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Passive mine water treatment: the correct approach?[☆]

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Abstract

Passive waste water treatment technologies based on ecological principles for organic pollutants are gaining gradual acceptance in many industrial sectors in the western world. They represent a revival of the ancient stewardship of natural resources in response to the need for sustainable development. This revival has also lead to the use of wetlands for mine waste water with inorganic pollutants. Constructed wetlands for metal-laden acid mine drainage (AMD), the major environmental issue in mining, are only part of the solution, as the metals in the waste water need to be mineralized in sediments. The principles of ecological engineering need to be embraced if sustainable solutions are to be found. Neither the scientific community working in mine-site restoration nor the mineral sector itself has fully integrated ecological engineering principles into restoration efforts. The many delaying factors are explored in this paper.

A precise understanding of the underlying microbial dynamics of AMD generation is a prerequisite to any successful remediation strategy. The effectiveness of sediments in the open water sections of wetlands which bio-mineralize nutrients and organics, reduce metal acidity and increase pH has been widely demonstrated but the message doesn't seem to be getting out. In addition to gaining an understanding of the underlying processes, effective treatment systems need to be designed, constructed and monitored over a sufficient time period to assess the sustainability of the approach. A few mine waste management areas have been developed where ecological engineering principles are utilized and demonstrate that through supporting biogeochemical cycles, nature's repair mechanisms are at work.

Keywords: Passive mine water treatment; Ecology; Ecological engineering; Biofilms; Mineral weathering inhibition; Mine decommissioning

1. Introduction

In 1953, Eugene Odum published *The Fundamentals of Ecology*, which defined the new science of ecology. Eugene and his brother Howard, both of whom died in 2002, taught us that systems are unified by the energy that flows through them and can be understood only by studying them in their entirety (Mitsch, 2003). *The Limits to Growth,* by Dennis Meadows et al. (1972), and *Our Common Future,* by the BC, 1987, taught us about sustainability and in 1989, Mitsch and Jørgensen, carried those ideas further in *Ecological Engineering: An Introduction to Ecotechnology*. The roots

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of ecological engineering may go back all the way to the ancient Chinese view of the earth (yin) and heaven (yang) as a system composed of and defined by a series of ecological techniques that facilitate a synchronized development of economic benefits and ecological, environmental, and social advantages.

Ecological engineering is a scientific discipline aimed at applying knowledge of natural biological systems to achieve human (industrial) objectives in a natural self-sustaining way. It encompasses such diverse activities as the re-vitalization of rain forests, the construction and population of artificial marine reefs, the rejuvenation of depleted farming soils, the reversal of desertification, and the re-establishment of wetlands in previously drained riverbeds. A typical ecologically engineered project would be the restoration of wetlands to control eutrophication or degrade persistent organic pollutants.

Mining activities disturb the land, surface waters, and ground water. The mining industry has made progress in growing vegetation on tailings deposits with a considerable investment in fertilizer and limestone, mostly to control dust, and it is beginning to learn that hardy, indigenous species can do a similar job. With this, the acceptance of restoration ecology, remediation, and conservation efforts grows. But the industry has never embraced the principles of ecological engineering or applied them to the major problem posed by mining wastes, that is, to the amelioration or prevention of acid mine drainage.

Slow progress is also apparent in a recent issue of the journal *Ecological Engineering* containing papers presented at a 1999 symposium—"Ecology of Post Mining Landscapes", in Cottbus, Germany (Hüttl and Bradshaw, 2001). The editors concluded in their introduction that a narrow engineering approach to restoration is not enough. Yet, only a single paper in the special issue dealt with the treatment of pyrite or pyritic wastes. It presents water management formulas to determine the rate at which fresh water must be provided and acidified groundwater removed from flooded coal pits to keep the overall acidity within acceptable levels. The old mantra—the solution to pollution is dilution, has been soundly discredited in the rest of the world but apparently not in the management of mining waste water. Surely, there has to be a better way.

In the past 50 years, we have finally recognized the size of the footprint we have left on the planet. But the gap between technological implementation and scientific understanding has only widened. We are building a municipal waste treatment plant in Singapore that will contain 90 km of deep tunnels, 170 km of linking sewers, two centralized waste treatment plants, and a 6-km outfall pipe into the Straits of Singapore (Sutter, 2004). But the further study of bacteria that will drive that system is largely ignored. Similarly, the mining industry is building ever bigger and more energy-intensive treatment plants, and it too has largely ignored the alternatives offered by bacteria. The objective of this paper is to examine the reasons for this.

2. Environmental management in mining

Environmental issues associated with mining have been known since Agricola, who stated in 1556 that "...when the ores are washed, the water used poisons the brooks and streams, and either destroys the fish or drives them away...it is clear to all that there is a greater detriment from mining than the values of the metals which are produced" (Agricola, 1556). Since then, metal values have become even more integral to society while larger rock volumes are mined and moved. As in other industries, the mining sector has largely ignored the economic consequences of clean air, water, and soil. Consequently, the scale of mining increases exponentially, as do its detrimental effects.

Typically, the mining industry seeks engineered solutions to its environmental problems. It looks for ways to confine wastes, retain the run-off, and isolate the waste from oxygen and water; no easy task given the million of tonnes of waste generated by even a small mine. The logic is that if less water gets to the surface of minerals, less oxidation occurs, less AMD is generated, fewer or smaller treatment plants are required, and less disposal space is needed for the contaminated sludge that such plants generate. It is assumed such plants will operate for 100–1,000 years, in the case of uranium mines (Wittrop, 2002), or 10–15 years for base metal mines; for the purposes of shareholders this means "in perpetuity," a concept that no one in the mining industry seems to think is unreasonable.

Meanwhile, scientists have begun to better understand the role of bacteria in the process of oxidation, the timetable by which mineral surfaces weather, the limitations imposed on contaminant generation by the transport of oxygen by advection, convection, or diffusion, and the movement of weathering products in surface run-off and groundwater (Barker et al., 1997). Like the workings of a fantastically complex watch, each of these interlocking cycles rotates at a speed of its own, turning in seconds, decades, or centuries. It follows that any effort to interrupt those cycles must work on the same time scale. And what is more important, remediation efforts must be given appropriate time spans in which to prove themselves.

Typically, when the mining industry wants a solution, it wants it yesterday. So, for the past many decades it has lurched from one quick fix to the next. Mine managers used to dump mine wastes into any available water body, mostly on the theory that what was out of sight was out of mind. Then regulators decreed that acid-generating wastes must be kept out of the water. Now we are back to subaqueous storage. Similarly, elements of the industry have embraced passive water treatment systems as a panacea and have struggled to incorporate them into conventionally engineered systems.

Wieder and Lang (1984) were among the first to notice that acid mine drainage flowing through a bog was much improved. Soon, more than 100 constructed wetlands were being planned or built (Brodie and Wildeman, 1993). Microbial sulphate reduction was identified and acclaimed. The following years produced a flood of conferences on constructed wetlands (e.g., Hammer, 1989; Cooper and Findlater, 1990). More recently, Willscher (2001), to quote a European review, has compiled a list of reduction procedures used to reduce acid generation, including the exclusion of water and air, inhibition of microbial oxidation, and the promotion of sulphate reducing bacteria, to mention the most common practices worldwide. Brown et al. (2002) produced a comprehensive compendium on mine water treatment, including passive approaches. The literature on these topics is vast. Willscher (2003) elegantly summarized at least seven different ways to utilize limestone in combination with wetlands. She concluded that passive and semi-passive treatment methods need to be improved and that we should adopt an interdisciplinary approach. In the same year, a similarly eloquent review of the natural alkalinity generating processes for extremely acidic mining lakes was compiled by Totsche and Steinberg (2003), who concluded, sadly, that there simply is no economic, practical way that those lakes can be saved.

In spite of the extensive resources expended by government, industry, and academe, the short time horizon available for research, development and implementation is leading us to false conclusions. The best available, economically-achievable technologies are changing too fast and the not unexpected failures could have been avoided by bridging the gulf between scientific knowledge and its application. Ecological engineering has been left off the technology treatment train. This is especially unfortunate because, after two decades of research and field-testing, it is just now beginning to prove itself (Fyson et al., 1998; Kalin, 1997; Kalin et al., 1999; Kalin, 2001a, 2001b; Kalin et al., 2001c, 2003; Kalin and Caetano Chaves, 2003). This author contends that we are still not addressing the origins of the problem, that is, reaction rates and the contaminant generating processes. Treatment approaches must be assessed for their effectiveness on appropriate time scales if we are to find truly sustainable solutions. There is no doubt that passive treatment systems and/or constructed wetlands effectively reduce organic water pollution. But when the run-off from mining wastes flow through wetlands, the deposition of metals onto adsorption sites can overload them, leading to system failure and wetland destruction (Kalin et al., 1995).

In a narrow sense, constructed aerobic and anaerobic cells as well as reactive walls, which establish ecological communities and for some limited time achieve specific objectives, can be considered ecological engineering. Those techniques have certainly advanced our understanding of the potential of natural systems. But they are not self-sustaining. Given their limited, functional life span, they are not true applications of ecological engineering.

To ensure that a wetland treatment system is self-sustaining and longlasting, it must be protected from the metals and/or inorganic pollutants in mine waste run-off. This can be done in two natural treatment steps. First, the metals must be adsorbed onto particulates, either inorganic (e.g., clays) or organic (e.g., humic substances, living cells), forming organic metal complexes or colloids. This particulate matter then settles to the sediment where microbial mediated biomineralization takes place, supported by organic matter input. In the deeper portions of the sediments, the organically bound metals are mineralized into stable compounds. This approach can retain the metals within the mine management area but does not solve the problem of contaminant generation.

2.1. Knowledge increases complexity

Bacterial activity on minerals, which was recognized with the role of *Thiobacillus ferrooxidans* in copper bioleaching, has since been described for many minerals. The chemistry of weathering is better understood and so are the reactions of weathering products in water. Geomicrobiology and biogeochemistry have begun to study acid mine drainage on the micro-scale, looking at the corrosion pits on pyritic surfaces where it originates and the biofilms that prevent it. New concepts of dissolved and particulate matter have been defined and surface science has been advanced with newer microscopic techniques to advance our understanding. Academics have been thrilled to discover that bacteria are everywhere.

As the problem has become more multidisciplinary and more complex, however, a practicable solution is retreating over the horizon. Engineering solutions tend to break down problems into their component parts, so that each facet can be solved in isolation. Bacteria do not lend themselves well to such treatment and the industry has been slow to embrace them. Moreover, the inevitable conclusion of scientists to any investigation that more study is needed—is not warmly received by the mining industry or the engineering fraternity. It is therefore, useful to quote Prigogine (Tiezzi, 2003): "I believe the days of the scientist in his ivory tower and of flights into pure reason are over. Today is a time of complete reimmersion in life, nature..." And this quote only reminds us of what Pasteur proclaimed in 1871 (Karavaiko and Groudev, 1985): "No, a thousand times no, there is no category of science which could be named 'applied science'. There are science and application of science related to it as the fruit to the fruit-bearing trees." Ponder these statements, as they reflect a 25-year struggle to establish ecological engineering for the management of mine wastes.

2.2. Mineral surfaces: the site of the problem and the solution

The oxidation of sulphide particles in tailings, waste-rock piles, underground workings of mines, and open-pit walls is limited by the transport of oxygen that in turn is determined by convection, advection, or diffusion to the mineral surface where bacterial biofilms display various degrees of activity. Microbes are quick to respond to changes in the environment, and nothing changes the environment more than mining followed by changes due to "restoration." Microorganisms populate the near earth surface, where mining takes place, at a rate greater than 10^8 cells per gram of soil or sediment. Densities are lower on rock surfaces but even there, one cell is present per μm^2 of mineral surface or $10^6/mm^2$ (Nordstrom and Southam, 1997). Given those numbers, it is no surprise that microbes accelerate the oxidation rates of pyrite change by orders of magnitude. Such densities speak to the importance of biofilms in the contaminant generation process; hence, they should be realized as part of the solution: the arresting of the process. Microbial communities do not die. They merely become inactive when they deplete the available food source. Mining wastes should not be viewed as de facto toxic to microbes, but conditions should be created that keep them inactive, by physical and biological interference on the mineral surface, which will reduce their access to the mineral. Since, microbes are dependent on the oxygen transported to the mineral surface, coatings of biofilms with organic and or inorganic metal precipitates in the corrosion pit can lead to inactivity and dormancy.

It is here, at the mineral surface, where metals deteriorate and acid is generated, that the solution has to be found. Corrosion of metals is a surface deterioration phenomenon, very similar to that which takes place on the mineral surfaces in mining wastes. The formation of rust is inhibited with phosphate. We know that phosphate is nature's control on iron availability in the environment. So why, then, have we not applied phosphate as a likely inhibitor of mineral weathering?

Phosphate dispersed by the same rainwater that stimulates the production of acidity will produce a precipitate on mine wastes that physically obstructs both oxygen transport and bacterial activity. Phosphate minerals placed on tailings or waste rock so that it can be weathered by rainwater have produced promising results in field and laboratory experiments (Fyson et al., 1995; Kalin et al., 1997, 1998, 2003). Work is in progress to define the microbial and mineralogical composition and stability of the precipitate layer formed on the mineral surface (Ueshima et al., 2002, 2004).

3. Conclusion

It has been said before; it merits saying again: the solution to acid mine drainage will be found only when geomicrobiology has been fully integrated into waste treatment strategies Active/chemical treatment simply does not offer an economically or environmentally acceptable solution. A substantial expansion of the field of ecological engineering is expected in the next quarter of the century. It will be the accepted and critical driver in the improvement of terrestrial and marine environments. Mature ecological engineering projects will demonstrate the power of this new field.

Wetlands, or passive treatments systems used appropriately will become an essential component of ecological restoration because of their sediment generating capacity, rather than their treatment capacity, i.e., biomineralization. They generate TSS for metal binding in open ponds within the wetland and they provide the carbon source for the microbial ecology of the sediments to support biomineralization. More work need to be done, of course, with an emphasis on in-situ treatment and biological polishing. But we now know that ecosystems and their resources can be managed or modified to control biogeochemical cycles and so immobilize contaminants. All stakeholders need to take a fresh look at an old problem. Nature's repair mechanisms may be slow but they're thorough. We must find ways to assist and expedite them.

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