining lakes may have beneficial end uses, such as recreation, water supply, or habitat for aquatic life (McCullough and Lund, 2006; Gammons et al., 2009a). Monitoring is obviously needed to inform managers whether the desired end use is being attained, or if management intervention is needed to get there. The use of amendments, addition of lime or nutrients, during pit filling could help avoid or minimise future water quality problems (see Dowling et al. (2004) for a good example). Water quality profiling is needed to determine the presence or absence of vertical stratification in a lake, and whether the stratification is permanent (meromictic case) or seasonal (holomictic case). In some cases (Island Copper, BC, Canada, Pelletier et al., 2009), a meromictic lake may be engineered so that more saline, contaminated water is stored permanently in the bottom of a lake while more dilute, high-quality water floats on top. In other cases (e.g. Colomac Zone 2 pit, Northwest Territories, Canada, Chapman et al. (2007) meromixis may be a hindrance to achieving water quality targets, in which case the lake may need to be artificially mixed.

The purpose of this chapter is to provide an adaptable framework for monitoring the water quality of pit lakes. Because every lake has its own unique set of physical, chemical, and biological characteristics, there is no single set of measurement protocols that will be optimal (i.e. best balance between measurement intensity and cost) for all cases. The following discussion focusses mainly on inorganic solutes. Some important concepts are illustrated using the Berkeley Pit lake (Montana, USA) as an example. This lake (Figure 1) is well-known amongst the mining community, and has a much longer record of water quality monitoring than most other pit lakes. It is also a good example of how monitoring of pit lake water quality has informed the application of management strategy.

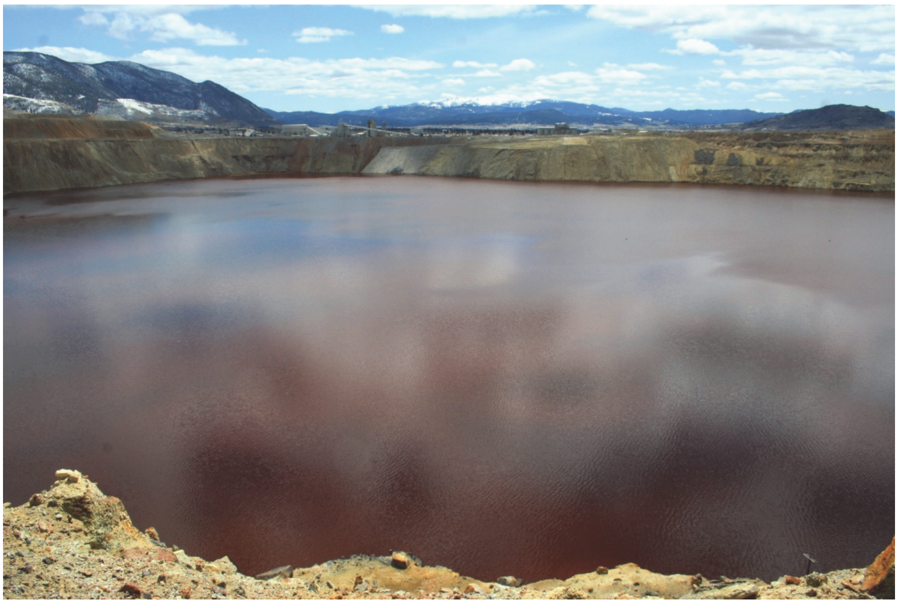

Figure 1 Photograph of the Berkeley Pit lake, looking south (Photo courtesy of C. Gammons, May, 2009)

2 When, where and how to collect samples

2.1 When to sample

Ideally, water quality monitoring should begin during the active mine life. Locations to collect samples include major seeps and springs, nearby surface waters (including tailings ponds, ditches), and groundwater collected from dewatering pumps. After closure, it is important to begin a pit lake sampling regimen immediately, so that any developing water quality problems can be recognised as soon as possible and early enough that management intervention can be successfully implemented. Most large open pits will take several decades to fill, unless large volumes of water are diverted into the pit from external sources. If water quality problems are found in the early stages of flooding, mitigation strategies can be identified and implemented. Once a pit lake has filled to a steady-state volume, it is important to continue water quality monitoring. All young, artificial lakes (including reservoirs) go through an extended period of transition where solute chemistry, nutrients, and aquatic life are continuously adjusting to the new hydrologic regime. Some lakes that are meromictic upon flooding may transition to being holomictic over time, either through incremental processes such as erosion of the chemocline during seasonal turnover or mixing events triggered by physical processes such as a major landslide down the pit walls. Alternatively, some lakes that are holomictic after flooding may slowly develop permanent stratification, e.g. by release of solutes (such as Fe^{2+}) from the pit lake sediment resulting in the development of a high-density bottom layer.

The number of times that a given pit lake should be sampled each year depends on how the lake is stratified, and to what degree the limnology changes on a seasonal basis. If access is good and funds are available, collection of monthly depth-profiles is recommended. Continuous data on lake stratification can be obtained at low cost by deploying small, submersible temperature-loggers on a cable at different depths. After a period of several months, the data are downloaded and the temperature traces can then be used to pick dates when partial or total lake turnover occurred, and which portions of the lake were vertically mixed (see below for an example from the Berkeley Pit). Collection of water samples for chemical analysis should be done seasonally.

2.2 Where and how to sample

Most pit lakes differ from natural lakes in that they are deep and often have no major surface water inlets and outlets. The majority of pit lakes therefore have relatively minor gradients in chemistry in a horizontal direction, and much greater changes in a vertical direction. Nonetheless, it is important early in a monitoring programme to collect samples at different x-y locations to test for lateral heterogeneity. If horizontal gradients are minimal, then the best location to collect long-term data will be in the deepest portion of the lake. A complete depth profile of field parameters (i.e. depth, pH, SC, dissolved oxygen, redox) is usually sufficient to locate vertical discontinuities in temperature or salinity.

Enough water samples for chemical analysis should be collected to represent each of the vertical compartments of the lake, with closer-spaced samples through zones of transition. Lake samples are typically collected using point samplers (e.g. Van Dorn or Niskin samplers) or by pumping water to the surface with a submersible or peristaltic pump. Each of these methods has its advantages and disadvantages. Peristaltic pumps may result in loss of dissolved gas (e.g. CO_2) due to depressurisation, with subsequent pH change. Submersible pumps avoid this problem but are more expensive and more sensitive to corrosion. Point samplers are the least expensive method, but are more prone to atmospheric contamination.

Whenever possible, field parameters, such as water temperature, pH, and dissolved oxygen, should be collected using a submersible multi-parameter meter that is capable of withstanding pressures corresponding to the maximum lake depth. Field parameters can change as water is pumped or hauled to the surface. A number of commercially available multi-parameter meters are available, most of which will cost in the range of US$ 4,000–8,000. Individual sensors (e.g. pH electrode) have a finite working life, and therefore an ongoing operational budget needs to be developed to cover replacement parts and maintenance. CTD (conductivity-temperature-depth) sensors, widely used by oceanographers, are more expensive but have greater precision than most conventional multi-parameter probes due to the addition of an internal circulating pump and other features (see Stevens and Lawrence, 1988).

Besides the pit lake itself, it is also recommended to collect samples of nearby surface waters, groundwaters, storm runoff, and, in some cases, precipitation. Any prominent groundwater inflows (e.g. seeps or springs) should be sampled prior to flooding as this information may be critical later on to understand the factors driving the development of pit lake chemistry. All surface water inputs should be sampled frequently enough to define seasonal or long-term changes in chemistry and flow. If possible, it is recommended to capture mine-wall runoff during storm events (Morin and Hutt, 2001). Finally, if a weather station exists near the mine site, it is recommended to collect composite monthly samples of precipitation for later water chemistry and stable isotope measurement. Such samples are relatively easy to collect and archive.

It is possible to collect samples of suspended sediment falling through the water column using an Imhoff cone (Figure 2a) or similar device. The mass of sediment collected over an integrated time period can be used to estimate the vertical flux of particulate matter to the lake bottom. Samplers can be deployed at different depths to see if there are changes in particulate mineralogy or if dissolution of solids occurs as they settle below the chemocline. If the pit lake is shallow, pore-water samplers (e.g. “peepers”) can be deployed into the lake sediment (Figure 2b). These samplers are very useful to document cm-scale vertical gradients in solute chemistry near the sediment-water interface. Vertical concentration gradients can be used to estimate the diffusive flux of solutes from the sediment into the overlying water column (Martin and Pedersen, 2002). Finally, if possible, lake-sediment cores should be retrieved for mineralogical, chemical, or microbiological testing (Figure 2c). As such sediment is likely to be anaerobic, special precautions need to be taken to prevent sample oxidation prior to analysis (Twidwell et al., 2006).

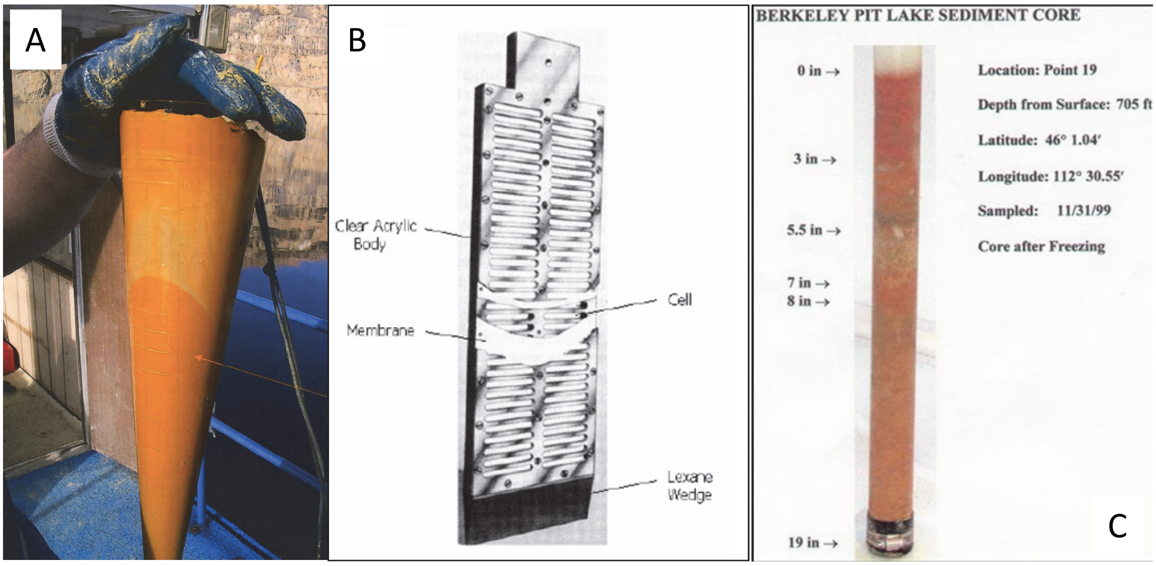

Figure 2 Miscellaneous sampling devices: A) an Imhoff cone being retrieved after deployment in the Berkeley Pit lake for four months. The cone is filled with a large mass of secondary mineral precipitates that descended through the water column; B) diagram of a peeper used for sampling sediment pore water (modified design of Hesslein, 1976). This sampler is approximately 40 cm tall and each cell has a volume of roughly 6 cm^3; C) sediment core (~ 50 cm long) collected from the bottom of the Berkeley Pit lake in 1999

3 What to measure

Table 1 provides an annotated list of important analytes that could be included in a pit lake monitoring programme. Some of these are critical for virtually any study, e.g. temperature, specific conductance (SC), major and trace element chemistry, whereas others are optional, but nonetheless may provide unique and valuable information that can help define processes driving water quality in the lake. A brief discussion is provided for each of the parameters listed in Table 1. Although not discussed further in this chapter, it is highly recommended to install a permanent weather station near the pit lake. Data such as solar radiance, temperature, relative humidity, precipitation, surface wind speed, and wind direction are needed to perform detailed limnological modelling.

Most multi-parameter probes used in pit lake monitoring studies are equipped with sensors to record water temperature, specific conductance (SC) (also known as EC or C25), pH dissolved oxygen (DO), and some measure of redox potential. Special attention should be paid as to whether conductivity measurements are “actual” (i.e. referenced to the temperature of the water sample) or “specific” (i.e. adjusted to 25°C). One of the ways that SC measurements are commonly used in pit lake studies is to estimate the concentration of total dissolved solids (TDS) and salinity, which, in turn, is needed to calculate water density. A correlation first needs to be established between SC and TDS, where the latter is determined from a complete chemical analysis. Since each lake has its own unique mixture of cations and anions, it is not recommended to use a generic formula to compute TDS from SC, even though your meter may give you this option. “Clark-cell” DO electrodes consume DO near the tip of the probe, and water must be stirred to get an accurate reading. Many newer multi-parameter instruments use a luminescent DO sensor that does not require stirring, and holds its calibration longer. For electrical potential measurement, it is crucial to know whether the instrument is reporting mV relative to an Ag-AgCl reference solution (often referred to as "Oxidation-Reduction Potential", or ORP), or relative to the standard hydrogen electrode, i.e. Eh. This is a very common source of error in the reporting of redox data.

Table 1 Annotated list of parameters that may be monitored in pit lakes

Parameter	Comments
Water temperature (T_w)	Needed to estimate water density. Collect T_w in situ, with a submersible sonde or a string of temperature loggers.
Specific conductivity (SC)	Needed to estimate water density. Know whether your meter is reading raw conductivity or SC (adjusted to 25°C).
pH	The pH of a deep water sample may change during pumping to the surface or during storage.
Dissolved oxygen (DO)	Always calibrate to local barometric pressure. Values < 1.0 mg/L should be interpreted with caution. Use a mixer for Clark-type electrodes.
Eh and ORP	Know whether your meter is reading ORP or true Eh. Eh/ORP has limited utility in toxic waters.
Turbidity or TSS	Establish a relationship between TSS and turbidity. Deploy samplers to estimate vertical flux of solids.
Light penetration or PAR	Secchi disks provide a rapid measure of light extinction. Submersible sondes can be equipped with PAR and/or chlorophyll a detectors.
Major and trace elements	Decide whether you want filtered or non-filtered (total) concentrations (good to include both). Usually analysed by ICP-AES or ICP-MS.
Alkalinity or acidity	Perform titrations as soon as possible after sampling, especially if samples are rich in ferrous iron. Follow a standard method.
Dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC)	Usually quantified by a total carbon analyser. Needed to quantify dissolved CO_2 for waters with $pH < 4.5$.
Major anions	Usually quantified by Ion Chromatography (IC). IC is the best method for analysis of sulfate, chloride, and nitrate.
Nutrients and H_2S	Colorimetric methods have low detection limits for H_2S and nutrients, but are prone to chemical interferences (e.g. with Fe).
Weakly-acid dissociable (WAD) cyanide, total cyanide and degradation products	Especially critical for mines where cyanide was used for metal recovery (e.g. most gold mines). Degradation products of cyanide include thiocyanate, ammonium, and nitrate.
Stable isotopes of O and H in water	Useful to examine lake stratification, evaporation, and different sources of water.
Stable isotopes of S and O in sulfate	Can be used to determine sources of dissolved sulfate and whether or not bacterial sulfate reduction is occurring.
Stable isotopes of N and O in nitrate	Can be used to determine sources of nitrate, and to track nitrate-attenuation mechanisms, such as denitrification.
Stable isotopes of C in DIC	Can be used to discriminate between DIC sourced from dissolution of carbonate minerals versus microbial respiration.

Turbidity and total suspended solids (TSS) are important data to collect for most pit lakes. Fine-grained suspended matter is often enriched in trace metals, microorganisms, and nutrients. Turbidity sensors can be attached to a multi-parameter probe or CTD probe to obtain a continuous depth profile. By collection of a subset of samples for conventional TSS measurement (filtering and weighing), one can establish a correlation between turbidity and TSS. If TSS is high, then this influences water density, which could be important for lake stratification. For example, some waters discharged into a pit lake, such as mill tailings or lime-treatment sludge, may have relatively low TDS but very high TSS. Such waters will normally sink to the bottom of the lake because of the contribution of suspended sediment to the total density.

Sunlight penetration is important to determine the depth range where primary production of O_2 takes place in a lake (often approximated by the 95% light-attenuation threshold). This can be quantified using a light sensor, usually set to measure a range of wavelengths corresponding to photosynthetically active radiation (PAR). Depth of the photic zone can also be approximated by lowering a secchi disk and recording the depth where the black and white quadrants on the disk can no longer be discerned to the observer. Turbidity is the most common reason for rapid attenuation with depth of sunlight in pit lakes. However, some lakes with low pH contain a high concentration of dissolved ferric iron which is also a strong absorber of visible light. Such lakes appear black when observed from above.

After a representative water sample is collected, it is usually split into several containers for different laboratory analyses. One bottle is typically used for analysis of a suite of major and trace elements by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). The sampling plan should decide early on whether samples for ICP-AES analysis should be filtered or non-filtered, and how much acid of what type and purity should be added to preserve the samples. If filters are used, then the same filtration procedure should be followed for each visit. A common procedure is to use filters with a nominal pore size of 0.45 µm, which is sufficient to exclude most of the suspended sediment, plankton, and bacteria. Smaller pore sizes (e.g. 0.2, 0.1 µm) will capture more of the colloidal-sized particles, as well as the smaller bacteria, but are more prone to clogging. Procedure blanks made from de-ionised water should be prepared to test for the presence of trace elements (e.g. Zn) leached from sampling apparatus (e.g. gloves, syringes, filters, tubing, bottles) or preservation reagents. For trace metal work, it is recommended to acid-rinse bottles and syringes and to flush filters with de-ionised water prior to use. The analytical detection limits of inductively coupled plasma atomic emission spectroscopy (ICP-AES) are typically >1 to 10 ppb, and may be insufficient for analysis of some trace metals. Inductively coupled plasma mass spectroscopy (ICP-MS) or graphite furnace atomic absorption spectroscopy (GF-AAS) have greater sensitivity, but are also more expensive.

A 250 or 500 mL sample of raw (unfiltered) water should be collected for alkalinity and/or acidity titration, as well as laboratory checks on field parameters such as pH and SC. Alkalinity is a critical measurement that is used, along with pH and temperature, to speciate DIC between carbonic acid (H_2CO_3 or dissolved CO_2), bicarbonate ion (HCO_3^-), and carbonate ion (CO_3^{2-}). Alkalinity titrations should be performed as soon as possible after sample collection. This is especially critical for samples that contain dissolved ferrous iron: oxidation of Fe^{2+} produces ferric hydroxide and releases protons that will react with bicarbonate ion to form CO_2. Samples of raw water that turn orange or red during storage have “gone off”, and will give falsely low alkalinity values. If this problem persists, it might be a good idea to train samplers to perform alkalinity titrations in the field immediately after the water samples are collected. This can be done quickly using field alkalinity kits that employ a hand-held digital titrator and pH-sensitive indicator dyes. Acidity titrations are less commonly included in pit lake sampling plans, but provide useful information on the total acidity (i.e. sum of dissolved acids, including species such as Al^{3+}, Fe^{2+}, Fe^{3+}, Mn^{2+}, HSO_4^-, and dissolved CO_2) in a water sample, which must be known to predict how much lime or other reagent will need to be added during future chemical treatment. Compared to alkalinity titrations, acidity titrations are somewhat complex to set up and interpret (see Kirby and Cravotta (2005) for a good review on the subject).

If the pH of a lake is <4.5, then the concentration of DIC cannot be determined by alkalinity titration, and a carbon analyser must be used. This method involves conversion of DIC to CO_2(g), which is measured spectroscopically. If DOC is present, then the carbon analyser can quantify both forms of carbon. DOC is important for several reasons, including its role in photochemical and microbial reactions and its ability to bind with heavy metals which, coincidently, decreases their toxicity to aquatic organisms, such as fish. The so-called “Biotic Ligand Model” incorporates DOC-metal interactions (Niyogi and Wood, 2004), and is being used by the US Environmental Protection Agency to set new regulatory targets for protection of aquatic life.

Major ions, including chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), and sulfate (SO_4^{2-}), are usually determined on filtered, non-preserved samples using ion chromatography (IC). Bicarbonate ion cannot be quantified by IC. Colorimetric analysis is also possible, and indeed the detection limits for several important nutrient species such as nitrate, phosphate, nitrite (NO_2^-) and ammonium (NH_4^+) are typically orders of magnitude lower using colorimetry as opposed to IC. The problem with colorimetry is that the results are often subject to matrix interferences. Method development is recommended using spiked samples and certified standards to confirm the reliability of any colorimetric test. Portable, battery-powered spectrophotometers are commercially available that can perform hundreds of separate tests. One test that is particularly useful is the analysis of dissolved sulfide ($H_2S + HS^-$). If free sulfide is present at depth, the chemistry of the lake waters will be drastically changed compared to shallower water that is devoid of sulfide. Dissolved sulfide is toxic to most aerobic organisms (including humans) and for this reason any lake with high sulfide concentrations at depth should be monitored for a possible release of H_2S gas. Colorimetry is also commonly used to speciate total dissolved Fe between ferrous and ferric species, i.e. Fe(II) and Fe(III), respectively, as shown in the example from the Berkeley Pit.

Dissolved cyanide (CN^-) may be an important contaminant of concern, especially if a pit lake is located near an active or former cyanide mill or heap-leach pad. The chemistry of cyanide is complex (Smith and Mudder, 1999), and often requires analysis of more than one chemical form. Total cyanide and WAD cyanide are the two most common types of analyses. The difference between total and WAD cyanide represents cyanide that is bound up in strong complexes, such as $Fe(CN)_6^{3-}$. In a pit lake environment, WAD cyanide will break down fairly quickly to a mixture of bicarbonate ion and ammonium ion (NH_4^+). If DO is present, the latter will be oxidised to nitrate. In contrast, strong metal-cyanide complexes are resistant to degradation and may persist long after all of the WAD cyanide is gone. If sulfate is present (which is usually the case in mine lakes), high concentrations of thiocyanate (SCN^-), another toxic compound, may build up as the WAD cyanide is broken down. Any monitoring programme for a pit lake where cyanide is a concern should also monitor thiocyanate.

Isotopic data may not be a critical component of a pit lake sampling plan, but nonetheless could provide unique insights that conventional chemical analysis would miss (Seal, 2003). With the advent of new bench-top instrumentation, stable isotope analysis of water samples has become both rapid and inexpensive, e.g. < US$ 20 for a combined O- and H-isotopic analysis. Different water inputs into a pit lake may have different isotopic signatures, making it possible to determine sources of recharge and to develop a water budget for the lake. Stable isotopes can also be used to estimate the mass of water lost to evaporation. Other stable isotopes may be useful to address specific questions, such as the identity of sources of S, N, or DIC. For example, is sulfate in a given lake sourced by oxidation of pyrite, or by dissolution of gypsum or hydrothermal sulfate minerals? Is bacterial-sulfate reduction occurring in the deep lake? Did nitrate come from blasting explosives or the oxidation of cyanide? Is denitrification occurring in the deep lake? Did high concentrations of CO_2 or bicarbonate ion come from the oxidation of organic matter, or dissolution of carbonate minerals? Like water, many laboratories now provide C- and O-isotopic analysis of DIC for surprisingly low cost. S and N isotopes are more expensive, but may still cost less than a complete inorganic suite of chemical analysis.

Samples for stable isotopic analysis of water need no special preparation, can be small volume (e.g. 10 mL), and, if tightly sealed with no head space, can be stored indefinitely. Thus, it is a simple matter to collect and archive water samples for later analysis. Samples for isotopic analysis of sulfate are processed by acidification with HCl, followed by addition of $BaCl_2$ to produce a $BaSO_4$ precipitate (Carmody et al., 1998). Samples for isotopic analysis of DIC are obtained by addition of $SrCl_2$ to make a $SrCO_3$ precipitate. The $BaSO_4$ or $SrCO_3$ precipitates are filtered, dried and weighed, and can be stored indefinitely. Isotopic analysis of nitrogenous species (e.g. nitrate, ammonia) usually requires a large volume, filtered sample (e.g. > 1L) which is processed at the isotope laboratory. If stored in plastic containers with a small amount of head space, the water samples can be frozen for longer-term storage.

4 Case study — the Berkeley Pit

The Berkeley Pit (Figure 1) is one of the largest and most acidic mining lakes in the world, with extremely high concentrations of dissolved metals (e.g. > 100 mg/L each of Al, Fe, Mn, and Zn). The pit began filling with water shortly after mining ceased in 1982, and continues to fill at a rate of $7.8e^{06}$ to $1.1e^{07}$ L/day, mainly from deep groundwater and underground mine pools (Gammons and Duaime, 2006). Since 2002, a monthly water level monitoring and semi-annual water quality monitoring programme has been conducted by the Montana Bureau of Mines and Geology (MBMG). This monitoring programme was implemented by the state and federal regulatory agencies as a tool to determine when in-perpetuity treatment of the lake system will begin, and to track changes within the lake and surrounding flooded underground mines which may or may not affect the quality and volume of the water to be treated. Additionally, the monitoring data are being used to optimise an ongoing resource recovery project that is extracting copper from the lake.

4.1 Berkeley Pit — field measurements

Figure 3 is an example set of field profiles collected from the Berkeley Pit in June, 2008, as part of the semi-annual MBMG sampling programme. The temperature and specific conductance (SC) profiles clearly show the vertical stratification in the lake, with a shallow, poorly mixed layer (epilimnion), an intermediate, well-mixed layer (hypolimnion), and a deep, well-mixed layer (monimolimnion). Profiles for other parameters, such as pH and Eh, show inflections at the limnological boundaries. Dissolved oxygen (DO) was present at detectable levels only in the epilimnion. The surface layer also had very high turbidity owing to oxidation of dissolved Fe^{2+} to secondary Fe(III) precipitates (Figure 2a).

The MBMG typically collects vertical profiles of field parameters prior to collection of water quality samples. By examining the field profiles, it is easy to pick which depths to collect discrete water samples. This is important because, in some years, there are only funds to analyse a small number of samples. Given this constraint, the samplers must be sure to collect at least one water sample from each of the major water layers in the lake.

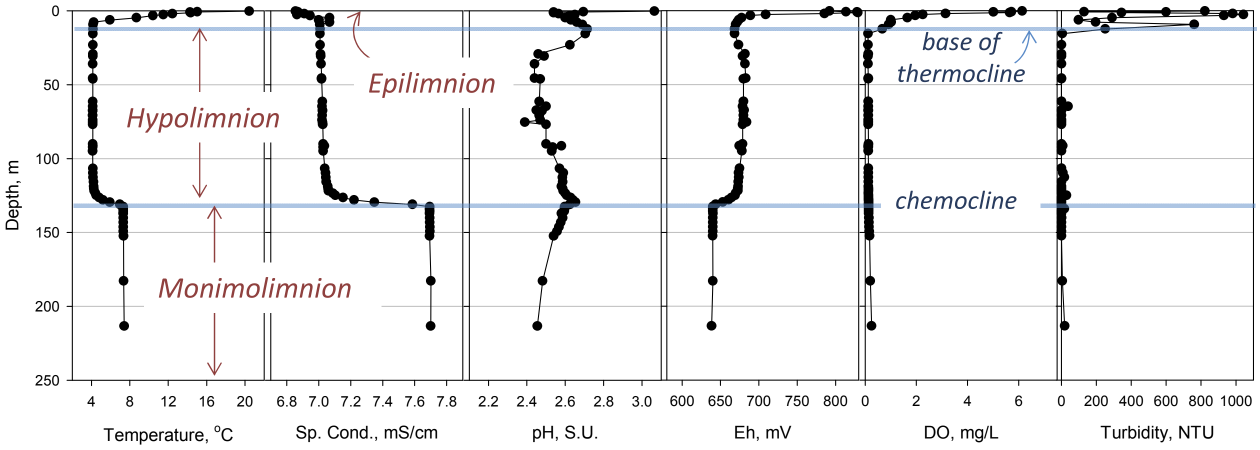

Figure 3 Berkeley Pit profiles collected in June, 2008 (MBMG, unpublished data). Sp. Cond. = Specific Conductivity, DO = dissolved oxygen, NTU = nephelometric turbidity units (Duaime and Tucci, 2009)

Five months of time-series data collected from temperature loggers suspended in the lake at different depths are shown in Figure 4. The data indicate that the surface layer of the lake during this time was poorly mixed. In contrast, the temperature traces between 15 and 61 m depth plotted right on top of each other, suggesting continual mixing of the hypolimnion. A third layer of water between 137 and 229 m (monimolimnion) had a constant temperature of 7.3°C until late September, at which time the chemocline of the Berkeley Pit lake was drawn down below an elevation of 137 m causing the two temperature traces to diverge. The lake mixed to a depth of at least 61 m following a sharp cold weather pattern in early October. However, due to its higher TDS, the deep lake (shown by the 229 m trace) remained stratified.

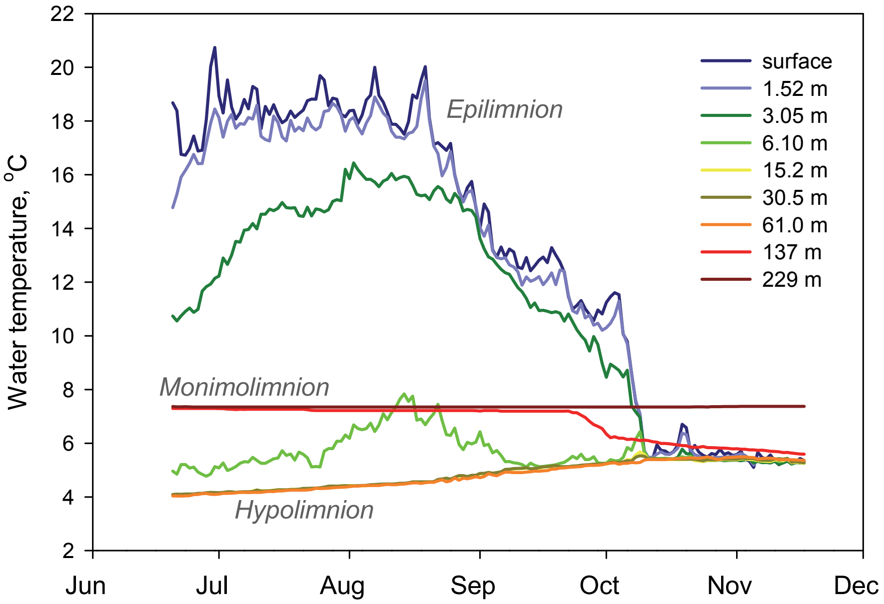

Figure 4 **Trends in water temperature with time at selected depths in the Berkeley Pit lake, 2008 (Duaime and Tucci, 2009)**

4.2 Berkeley Pit— chemical analyses

All chemical analyses of the Berkeley Pit lake collected as part of the MBMG semi-annual monitoring are available electronically at GWIC (2011). Summaries of these data are published annually by the MBMG as Open File Reports (Duaime and Tucci, 2009, 2011), many of which are available in PDF format at MBMG (2011). In this chapter, we have chosen to show some example data for dissolved iron (Fe). Figure 5a shows changes with depth in the concentration and redox speciation of Fe in June 2008. Note the abrupt transition from Fe^{2+} > Fe^{3+} at depth to Fe^{3+} > Fe^{2+} above the chemocline. This was important information for the active mining company, who is recovering dissolved copper from the pit lake by a cementation process. Water from the lake is pumped to the surface where dissolved Cu^{2+} is plated onto scrap iron as Cu metal. The Cu-depleted water is then returned back to the surface of the lake. Because high concentrations of ferric iron (Fe^{3+}) interfere with the Cu recovery process, the pump intake needs to be placed below the Fe^{3+}/Fe^{2+} transition. Figure 5b shows how the ongoing Cu recovery operation steadily drew down the elevation of the chemocline in the lake between 2005 and 2009, effectively changing the lake from being meromictic to being vertically mixed.

The dramatic decrease in the concentrations of dissolved Fe shown in Figure 5b was an unexpected consequence of the Cu recovery operation that may have a beneficial impact with respect to future pit lake management. Recent calculations suggest that the total acidity (i.e. sum of H^+ + dissolved metals) of the lake has decreased significantly compared to pre-2005 levels. This may translate into a substantial savings in the cost of lime when full-scale treatment of the lake begins, sometime after 2020.

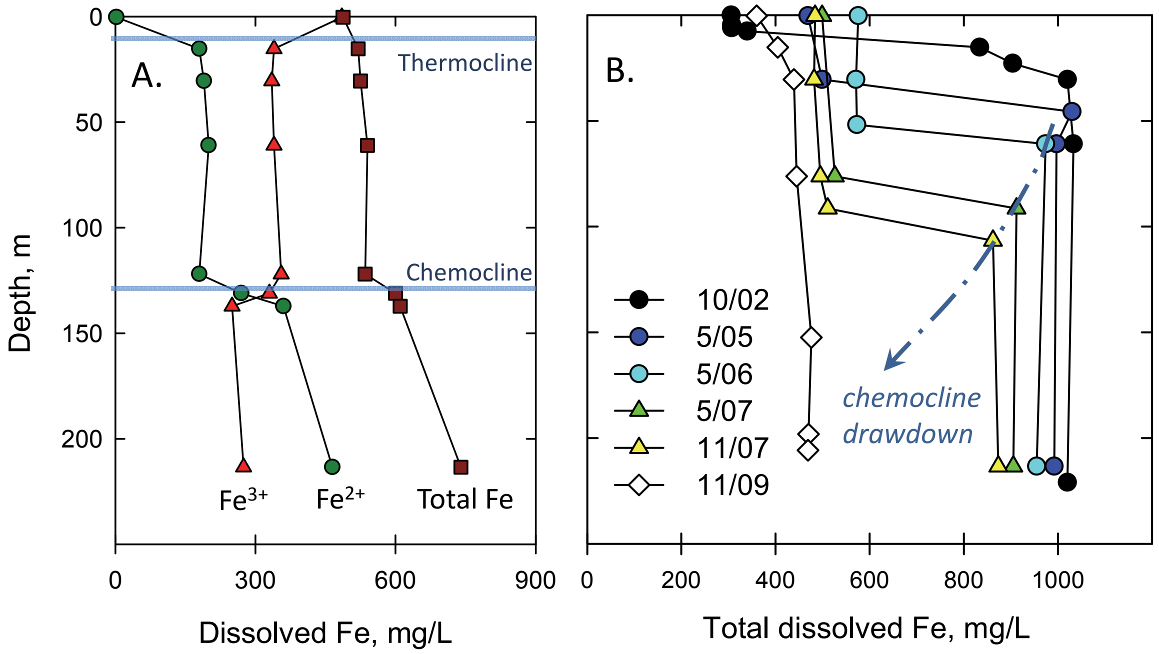

Figure 5 **Trends in Fe concentration and speciation with depth and time in the Berkeley Pit lake: A) data from June, 2008; B) comparison of total Fe data from 2002 to 2009, showing drawdown in the chemocline (Duaime and Tucci, 2011)**

4.3 Berkeley Pit — stable isotope analyses

Although not part of the MBMG's routine sampling plan, samples for stable isotope analyses have been collected from the Berkeley Pit and surrounding mine waters by researchers at Montana Tech. Trends in the stable isotopic composition of water in the Berkeley Pit lake are shown in Figure 6. The pit lake water was approximately 10–25% evaporated in 2003, with an increase in the extent of evaporation towards the surface, i.e. above the elevation of the 2003 chemocline, at about 50 m. In contrast, the isotopic compositions of the surrounding flooded mine shafts in Butte plot close to the local meteoric water line, indicate minimal evaporation prior to recharge. At the other extreme, water contained in a large tailings pond north of the Berkeley Pit was highly evaporated in 2003 (>40% water loss).

Trends in the stable isotopic composition of dissolved sulfate in the Berkeley Pit and surrounding mine waters of Butte are summarised in Figure 7. The Berkeley Pit lake has extremely high concentrations of sulfate (> 7,500 mg/L as SO_4). The isotopic composition of this sulfate is homogenous with depth in the lake, and overlaps with that of pyrite from the Butte orebody (Figure 7). This result is consistent with the hypothesis that most of the sulfate in the lake was sourced by oxidation of pyrite. In contrast, the sulfate-S present in the surrounding flooded mine shafts in Butte consists of a mixture of pyrite-derived S and sulfate released by dissolution of the mineral anhydrite ($CaSO_4$). Anhydrite is a common high-temperature alteration mineral in porphyry copper deposits, and is moderately soluble in cold water. In Butte, most of the early anhydrite that formed in the vicinity of what is now the Berkeley Pit was destroyed during later hydrothermal events, being preserved only in the deeper and more peripheral parts of the district. This interpretation of the geologic history is consistent with the isotope data since the water from the mine shafts flooded with water that is deeper and located outwards from the centre of the district contains sulfate that has a partial anhydrite signature.

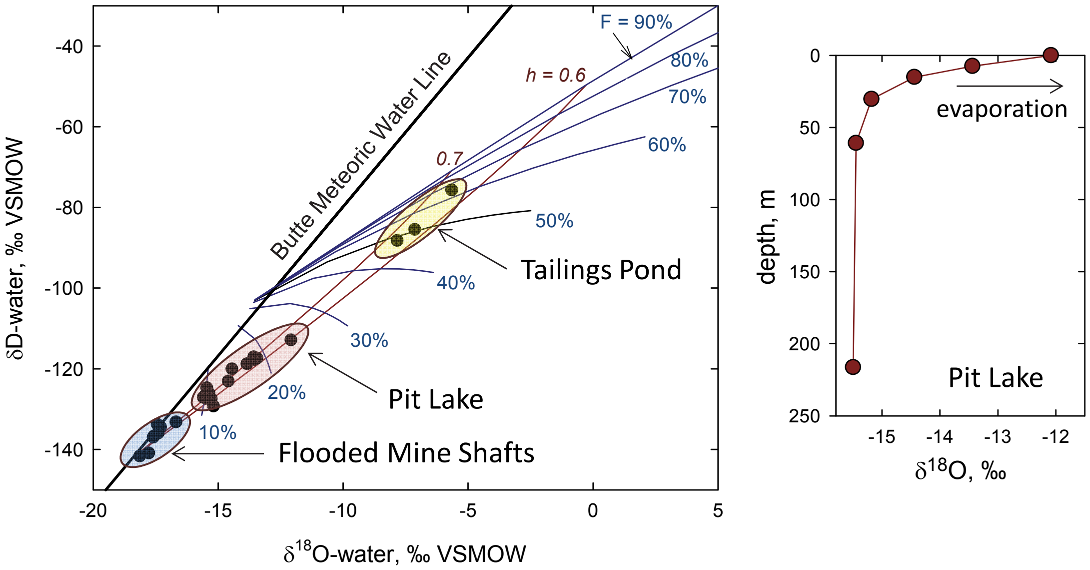

Figure 6 **A) Stable isotopic composition of the Berkeley Pit lake and surrounding waters. F = fraction of water evaporated; h = relative humidity. B) Changes in O-isotopic composition of the Berkeley Pit lake (October, 2003) with depth. Both graphs are modified from Gammons et al. (2006)**

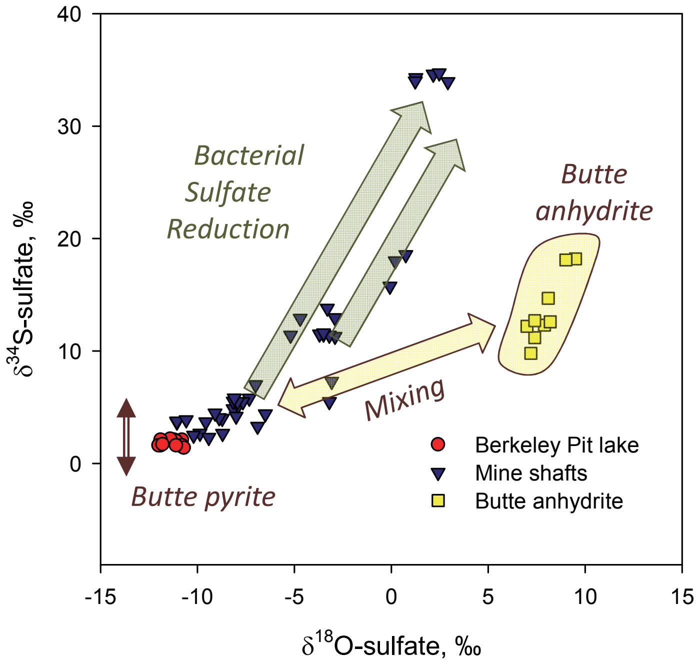

Figure 7 **A) Stable isotopic composition of dissolved sulfate in the mine waters of Butte compared to the isotopic composition of pyrite and anhydrite in the orebody. Sulfate in the pit lake was derived almost entirely from oxidation of pyrite, whereas sulfate in the flooded mine shafts is a mixture of pyrite-S and dissolution of anhydrite, modified by bacterial sulfate reduction (adapted from Gammons et al., 2009b)**

A few mine shafts plot off the mixing line between anhydrite and pyrite, and contain sulfate that was noticeably enriched in both ^{34}S and ^{18}O (Figure 7). These waters had a sharp odour of hydrogen sulfide (H_2S). The S-isotope ratio data confirmed that the dissolved sulfide was formed by bacterial sulfate reduction (Gammons et al., 2009b). Despite the fact that the deep Berkeley Pit lake is anoxic, no chemical or isotopic evidence has been found for significant activity of sulfate-reducing bacteria (SRB) in the lake. The lake sediment contains abundant organic carbon in both dissolved and solid form (Cameron et al., 2006). Thus, the paucity of SRB is probably due to the low pH of the lake, coupled with the extremely high concentrations of dissolved metals, such as Cu and Zn, which are known to be toxic to many species of SRB.

5 Conclusion

This chapter has outlined a framework to assist with the development of an appropriately focussed sampling plan to monitor the water quality of a pit lake. Although no single sampling design will be optimal for all lakes, the basic tenants of good measurement design and quality assurance/quality control (QA/QC) are universally applicable (see EPA, 2002). Namely:

1. The sample database must be representative of the environmental condition (i.e. make sure enough samples are collected to fully characterise the lake, and that the samples do not degrade prior to laboratory analysis);
2. The data collected in a given year must be comparable to similar data collected in other years (i.e. use standard field and laboratory methods);
3. The database must be complete (i.e. avoid large data gaps in the types of analyses performed or the dates of sampling);
4. The data must be accurate (i.e. follow proper calibration procedures to optimise precision and eliminate systematic error);
5. The analysis method used must be sufficiently sensitive (i.e. choose a method with a detection limit that is low enough so that the data can be interpreted within the context of relevant applicable water quality guideline criteria).

In most cases, certified laboratories will provide a full QA/QC report on demand, at no additional cost. This information should be archived as part of the project database. If analyses are done in-house, then QA/QC protocols can be customised to address the needs and capabilities of the monitoring plan.

In the authors' experience, and in conversations with other pit lake researchers, it appears that there are relatively few mining lakes world-wide with a water quality database that meets all of the measurement design and data-quality criteria outlined above, and even fewer where the data are publically available. Sufficiently comprehensive high-quality time-series databases are essential not only to empirically understand the status of a pit lake but to enable the refinement and calibration of physico-chemical prediction models. Lack of such comprehensive data is probably the single biggest factor that is holding back the science of pit lake research.

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Working near pit lakes – health and safety considerations

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Abstract

Pit lakes and their surrounding environment represent significant occupational health and safety (OH&S) risks to workers, whether they are on an operational or a relinquished (abandoned) mine site. Employers of staff working near pit lakes have a legal obligation to protect the health and safety of our employees and organisations and project leaders will benefit from improved OH&S reducing costs and increasing productivity.

The most significant acute OH&S risks around pit lakes relate to drowning. Other significant risks are heavy lifting of boats and other equipment, and off-road travel to site. Environmental exposures to extreme hot or cold may also occur where mining sites are located in extreme climates such as tropical, desert or cold-temperate regions. Diving in pit lakes is a particular hazard that should be avoided where possible by using engineering alternatives such as remote sampling devices. Protective personal equipment (PPE) should be a combination of standard field environmental protective clothing, e.g. sun hat and strong footwear, and mine site PPE requirements such as hard hat and long pants/shirt sleeves.

Chronic OH&S risks include inappropriate and sustained physical exertions and health effects from contaminated pit lake water such as elevated metals and metalloids. However, standard water quality contact issues such as pathogenic contamination may be more significant.

A risk-based approach is recommended to address risks, as an intrinsic component of near pit lake work planning and prior to entering the pit lake environment. This should be understood by all pit lake workers and regularly updated by learnings and other experiences.

1 Why health and safety?

Businesses and individuals have moral obligations to health and safety (OH&S); however, attention to OH&S is not just about being socially responsible. It also makes good business sense and OH&S should be regarded as just as important as the achievement of any other key project objective. Good health and safety practices can also help to enhance perception of their organisation as a socially responsible group. Good OH&S practices can:

- reduce absences and increase the productivity of workers
- increase motivation and the commitment of staff
- reduce project costs, such as insurance premiums, and decrease project disruption.

There are also legal and financial responsibilities which most countries have as laws and regulations. If businesses get OH&S wrong, the costs of accidents and ill-health can be substantial. For the individual, there are the costs of care, loss of earnings and loss of quality of life.

For large mining companies, OH&S incidents can therefore lead to significant disruption of productivity, claims for damages, government enquiries and inspections, loss of from communities and workers goodwill and loss of staff confidence in management. For small organisations such as research institutions and small consultancies, occupational accidents can have a major financial impact and delay or even prevent project outcomes being realised.

2 Risk management

The identification, assessment and management of risk are fundamental to effective health and safety and is a critical part of the decision making and planning process. It is important to understand the difference between hazard and risk.

Table 1 Hazard and risk definition

Hazard	A source or situation with a potential for harm in terms of human injury or ill-health, damage to property, damage to the environment, or a combination of these, e.g. deep lake water.
Risk	The combination of the likelihood of an occurrence of a hazardous event or exposure(s) and the severity of injury or ill health that can be caused by the event or exposure(s), e.g. deep lake water and a chance of falling in.

Standards and legislation regarding risk management vary depending on the country or state. However the methodology and principles of risk management remains constant regardless of location.

The guiding principles of risk management are:

- Hazards are identified and considered in the decision making process for projects, purchases and significant changes.
- Risks are assessed using tools and methods appropriate to the nature and scale of the task.
- Stakeholders are consulted when assessing risk and determining control measures.
- Risk controls are communicated to employees and contractors.
- Risks are reviewed following implementation and when significant changes occur.

2.1 Responsibilities

Everyone has a responsibility to take care of their own safety and that of others. However, effective risk management requires clear responsibilities to be determined at the outset. An example of safety responsibilities for a pity lake project may look like this:

- Staff are aware of a risk management framework and equipment used on the project.
- Risk management is implemented into the decision-making process.
- Risks associated with the project have been identified and adequately controlled.
- Staff on the project are aware of risk controls required.
- Staff have the tools and understanding to apply risk management principles during the project.
- A review of the adequacy of risk management process is undertaken at the project’s conclusion.
- Conversely, staff should ensure they raise concerns in relation to safety issues with their manager and that they comply with the risk controls in place for the project.

2.2 Hazard identification

The first stage in risk management is to identify the hazards involved in the work to be undertaken.

Identifying hazards early in the process assists in clarifying responsibilities and or controlling or even eliminating the hazards throughout the lifecycle of the project. Identifying hazards may also avoid significant design changes late in the project and prevent injuries to direct employees and contractors working around the lake.

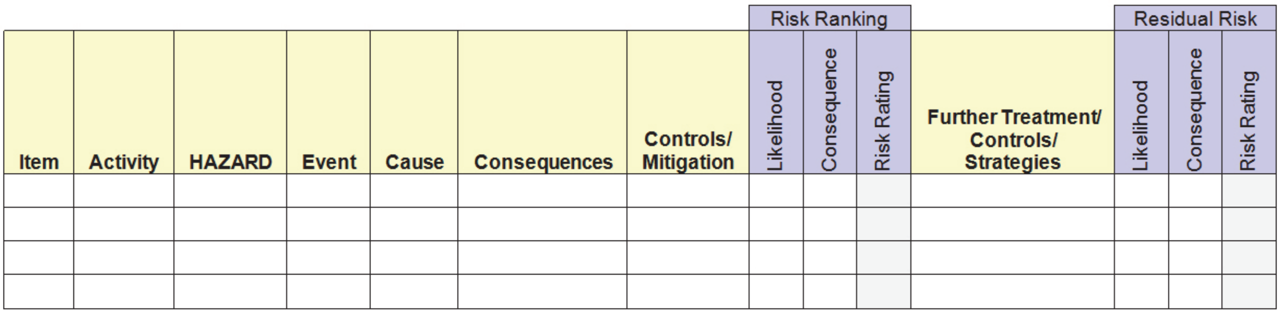
An effective risk management tool is the utilisation of a facilitated Hazard Identification Workshop (HAZID) at the beginning of the project to identify or review any general or specific health and safety hazards.

The objective of a HAZID workshop is to share and document project health, safety and environment risks and to ensure that measures are mitigating the risk. Consultation is a central feature of risk management because involving the people who do the work in identifying hazards and deciding how to control risks is the most effective way to manage health, safety and environmental risks. To obtain the most value from a HAZID workshop a health and safety representative from the pit lake project workers, contractors and mine company representatives should attend.

Representatives at the workshop should have detailed knowledge of the tasks, health and safety issues and risk controls relating to the work they will be undertaking. The attendees should also be at a level to influence preparation and execution of project activities within their own company. Experience shows that the most effective starting point for a HAZID workshop is to break the project into the main activities such as:

- travel to site
- project work
- discipline areas (e.g. hydrological, environmental)
- work environment, i.e. issues that are common across the work environment such as, hazardous fauna and environmental, e.g. heat, etc.

Once the main activities are identified the next step is to identify what hazards are likely to be present in each activity, what would cause those hazards to be realised, the consequences if they were realised and what controls are already in place to mitigate the hazards (Figure 1). If the risk rating remains high even with the current controls in place then further controls should be identified and, once these are in place, the risk reassessed. The resultant hazard is then risk assessed using a risk matrix.

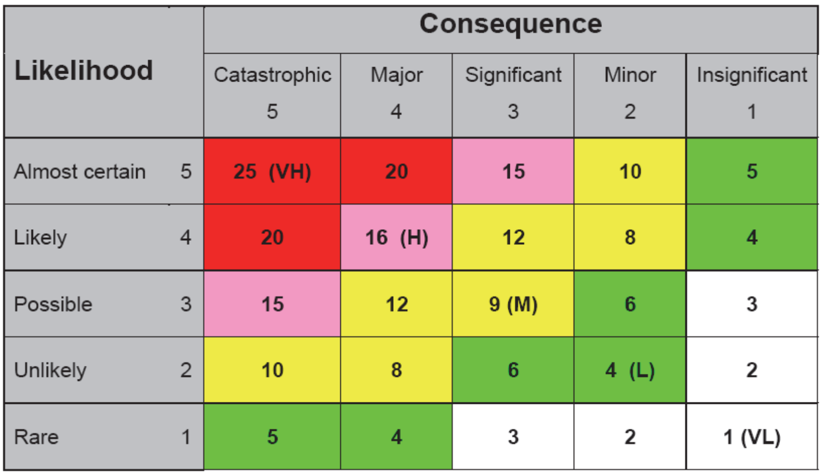


							Risk Ranking				Residual Risk		
Item	**Activity**	**HAZARD**	**Event**	**Cause**	**Consequences**	**Controls/ Mitigation**	Likelihood	Consequence	Risk Rating	**Further Treatment/ Controls/ Strategies**	Likelihood	Consequence	Risk Rating

Figure 1 A HAZID worksheet to help identify and then control project risks

2.3 Risk assessment

Risk assessment should evaluate both the likelihood of a specific hazard being realised and the reasonable potential consequence that would result. Risk should be assessed through the use of a Risk Matrix. An example of a standard 5 x 5 risk matrix is shown in Figure 2.



Likelihood	Consequence				
	Catastrophic 5	Major 4	Significant 3	Minor 2	Insignificant 1
Almost certain 5	25 (VH)	20	15	10	5
Likely 4	20	16 (H)	12	8	4
Possible 3	15	12	9 (M)	6	3
Unlikely 2	10	8	6	4 (L)	2
Rare 1	5	4	3	2	1 (VL)

Figure 2 A typical 5 x 5 risk assessment matrix

Different organisations may use different risk matrices; some may use a 6 x 6 matrix or reverse the numerical ranking so that a value of 1 represents a Very High rather than Very Low risk. The format of the risk matrix is less important than ensuring that when assessing the risks all parties are working from the same agreed matrix format. To assist with determining the likelihood and consequence levels definitions are provided for each value (Tables 2 and 3).

Table 2 Likelihood descriptors

Likelihood	Rating	Description
Almost certain	5	Incident will occur in every circumstance (e.g. every time).
Likely	4	Incident will probably occur (e.g. 1 in 10 times).
Possible	3	Incident may occur at sometime (e.g. 1 in 100 times).
Unlikely	2	Incident is not expected to occur, but is conceivable (e.g. 1 in 1,000 times).
Rare	1	Incident would only occur in exceptional circumstances (e.g. 1 in 10,000 times).

Table 3 Consequence descriptors

Consequence	Rating	Description
Catastrophic	5	Death, large scale, long term environmental impact with detrimental effect, very high financial loss.
Major	4	Extensive injuries, loss of production capacity, environmental impact with potential long-term impact, high financial loss.
Significant	3	Medical treatment required, short-term environmental impact requiring assistance to manage, moderate financial loss.
Minor	2	First aid treatment, environmental impact can be managed with existing procedures and equipment, limited financial loss.
Insignificant	1	No injuries, low financial loss, minimal environmental impact.

As with risk matrices, the descriptions for likelihood and consequence will be different for each organisation. For example, what may only be considered a low financial loss for a large mining company may represent a much higher consequence for a small consultancy.

2.3.1 Risk assessment tools

A variety of tools are available for assessing risk dependant on the activity and level of risk. Regardless of the tool used the process for assessing the risk must remain consistent throughout the project, i.e. risk ratings are always referred back to the same matrix and likelihood and consequence descriptors.

2.3.1.1 Health, safety and environmental plans (HSE)

A HSE plan is developed from the results of the HAZID Workshop. The HSE plan details the hazards and risk associated with a specific project and the control measures in place to mitigate these. A HSE plan is a working document that must be accessible at the work site and is subject to continual review and updating to reflect changes to the project which may impact on safety.

2.3.1.2 Safe work procedures (SWP)

Sometimes referred to as standard work procedures, an SWP is a supporting document that details the minimum acceptable controls to manage potential hazards present in a standard operation. SWP may be generic to a task, i.e. water sampling in a pit lake, and so will not address the hazards specific to different sites or the use of different equipment.

2.3.1.3 Risk assessment form

The risk assessment form is used when a single issue is being assessed (e.g. fatigue) or a new piece of equipment is being purchased. Multiple hazards relating to the issue or piece of equipment can be recorded on the form. For example, hazards associated with use, storage, transport and disposal of new equipment.

2.3.1.4 Job safety analysis (JSA)

Also known as a job hazard analysis, work method statement or job safety and environment analysis, a JSA is a tool to guide a person or small group through an exercise in hazard identification and control in relation to a specific task. A JSA is the process of breaking a task down into steps and identifying the hazards associated with each step. This allows for the task to be critically examined prior to commencement to identify the hazards of the job and to identify ways to eliminate or control the risks. A JSA can be developed for a standalone task or to manage risks associated with an onsite safety issue not identified in the HSE plan. A JSA must be signed as read and understood by the personnel involved in the task and usually have an expiry date after which they must be re-drafted. The expiry is to ensure that a JSA remains current and takes into account any changes relating to the task or site. As JSA are specific to the task and location they are the ideal supporting documents to the more generic SWP.

2.4 Control and mitigation

Once the hazards have been identified and the risks from those hazards ranked, it is time to consider the appropriate level of controls to mitigate the risks. The hierarchy of controls approach should be used when determining the most effective controls to be implemented (Figure 3 and Table 4).

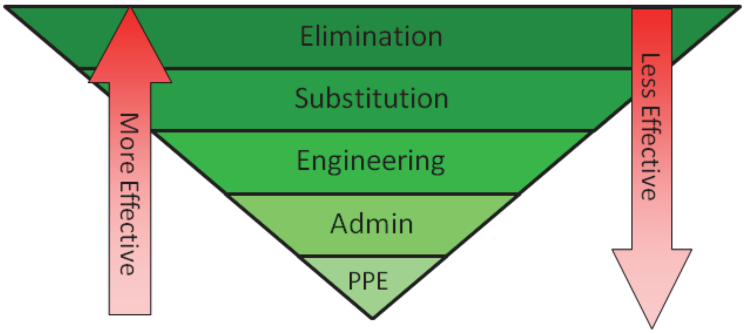


Figure 3 The hierarchy of controls for managing project risks

Table 4 Actions in order of priority to reduce risks

Action	Description
Elimination	Remove the hazard completely.
Substitution	Substitute the hazard with something less hazardous.
Engineering	Modify/guard the process to prevent people contacting the hazard.
Administrative	Implement processes, procedures, training, etc., to assist people in working with the hazard.
Personal Protective Equipment	Provide equipment and clothing to protect people should they contact the hazard.

Wherever possible a hazard should be eliminated. If that is not possible it should be controlled at its source through the use of an engineering control. Some hazards may require a combination of controls, i.e. engineering, administrative and PPE. The amount of time and resources put into controlling a hazard should reflect the risk which the hazard presents (Table 5).

Table 5 Guidance for implementing controls

Risk magnitude	Management requirement
Very Low Risk (VL)	No additional controls necessary. Continue to monitor risk.
Low Risk (L)	Consider additional controls to further reduce risk.
Moderate Risk (M)	Controls must be implemented to control risk.
High Risk (H)	Risk unacceptable. Do not proceed without additional controls. A minimum of engineering controls required.
Very High Risk (VH)	Risk unacceptable. Do not proceed without additional controls. A minimum of substitution or elimination controls is required.

3 Fieldwork safety

This section will briefly examine the hazards which are present in most operations undertaken in the field. Some of the hazards are applicable to sites in most parts of the world (vehicles, emergency response) while others may be more applicable to sites in Australia (snakes).

3.1 Fitness for duty

An employer's duty of care requires that reasonable steps be taken to provide a workplace free of hazards and to ensure that individuals are fit for work. Fit for work means that an individual is in a satisfactory physical, mental and emotional state to perform assigned tasks competently and in a manner which does not compromise or threaten the safety and health of themselves or others.

An individual may be unfit for work for a variety of reasons including the adverse effects of fatigue, stress, alcohol or other drugs and a range of physical and mental health issues. The consumption of alcohol or unauthorised drug intake should be strictly forbidden during work operations. Screening for alcohol and other drugs may be undertaken in accordance with the relevant Standards.

Personnel may also be required to undertake pre-mobilisation medical fitness tests and on-going medical surveillance during a project. Personnel returning to work following injury or illness may require additional medical examination at an approved medical centre to be confirmed as fit for duty.

3.2 Climate considerations

A combination of heat and humidity greatly increases the risk of heat-related illness. A combination of heat, humidity and wind speed allows a calculation of thermal comfort, sometimes called apparent temperature.

3.2.1 Hot and dry climates

Working in the heat can significantly increase of illness and also fatigue, which in turn can exacerbate a range of risks associated with the work. If the work does not involve significant movement, arrange for a portable shade structure to be erected to provide protection from the heat. Where possible, schedule physically demanding work in cooler parts of day and take regular breaks in a cool or shady area. This may be in the air-conditioned cab of the field vehicle.

Drink water regularly. You may need up to 8 L/person. Minimise intake of caffeine and soft drinks. Be aware of the heating effects of protective clothing such as coveralls, gloves and hard hats as these can reduce your body's ability to dissipate heat. Monitor for signs of heat stress and levels of fatigue. Consider protective gloves to handle equipment that retains heat from the environment (e.g. metal equipment).

Notify your project leader if you have a condition or are taking medication that affects your ability to work in the heat. Conditions that increase the risk of include: asthma, influenza, gastro, diabetes, pregnancy, heart conditions and epilepsy.

3.2.2 Hot and humid climates

There is an increased risk of heat-related illness when:

- the air temperature is between 31–35°C and the relative humidity is greater than 30%; or
- the air temperature is greater than 36°C and the relative humidity is greater than 25%; or
- the air temperature is greater than 37°C regardless of the humidity.

In these situations the following additional controls are required:

- Personnel working in the area should be acclimatised to the conditions.
- Rest breaks should be taken every hour as a minimum.
- An additional 4 L of water/person/day should be provided and personnel should drink 150 mL every 15 minutes during activity.
- Broad brimmed hats and loose fitting long sleeves and pants will protect from the sun's heat and UV exposure (Figure 4).

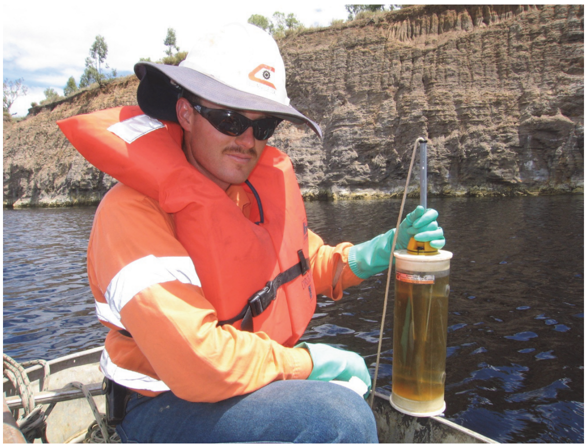


Figure 4 PPE can consist of a number of items: protection against impact, cuts and abrasions; protection from AMD waters; protection from the sun; and buoyancy aid in case of immersion in the lake (Photo courtesy of C.D. McCullough)

3.2.3 Cold climates

Working in wet and cold environments can make handling items more difficult due to a lack of blood flow to the fingers. The use of gloves can also impact on manual dexterity. Wind chill can also significantly affect the apparent temperature particularly in conditions of high humidity as water conducts heat away from the body 25 times faster than dry air. Control measures for cold climates include:

- wear jackets, hoods, beanies and other clothing as required
- take regular breaks in warm areas, such as the cab of the vehicle
- monitor for signs of cold stress
- eat regularly and stay hydrated.

A number of factors may increase your susceptibility to the effects of a cold environment, including:

- previous cold-related injury
- predisposing health conditions:
  - fatigue, poor physical condition, old age
  - poor nutrition
  - medication
  - alcohol and caffeine.

3.3 Vehicles

There may be a number of types of vehicles on an operational mine site including heavy machinery (trucks, excavators, drill rigs) and light vehicles (project related, public vehicles and recreational vehicles). All vehicles represent a significant risk to the operator as well as personnel working in the vicinity. Controls for vehicles may include completion of any mine site pre-mobilisation inspections and adherence to site specifications/standards. There may also be site requirements for restricted roads and safe distances from moving plant such as haul trucks. The requirements for vehicles operated on site may include the following items in addition to the standard safety equipment in a domestic vehicle:

- roll over protection structure (ROPS)
- revolving flashing beacon
- bull bar
- cargo barrier
- first aid kit capable of treating minor injuries
- fire extinguisher
- breakdown kit (torch, warning triangle/cone and reflective vests)
- reversing alarm
- uhf radio, or satellite phone in more remote areas
- whip aerial and flag
- engineered/rated recovery points.

Personnel who are required to operate vehicles on a project should be adequately trained and possess the necessary skills to ensure the safe operation of the equipment. This may include specialist training in the vehicle itself and/or the terrain over which the vehicle is to operate, i.e. four-wheel driving training and/or training for driving off-road.

Figure 5 **Where driving terrain is unknown or unpredictable, a walking leader can help find the best route forward trial (Photo courtesy of C.D. McCullough)**

3.4 Emergency response and communication

In the event of emergency, the work activities should be stopped and the area made safe. If it is not possible to make the area safe, personnel should move to designated muster points and follow emergency procedures. The muster points should be designated prior to the start of work and there should be two muster points nominated for each work area.

A vital component of emergency management is effective communications. In the event of a crisis some or all of the following groups may need to be addressed:

- mine site contact staff
- other project staff
- family members of employees
- contractors
- members of the public
- regulatory authorities, i.e. police or environmental agencies.

Project emergency communications are likely to be conducted through a two-way UHF radio system and a dedicated emergency channel and backup channel should be agreed. Back up methods of communication may include:

- mobile phones
- satellite phones
- text messaging
- email.

Emergency response actions should form part of the projects HSE plan and should address as a minimum:

Table 6 Emergency response planning

Emergency	Suggested Actions
Medical	• Identify local medical facilities and support services. • Identify evacuation routes and methods. • Ensure First Aid is available in project vehicles or as personal issue. • Ensure filed personnel are trained to Senior First Aid level.
Fire	• Identify local fire support services. • Identify alarm signals, evacuation routes and muster points. • Ensure portable fire extinguishers are in project vehicles or available on site near the work area. • Ensure field personnel are trained in basic fire fighting.
Adverse weather	• Identify weather monitoring sources and delegate responsibility to monitor. • Identify evacuation routes and muster points. • Ensure field staff are aware, as applicable, of actions to take in the event of: ○ lightning ○ heavy rain ○ flood/tsunami ○ cyclones/hurricanes ○ strong winds.

Consideration should be given to the provision of post-emergency event support for personnel involved in a serious traumatic incident – either directly or indirectly.

3.5 Flora and fauna

Hazards may exist from local flora and fauna. Bites from fauna can cause health issues beyond the initial wound, i.e. leptospirosis from infected animal urine or Lyme disease from tick bites. Other bites may require special first aid treatment, i.e. compression bandages for snake bite. Similarly the toxic effects from flora can range from irritable dermatitis to poising causing minor health effects such as vomiting, or even death.

3.6 Manual handling

Muscle/ligament strains and back injuries due to poor manual handling practices are common in most occupations. Most legislation regarding manual handling, the most common cause of strain and back injuries, has moved away from the traditional prescriptive approach of specifying maximum lifting weights, etc. Instead, legislation now favours a hazard evaluation process to determine whether the specific individual is capable of conducting particular manual tasks.

The following risk control measures are suggested as only a few of many methods to reduce muscle strains and back injuries from manual handling. Do not attempt to move heavy or awkward items such as boats alone. Notify your supervisor and have heavy items moved with the aid of others. Drive as close as safe to the lake before unloading boats and use engineering solutions whenever possible to avoid directly lifting a heavy object, e.g. light trailers retractable wheels on boats.

- Do not make sudden, awkward, reaching or twisting moves while bending down. Your upper bodies contain significant weight; people have ruptured discs while bending over to pick up a paper clip.

- When lifting, crouch down, hold the object close to your body and keep your back straight.
- Do not spread your feet beyond the width of your shoulders, and use your leg muscles as much as possible to lift. When setting an object down, reverse the lifting procedure. Keep your back straight and lower with your leg muscles. Do not shift your feet or twist your back when lifting or lowering.

Figure 6 Loading and unloading from transport vehicles and carrying boats across rough and broken terrain is probably one of the greatest manual handling risks workers around pit lakes face (Photo courtesy of C.D. McCullough)

3.7 Hazardous materials

The storage and use of hazardous materials and substances presents both a personal injury and an environmental risk. Hydrocarbons and chemicals must be transported, handled, stored and disposed of correctly and in accordance with the relevant legislation.

Controls for hazardous materials should include:

- Reviewing storage and handling facilities for engine fuel and potentially hazardous chemicals such as sample preservative acid and ethanol before travelling to site.
- Include the minimum requirements for the handling and storage of chemicals and hydrocarbons in the safety induction.
- Keep a copy of the material safety data sheets (MSDS) where the hazardous materials are to be used and/or stored such as in laboratories.

As a general rule the product proposed should be the least hazardous to effectively perform the task for which it is being used and the quantity brought to site should be the minimum necessary to complete the job. For example, transport of dilute acid for metal preservative or ethanol instead of formalin for biological specimens.

4 Working safely near pit lakes

4.1 Access/egress

Due to the nature of their formation from previous mining operations, pit lakes tend to have steep sides and access can present a significant hazard in itself. To increase the risk the edges of the pit may be formed from unstable, slippery, soft or crumbly material.

Obvious hazards to consider are slips, trips and falls whilst negotiating the slopes as well as movement of the slopes themselves, potentially leading to earth-slips or landslides. Even a minor earth-slip may dislodge rocks which could pose a risk to other personnel on the slope or working in the pit lake. Use of a rope or firmly anchored ladder may assist with access and egress.

Care should be taken to limit the impact on vegetation by using approved tracks and also by defining exclusion zones around sensitive vegetation. Sensitive vegetation includes riparian (waterway) vegetation, habitat for endangered species and cultural heritage areas. Some of these areas are under protection orders of the local Environmental Protection Agency.

Prior to entering a pit lake consideration should be given to how you would manage a medical evacuation from the pit if required. Unless you have visited the site previously it is unlikely that an effective strategy could have been developed at the project HSE plan stage. A JSA or risk assessment should be conducted on site to address the location specific hazards to evacuation that are present in the pit and surrounding site.

4.1.1 Public access

Some pit lakes may be accessible by the general public and/or other workers on the site. On sites where public access is possible consideration must be taken to ensure that the project's operations do not present a risk to other people. People are naturally curious and controls should be considered with this in mind. Controls may include signs warning of the hazards, physical barriers around the work area, closure of access roads, site security and/or controlled entry. Similarly any equipment which is to be left on site should be secured to prevent theft, vandalism or unauthorised use, i.e. children using the project's boat to play on the pit lake.

4.2 Working around water

4.2.1 Water quality

The water within pit lakes may present a number of hazards due to poor water quality or other contamination. Dangerous gases such as carbon dioxide and hydrogen sulphide may be concentrated in the catchment or may be released in the event of a partial or complete lake turnover. Released gases may be heavier than air and form a lethal layer of CO_2-rich, H_2S-rich or O_2-poor air just above the lake surface. Use of direct-reading gas monitors and/or personal monitoring badges should be considered for establishing and on-going monitoring of the air quality in the work area.

In addition to the standard PPE for field work (high-visibility long trousers and shirts, safety helmets, boots and glasses) consideration should be given to personal respirators, chemical resistant gloves/aprons and safety goggles and/or face masks.

Prolonged contact with contaminated pit lake water may cause skin disorders like dermatitis and highly acidic waters can cause accelerated corrosion of equipment including aluminium boats. Given the chronic and acute effects which can be caused by pit lake water quality consideration should be given to implementing regular health surveillance screening for personnel involved in the field work.

4.2.2 Working near water

By nature the area surrounding natural and man-made watercourses is likely to be slippery and presents numerous trip hazards. Water and algae or similar substances significantly increases the risk of slipping. While obstacles such as exposed tree roots, eroded gullies etc present an obvious trip hazard.

While working in pit lakes there is an ever-present risk of falling into the water. This can be reduced by considering the work being performed and establishing the most stable place to perform it from and minimising the time spent by the water side. Carry only equipment needed to complete each task. If bags or belts are used to carry equipment, these should be designed to allow for quick release.

Processes to retrieve a person from the water shall be considered prior to commencing work. This includes the use of a personal floatation device (PDF) should the depth of the water be more than 1 m at the work location. When assessing which type of PDF to use consideration should be given to inflatable styles which are less likely to interfere with the manual dexterity and range of movement required to conduct the work. Inflatable PDF can be purchased which either inflates manually or automatically on contact with water. When working in cold weather a fall into water could also expose personnel to cold stress and hypothermia. Spare dry clothes and a means to dry off should be carried in such weather.

4.2.3 Working on water

Sampling activities may require the use of small boats. When selecting the type of boat to use consider the task being undertaken, the weight of passengers and equipment and the location in which the work is to be performed. An aluminium boat will be lighter and easier to launch and recover than a fibreglass boat.

A flat-bottomed 'punt' type of boat will provide greater stability than a traditional 'V' shaped hull which is important as sampling activities are likely to require leaning over the side of the boat. Stability will be further aided by remaining seated, careful weight distribution and clear communication before changing position. Unexpected collapse of the pit sides into the lake can also create a wave large enough to swamp a small boat and personnel should wear a PDF at all times and be confident swimmers.

The use of a boat for a project is likely to come under the classification of commercial usage. An operator of a commercial vessel must be able to demonstrate they comply with the relevant State or Federal legislation. Commercial vessels within Australia and New Zealand will generally be classified according to the number of passengers they can legally carry and the location or area of operation (e.g. offshore, smooth water). It is important to ensure the vessel has the appropriate classification prior to engaging it. Other vessels such as kayaks and small dinghies are sometimes exempt from legislative requirements such as licensing. Some provinces and states require the operator of even a small recreational vessel to hold a current marine skipper's ticket. Compliance with the local legislation relating to working from a boat should be established prior to undertaking fieldwork.

Maritime safety legislation stipulates the minimum safety and emergency equipment to be readily available on all vessels. This equipment will differ depending on the classification of the vessel. If the boat does not come under the classification of a commercial vessel consideration should be given to carrying the following safety equipment as a minimum:

- personal flotation device for each person on the vessel
- bailing equipment
- oars or paddles in addition to primary power plant
- basic tool kit suitable for the primary power plant
- anchor
- spare bungs
- first aid kit
- fire extinguisher appropriate for the type of vessel.

A watertight container with signalling equipment (flares; smoke, hand-held and/or parachute) may be required for large and/or particularly remote lakes.

Figure 7 **Life jackets should be worn when working with pit lakes; including boating and working around steep lake margins (Photo courtesy of C.D. McCullough)**

4.3 Diving operations

Due to the inherently increased risk when working underwater, diving operations should be avoided whenever possible. Elimination of the need for diving may include using remotely operated submersible equipment such as corers for sediment sampling. Where visual evaluation is required consideration should be given to the use of submersible still or video cameras.

Where diving operations are required drivers must be appropriately qualified. In some states a commercial diver qualification may be required whereas in others a recreational driving ticket may be acceptable. The client may also have minimum standards for driver qualifications on their site. Diving operations should never be undertaken alone and divers should always dive as a pair with the support of an experienced surface team. Prior to diving commencing a dive plan must be prepared and approved. As a minimum the drive plan should cover the following:

- Roles and responsibilities of the dive and above surface support team.
- Communication methods and signals (driver to surface/diver to diver/public awareness).
- Information about the dive site (access/egress, expected weather conditions, type of dive – boat/shore/drift).
- Intended depth and duration of dive (including repetitive dives/required safety stops/decompression breaks).
- Type and inspection of diving equipment (surface supply/re-breather/open circuit regulator/oxygen versus exotic gas mix).
- Minimum level of air at surface, i.e. 50 psi left in tank.
- Intended work to be undertaken.
- Emergency procedures (alternative exit points/local emergency services/nearest decompression facility and means of transport to same).

Some project operations may require a decompression chamber on site which will increase diving operations logistical complexity and cost. However, all diving operations, even those conducted regularly in the same pit lake, are different and should always be considered and managed as a high risk activity.

Figure 8 The risk of diving operations in pit lakes (left) may be able to be removed completely through the use of remote technologies such as 'bomb' sediment core samplers (right) (Photo courtesy of C.D. McCullough)

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