Addressing the Dilemmas of Long-Term Mining Impacts Using a Framework of Sustainability and Adaptive Management

H Kempton

ABSTRACT

Many operating hard-rock sulfide mines are predicted to require perpetual post-closure management to prevent environmental degradation. Causes include evaporative concentration of metals and other solutes in pit lakes, and acid rock drainage from sulfide waste-rock, tailings, and pit benches. Dilemmas posed by the prospect of perpetual management include:

1. Uncertainty in predictive models typically prevents reliable bounding on forecasts for the timing or magnitude of environmental impacts;
2. Comprehensive closure designs that can meet environmental standards may not be economically possible, particularly when applied retroactively to mines permitted under less stringent closure requirements;
3. The publication of site-specific environmental analyses in peer-reviewed journals is discouraged in the current regulatory environment, hindering scientific advancement; and
4. The durability of financial and government institutions cannot be assured for the long-time horizons over which mine impacts are predicted to occur.

Re-evaluating mine closure in a framework of sustainable development (as proposed by the Mining Mineral Sustainable Development forum), can resolve, in part, these dilemmas. Key sustainability goals include: assurance of the social and economic well-being of the local community; assurance of the long-term environmental integrity of the region; and establishment of institutions capable of addressing (and learning from) long-term environmental management. Under a sustainability framework, impractical plans for immediate attainment of perpetually-stable closure may be replaced with a fund for long-term management of environmental impacts (eg through contaminant migration controls and exposure barriers), and a set-aside long-term growth reserve intended to eventually fund more complete closure. Fund expenditures would follow Adaptive Management—a template for environmental-management institutions in which knowledge accumulated and uncertainty acknowledged explicitly. Under adaptive management, trusts would be flexible entities, supporting which knowledge accumulated and uncertainty acknowledged explicitly. Under adaptive management, trusts would be flexible entities, supporting accumulation of institutional competence.

INTRODUCTION

CAUSES AND EXAMPLES OF LONG-TERM MINING IMPACTS

Predictive modelling and practical experience indicate that many hardrock mines have the potential to cause long-term environmental impacts after closure (Kempton, 2000), specific impacts may include: health risk to wildlife or humans, degradation of groundwater quality, and loss of water resources. In mine pit lakes, initial water quality can be very poor if the pit walls contain net-acid-generating sulfide rock. Further, in semi-arid climates, the water quality of even neutral-pH pit lakes may eventually exceed risk-based thresholds due to evaporative concentration of groundwater. Waste rock and tailings facilities containing acid-generating materials can be similarly problematic—no management strategy short of subaqueous disposal has been shown to permanently prevent the formation of acidic water in such facilities. Examples of predicted long-term impacts abound: a waste-rock model predicted acid drainage impacts on groundwater for 9000 years at a Montana, USA mine (BLM, 1998); pit-lake models extrapolated to beyond 200 years in the future have predicted that evaporative concentration of trace metals to above drinking water standards at several Nevada, USA mines (eg BLM, 1999; Kempton et al, 1997); and empirical extrapolations suggests that seeps from the underground workings at the Iron Mountain mine in California, USA could produce acidic water for over 2000 years (Nordstrom and Alpers, 1995). The result is that many mines will require either perpetual management after closure to meet water-quality standards, alternative closure strategies to prevent such impacts, or variances to regulatory water-quality targets. In any event, mine operators, state and federal regulators, and the public are generally ill-equipped to address the implications of permanent environmental stewardship.

Regulators and policy guidance analysts are beginning to recognise the need to plan for long-term environmental impacts. The updated US EPA Guidance for estimating feasibility studies costs notes that ‘the blanket use of a 30-year period of analysis is not recommended,’ and requires instead ‘site-specific justification … for the period of analysis selected, especially when the project duration … exceeds the selected period of analysis’ (US EPA, 2000). Specific to mining, a 1999 National Academy of Sciences report recommends more comprehensive disclosure of environmental impacts and more complete financial assurance for reclamation and ‘long-term post-closure management of mine sites’ (NAS, 1999). The NAS report goes on to identify as ‘key’ the need for ‘research and development’ into environmental impacts of hardrock mining (to address) long-term water quality and water quantity, which affect riparian, aquatic biological, groundwater, and surface water resources’ (NAS, 1999).

The financial liability for long-term management of mine facilities can be a significant. While simple neutralisation of a 120 million m³ pit lake (100 000 acre-feet) could potentially be accomplished for a few million US$, more complete remediation (eg treatment to remove solutes such as antimony, arsenic, selenium, or sulfate) could cost US$ 30 million or more. (For comparison, backfilling such a pit would cost on the order of US$ 150 million.) Further, the costs for long-term management are strongly influenced by the level of treatment required. Pit-lake water quality targets based on protection of wildlife are relatively flexible, allowing compliance by altering water quality or habitat. However, the US states of New Mexico and Utah require pit lake water to meet groundwater standards (ie not exceeding human consumption standards or local background), meaning potentially higher costs if sulfate must be reduced to the 500 mg/L drinking water standard. Long-term mitigation of impacts associated with acid rock drainage from with other mine facilities (eg such as of removal of metal and sulfate from groundwater receiving rock leachate from waste rock or tailings) can be similarly expensive—on the order of US$ 20 - 40 million for perpetual treatment of a 5000 m³/day flow.

1. Integral Consulting, Inc, 1320 Pearl Street, Suite 210, Boulder CO 80302, USA.
Many potential impacts are delayed in time, lowering the present liability for future expenditures. The problem with any such cost speculation, however, is that current environmental models almost certainly do not bracket the actual uncertainty in the timing or magnitude of environmental impacts associated with mine facilities such as pit lakes, waste rock, and tailings. What is probable, particularly where large volumes of acid-generating rock are excavated, is that some type of long-term impact(s) will exist. Acid-generating mine-waste facilities and evaporating pit lakes thus represent perpetual management burdens to the future trustees of the land. The challenge addressed in this paper is developing a strategy for closure and long-term management of mine facilities that is economically viable, sustainable in terms of the environment and local people, and advances the understanding of environmental science.

**DILEMMAS POSED BY LONG-TERM MINE MANAGEMENT**

Considered collectively, the multiple constraints on mine closure—environmental regulations, prediction uncertainty, limited economic resources, and the effectiveness and implementability of remediation—pose a series of impractical requirements. These requirements are expressed here as four dilemmas.

**Dilemma 1 – Irresolvable uncertainty**

Permitting a mine generally requires disclosure of potential impacts and financial surety for environmental protection. The US National Environmental Policy Act is unambiguous on disclosure requirement, stipulating that environmental impact statements address both ‘direct effects’ on the environment and ‘indirect effects’ that are ‘later in time… but still reasonably foreseeable.’ Further, US State regulations target the protection of drinking water resources and wildlife (eg the administrative code of Nevada requires that mine lakes not have ‘the potential to degrade the ground waters of the state’, and that lakes must not have ‘the potential to affect adversely the health of human, terrestrial or avian life.’) Attempts to comply with such regulations have led to increasingly sophisticated forecasts of future water quality in mine pit-lakes and groundwater resources impacted by mine drainage.

The problem of relying on any prediction of future impact or financial liability from a mine facility is the fundamental tendency to underestimate uncertainty. Policy analysts have found that a ‘consistent tendency to underestimate the systematic error… [was] almost universal in all measurements of physical quantities that have been looked at’ (Morgan and Henrion, 1990). Their explanation is that ‘it is much easier to underestimate the existence or effect of little-known sources of error than to overestimate them.’ This tendency to underestimate uncertainty is almost certainly more pronounced in environmental models of natural systems, where the high degree of complexity necessitates subjective decisions about uncertainty. A 1999 model of the Cove Mine pit lake (Nevada, USA) predicted a sulfate concentration of 120 - 260 mg/L, yet the actual concentration in year 2002 was 1240 mg/L, indicating that wall-rock oxidation was underestimated by a factor of five to ten (Miller, 2002). Beyond the scientific complications is often a distrust of results produced with funding from financial stakeholders (Moran, 2000). Given the full breadth of parameter uncertainty, from global climate change to revised regulatory targets, developing confidently-bound estimates of the future liability associated with mining facilities may not be possible.

**Dilemma 2 – Financial impracticability of environmental restoration**

Regulations require that mining operations not degrade water resources, yet in the case of many existing mining operations, it may not be economically viable to prevent any degradation—particularly in cases where regulations are applied retroactively to operating mines designed and permitted under less stringent requirements. Increasing bond costs are further aggravating concerns over closure funding. The cost of mine closure bonds has increased two- to five-fold in the past few years due to increased concern over operator viability; and though operators can typically implement closure plans for approximately half as much as government agencies, public land managers, fearful of acquiring failed mines, are requiring bonds to cover full third party closure.

**Dilemma 3 – The liability of disclosure**

Although scientific publications support virtually all predictive modelling, operators are often reluctant to allow publications in peer-reviewed journals that cite studies at specific mines, regardless of findings. With scheduling a critical component in the feasibility of most mining projects, the liability of publication and associated broad review can outweigh the general benefits of advancing the science. While understandable from a business perspective, the effect is that those analyses most critical to the economic implications of environmental impacts are often subject to the least critical review, and scientific advances in the field are hindered.

**Dilemma 4 – Atrophy of vigilance**

Perhaps most intractable, this dilemma, identified in nuclear waste disposal debates (National Research Council, 2000), arises from the potential need for some form of environmental management over millennia (eg BLM, 1998; Kempton, 2000; Nordstrom and Alpers, 1995). A National Research Council report on stewardship of nuclear waste sites addresses this dilemma directly, noting that there is ‘no scientific basis from which to project the durability of government institutions over the period of interest, which exceeds that of all recorded human history’ (NAS, 2000).

Effective mine closures will require an honest accounting of the compromises intrinsic to these dilemmas. Barring significant technological advancement or regulatory revision, many mine closures will require long-term (ie essentially perpetual) environmental management. Inherent in this is accepting the passage of environmental liabilities to future generations through uncertainty in scientific predictions, future costs and institutional continuity.

**A PATH FORWARD FOR MINE CLOSURE – SUSTAINABILITY AND ADAPTIVE MANAGEMENT**

Presented here is a practical framework for addressing long-term management of closed mines based on two paradigms in environmental management:

- **sustainable development** – defined most generally as ‘meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs,’ this concept is used here as formulated specifically for the mining industry by the Mining Minerals and Sustainable Development forum (MMSD, 2002); and
- **adaptive management** – a concept developed by the International Institute of Applied Systems Analysis for manage ecosystems amidst evolving science and policy (Hollings, 1978).
The sustainable development concept provides a basis for valuing human and natural resources, with an eye towards respecting future generations. Adaptive management then provides a template (and considerable practical experience) for establishing institutions with some hope of providing perpetual management.

A starting point for framing mine closure are the ‘Seven Questions to Sustainability,’ developed by the Mining Minerals and Development group ‘to be posed in assessing a miner/mineral project’s or operation’s contribution to sustainability’ (IISD, 2002):

1. **Engagement** – Does the process ‘ensure all affected communities of interest … participate in the decisions that influence their own future’?

2. **People** – ‘Will people’s well-being be maintained or improved’ during and after closure?

3. **Environment** – ‘Is the integrity of the environment [people and other life forms] assured over the long-term’?

4. **Economy** – ‘Is the economic viability of the project assured, and will the economy of the community and beyond be better off as a result?’

5. **Traditional and non-market activities** – ‘Will the mine ‘contribute to the long-term viability of traditional and non-market activities in the implicated community and region’?’

6. **Institutional arrangements and governance** – ‘Are the institutional arrangements and systems of governance in place to ensure an ability to address operation consequences that will evolve through the full post-closure period?’

7. **Synthesis and continuous learning** – Is a system in place that actively incorporates knowledge gained from management into periodic re-evaluation of all alternatives, assuring a positive, long-term contribution to people and the ecosystem?

As a means of framing a discussion of mine closure, these 7 questions are considered here in terms of a hypothetical acid-generating waste-rock facility predicted to release acidic leachate to groundwater for the foreseeable future (eg few hundred to a few thousand years).

The first question, **engagement,** is a procedural component that is required of all projects to understand the values, and thus goals, of all stakeholders. The second question, the **people’s well-being,** is a measure of the long-term economic and social viability of their community. A healthy environment and opportunity for employment are cornerstones of this assurance, and, as such, sustainable development goals may diverge from environmental regulations. While rapid and complete closure, say by backfilling waste rock to a pit in a short-term effort, could perpetually prevent/reduce acid drainage release, capital flow to the local community under this option would cease abruptly, and future access to remaining ore inhibited, limiting the potential for future mining. Slower expenditures of closure funds may better meet the communities well-being. Although a closure plan that is ideal in a sustainability framework may differ from a closure plan oriented toward attainment of state environmental regulations, closure under a sustainability plan can still ensure the integrity of the environment (question three). Strict regulatory compliance typically means maintaining groundwater at drinking water standards—in this hypothetical example, this may mean amending waste rock to neutralise acid, then backfilling it into pit. Under a sustainable development strategy, a trust fund providing for perpetual groundwater treatment and limits on human and wildlife exposure, would offer a similar level of environmental protection, while allowing future access to pit ore and providing long-term (albeit low level) employment.

The response to question four, the future **economy** of the community, may also depend on the timeframe of the closure activities. Rapid closure often requires bringing in outside contractors to implement the bulk of the work over the short-term. As a result, local residents may prefer a slower, more locally-focused closure plan that better sustains the local economy with a level inflow of capital over the long-term. Perhaps more important, this provides a practical solution to both the shortage of closure funds and the atrophy of vigilance dilemma: given the time value of money, slower closure may ultimately allow trust funds to grow enough to eventually pay for more complete restoration for a fixed initial investment, avoiding true perpetual management. This same argument applies also to the **traditional and non-market activities question:** long-term closure implementation dampens the fluctuations in the amount of capital flowing to a mining community, which in some cases may better sustain the community.

The root of many mine-closures dilemmas is this: passive mine closure may not be economically possible, so how best to provide post-closure management? This is addressed by the concepts posed in the last two sustainability questions—**institutional arrangements** that can meet needs as they evolve through the closure process, and **synthesis and continuous learning** to ensure that site management improves with time through intelligent assimilation of knowledge. These concepts—establishment of institutions to acquire knowledge to better manage resources—are the cornerstones of **adaptive management.** In the hypothetical waste-rock facility used here, the mine operator may note that they don’t have the funds for complete passive closure, and/or residents may note that rapid closure is not the best use of available closure funding in terms of sustaining a viable community. Adaptive management is then a practical framework for designing a long-term management plan that will remain effective into the future.

Most broadly, adaptive management treats environmental disturbances as science experiments. Rather than expecting behaviour to match predictions, adaptive management is designed to ‘test clearly formulated hypothesis about the behaviour of an ecosystem being changed by human use,’ anticipate ‘learning over decade-long time scales,’ and respond as necessary with policy changes (Lee, 1993). Importantly, adaptive management has been applied to much more complex problems, such as rehabilitation of salmon runs on the Columbia River ecosystem, and lessons from this are meticulously documented (Lee, 1993). With judicious structuring of an adaptive management program, there is enormous potential to provide environmental protection and advance the science of mine closure.

The flexibility of adaptive management programs reduces significantly the pressure on operators and trustees for accurate predictions. If predictions fail, adaptive management ‘still permits learning, so that future decisions can proceed from a better base of understanding.’ (Lee, 1993). A USGS study of bank-sediments management in the Colorado River recently demonstrated that the tributary sand is exported too rapidly to be of much use in restoring banks during man-made floods, directly contradicting the environmental impact statement hypothesis (Rubin et al, 2002). While such model inaccuracies could, in a rigid framework, be viewed as failures (or worse, grounds for litigation), this discrepancy caused little concern under the Glen Canyon Adaptive Management Program, which was ‘established precisely to help incorporate such scientific advances into management decision making.’ While the potential exists to abuse such flexibility, the admission of this uncertainty is a more honest assessment; and if data are collected properly, uncertainty will be reduced in the future.
Establish trust funds for management of each mine

This trust would initially fund data collection and other research to improve predictive models, and then eventually fund remedial activities as warranted. Such a utilisation of capital generated from the mine for ongoing development meets the criteria of sustainable development. The BLM's current draft of the new 3809 regulations (currently on hold) does in fact contain an option to ‘establish a trust fund’ for long-term treatment (BLM, 1999), and a recent Nevada BLM memo on guidance for mine closure requires field managers to ‘understand and consider all the technical issues [including] long-term implications of closure’ (BLM, 2000). Key challenges here will be selecting an initial trust-fund value, which will be sensitive to both prediction uncertainty and the discount rate used to estimate the time-rate of capital accrual.

Consider sharing liability across trust funds

Assuming that uncertainty in model predictions is random, the under and over predictions of management costs should balance at some scale, and pooling of trust funds in an insurance model should provide better overall environmental protection.

Identify a central repository for technical reports

This need springs in part from the ‘liability of disclosure’ dilemma. A wealth of potentially useful environmental analyses of hard-rock mining exists, but is dispersed in consulting reports and essentially unobtainable. A university library is a logical repository for holding relevant mining studies.

Develop a technical management group to assimilate information on prediction and remediation

Incorporating future innovations into prediction and remediation of mine facilities will require a technically-proficient management team that includes representatives from academia, federal and state land management agencies, and the mining and environmental consulting industries. An immediate need exists to refine key model parameters—techniques to predict sulfide oxidation rates in pit walls and waste materials, metal releases following oxidation, net infiltration through waste-rock, and silicate neutralisation reactions are a few of the most critical. An assessment of remedial alternatives could proceed in parallel, ultimately leading to more accurate estimates for liability for perpetual management, monitoring, and if necessary, remediation of mine facilities.

Openly debate closure trade-offs

This starts with the admission that full closure with an assurance of perpetual non-degradation of water resources is technically impractical and/or financially impossible at many large hard-rock mines. Options include lowering environmental standards in select mining areas, analogous to ‘exclusion zones’ granted now in limited cases, or US ‘brown-fields’ laws that allow more lax risk-based cleanup standards for industrial areas. Spreading out closure funds expenditures over longer times may produce a relative increase in environmental degradation in the short-term; but if this also provides greater future capital for closure, such a strategy may in fact provide for a greater level of remediation over the long-term. Finally, in debates over pit backfilling, the potential future economic value of access to residual mineral resources (eg when future mining when metal prices are higher) must be considered.

Perpetual management of mines is an unavoidable component of future land management. Mine closure undertaken in a sustainable development and research-focused adaptive management framework, however, has the potential to improve the knowledge base of environmental science and avoid the need for perpetual management, yet stay within the limited capital available for closure at many large mines.

REFERENCES


