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TECHNICAL COMMUNICATION

# Towards Regulatory Criteria for Discharging Iron-rich Mine Water into the Sea

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**Abstract** Appropriate criteria are needed for regulating the discharge of mine water into the sea. Simply applying criteria developed for freshwater ecosystems to marine settings would be naïve and highly inappropriate because marine organisms have very different mechanisms for coping with high concentrations of cations than do freshwater species. Furthermore, the hydrodynamics and geochemistry of marine waters mean that certain processes that are very important in determining the magnitude of mine water impacts in freshwater ecosystems are largely irrelevant in the oceans. This is particularly the case relative to benthic smothering by ochre, which does not occur when mine waters are discharged to the sea. Visual impacts of mine water discharge are still important in marine systems, due to the possibility of developing unsightly "slicks" of suspended ochre on the water surface (albeit these are actually innocuous in ecological terms). Avoidance of ochre slicks is a common concern wherever ferruginous mine waters are discharged to coastal waters. Compilation of data from a range of case studies indicates that no visible plume of ochre would be expected where the rate of iron release is less than about 200 kg/day. Maintenance of iron loadings below this critical threshold can be ensured by calculating a target maximum iron concentration ($Fe_{MAX}$, in mg/L) for the final effluent (which must be achieved by treatment if necessary) using the simple formula: $Fe_{MAX} = 2{,}314.8/Q_{MAX}$, where $Q_{MAX}$ is the maximum anticipated flow rate in litres per second from the mined system (pumped or flowing by gravity).

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## Introduction

This paper has been developed to assist decision-makers in specifying appropriate concentration limits for the discharge of mine waters to the ocean. It is based on critical review of a variety of sources, including:

- The entire database of Proceedings of Symposia and Congresses of the International Mine Water Association, dating back to 1979,
- The entire contents of the journal *Mine Water and the Environment* back to 1998,
- Science Citation Index, and through it several hundred electronic journals including Marine Pollution Bulletin, Journal of Experimental Marine Biology and Ecology, and Ocean & Coastal Management,
- The http://www.metalsriskassessment.org web-site (maintained by the International Council on Mining and Metals),
- Open Internet searching,
- Correspondence with professionals known to be engaged in environmental management of coastal mining operations worldwide, and
- The professional experience of the author.

Although this paper considers information relating to a wide range of commonly reported mine water pollutants, the principal focus is on iron, which is often the principal contaminant of coal mine waters.

## Issues with Mine Water Discharge to Marine Environments

### The Irrelevance of Freshwater Standards

The regulation of mine water discharges to freshwater systems is far more widely practised than discharge to marine environments, not least because relatively few major mining operations are located precisely on the coastlines of the world. Given that experience with mine water management in freshwater systems far exceeds that in marine systems, there is a great temptation to attempt to transfer criteria for discharge from the freshwater to marine environments. Indeed, a very recent report of the "MERAG" (Metals Risk Assessment Guidance) initiative specifically addresses "use of freshwater data for the derivation of ecotoxicity thresholds for marine species". One of the principal conclusions of that study is that (MERAG 2007):

> "it should be acknowledged that the physico-chemical characteristics of saltwater environments show important differences compared to freshwater environments. For example, seawater is characterised by a higher ionic strength and the observed gradients in abiotic factors such as chlorine content have important consequences on [*sic*] composition, behaviour, physiology, reproductive strategies of species on one [*sic*] hand and could have consequences for the speciation and bioavailability of metals on the other hand. Consequently, marine risk assessments should use, where possible, data relevant to the marine environment that is considered".

Herein lies the problem: data relevant to *any* marine environment are remarkably scarce, so that there is great temptation to attempt some extrapolation from the more abundant (though still hardly prolific) data for freshwater systems. MERAG (2007) tentatively suggest how this might be done, at least for notoriously ecotoxic metals such as Cu, Cd, and Zn, using an empirical "assessment factor". To date, no practical applications of this approach have been reported.

Given the rarity of Cu, Cd, Zn, and other such metals in coal mine drainage, these tentative recommendations are of limited relevance to coal mine waters, in which the principal contaminants of concern are Fe and Al. The limited data available are consistent with the conclusion that direct toxicity effects of Fe and Al in marine waters are likely to be negligible for all but the most extreme loadings (cf. Younger 2000; Gnandi et al. 2006). Although Al is strongly toxic to freshwater organisms, it quantitatively precipitates as innocuous $Al(OH)_3$ wherever pH rises above 4.5—which is inevitable upon mixing with well-buffered sea water. The case of Fe is even more encouraging: far from being regarded as a toxicant in marine ecosystems, Fe is in fact a limiting nutrient, so that introduction of Fe into marine waters actually *stimulates* algal primary production. This is exactly why major experiments in iron dosing of the southern ocean have been undertaken in recent years (see: http://lgmacweb.env.uea.ac.uk/soiree), with a view to stimulating algal blooms as a means of sequestering $CO_2$ from the atmosphere.

However, it is important to note that direct toxicity is not a key issue for Fe in freshwater systems either (Younger 2000). Rather, for both Fe and Al, a key ecological impact process in freshwater ecosystems is benthic smothering, in which bed sediments (the principal focus of photosynthetic primary production by attached algae) are so cloaked with opaque ochres and/or alums that light cannot penetrate to the algae, so that primary production is prevented. The knock-on effects up the food chain explain impoverishment of invertebrate and fish communities (Jarvis and Younger 1997). Benthic smothering principally arises from accretion of ochres/alums by hydrolysis of sorbed $Fe^{3+}/Al^{3+}$, rather than by settlement of hydroxides from the water column, since freshly precipitated hydroxides of these two metals are of very low density and thus tend to remain in the suspended load save under conditions of very low flow rates, as in settlement lagoons).

Benthic smothering is not a major concern in marine systems. This is because mine water (being generally fresh or brackish) is almost always significantly less dense than marine waters, so that it progrades on top of the dense marine water column. Mine water does not proceed along the sea bed, and therefore ochre accretion cannot occur in the way that it does in freshwater systems. Normally, hydroxides formed in the prograding mine water will gradually flocculate and fall out to the sea bed over a very wide area (Younger et al. 2005), so that a blanket of ochre does not accumulate. In summary, then, Fe and Al, as the principal contaminants of concern in coal mine waters, are not anticipated to be particularly problematic in marine ecosystems, due to their inability to give rise to benthic smothering and to the non-toxicity of the dispersed hydroxides into which they are both rapidly converted upon buffering by sea waters. What, then, *are* the real issues with coal mine discharge to marine environments?

### Issues Truly Relevant to Marine Environments

Review of the literature suggests that two major concerns arise frequently in relation to mine water discharge to marine environments:

a. *Visual impacts of stained water plumes*. The progradation of less dense, ferruginous mine waters above denser marine waters means that plumes containing highly visible ochre particles can extend over large areas of coastal waters around discharge points. Although such plumes have been found not to give rise to any ecological impacts (Younger et al. 2005), they are very unsightly, and negatively impact public perception of the wholesomeness of the local marine environment—with potentially negative effects on income from tourism and from sales of locally obtained marine produce.
b. *Localised impacts on seafood resources*. Extreme concentrations of Fe in near-shore marine waters can be expected to lead to bioaccumulation of Fe in fish and crustaceans to levels in excess of human consumption guidelines (cf. Gnandi et al. 2006). It is stressed that no such cases have been reported in practice in relation to coal mine discharges. However, it is conceivable that issues might arise if:
1. the mine water contained hundreds of mg/L of Fe, and
2. the mine water were run into the sea across a beach (as opposed to being introduced from a pipeline below the low-tide line).

Even then, it would only be an issue in the immediate intertidal zone; so as long as the mine water was not directed to enter an active seafood collection area, there would be no wider issues.

In all real cases for which information has been forthcoming, (a) above has proved the only real issue in practice. In the following section, brief summaries of these cases are collated.

## Collation of International Experiences with Mine Water Discharge to the Sea

### Non-coal Mines

1. *Wheal Jane, UK*. By far the best documented case is that of the Wheal Jane Sn/Zn mine in Cornwall, UK (see Younger et al. 2005 and extensive literature cited therein). The Wheal Jane mine does not actually discharge to the sea directly, but does discharge to a river only a short distance above its tidal limit; at times when the discharge to the river contained very high iron concentrations, this resulted in a plume of discoloured water prograding into the marine system of the Fal Estuary. Extensive monitoring and modelling established that (in this particular hydrodynamic setting) a discoloured plume was only visible when the loading of Fe entering the Fal Estuary exceeded a threshold of around 3,000 kg Fe/day. However, because the Environment Agency ended up owning the discharge consent for the Wheal Jane mine, they felt they had to limit themselves to a much lower consent than this to avoid being vulnerable to challenge on the grounds that they imposed stricter limits on others. Thus, the discharge consent criteria eventually adopted for the treatment plant at Wheal Jane amounted to a maximum iron loading of 151 kg Fe/day (corresponding to a maximum pumping rate of 350 L/s at a maximum concentration of 10 mg/L Fe). The concentration limit adopted for Al was 10 mg/L, corresponding to a maximum permitted loading of 300 kg/day.
2. *Skinningrove, UK*. The untreated discharges totalling 46 L/s from the Loftus and Carlin How Ironstone Mines at Skinningrove (Cleveland, UK) also enter a freshwater system (the Kilton Beck) a short distance from its confluence with the sea. In the 1970s, when iron loadings were still on the order of 600 kg/day, a plume was visible over an estimated 3,000 $m^2$ of the ocean surface around the mouth of the Kilton Beck. Iron concentrations in these discharges have decreased substantially from their early post-mine-flooding values, and with Fe concentrations currently averaging 17 mg/L, the total loading to the sea is only 67 kg Fe/day, and no longer result in a significant plume in the sea (albeit ochre staining remains severe in the freshwater course of the Kilton Beck).
3. *Stratoni, Greece*. This underground gold mine generally yields very little mine water, but after block-caving intercepted an ephemeral surface watercourse some years ago, measures had to be taken to prevent rapid ingress of storm runoff to the mine. At times, these measures have been overwhelmed by the quantity of flow in the wake of convective storms, and the result has been occasional outflows from the mine with loadings of iron peaking at an estimated 60,000 kg/day. Such an outflow in December 2002 gave rise to a highly visible ochre plume in the Mediterranean. Generally, the mine water treatment plant at the mine treats up to 70 L/s to maintain iron concentrations below the consented discharge limit of 15 mg/L, such that the Fe loading to the Mediterranean does not exceed 90 kg Fe/day.
4. *Britannia Mine, British Columbia*. This site has recently been the subject of a major tendering exercise for construction of a mine water treatment plant. The principal concerns at that site relate to Cu in the mine water, which has been shown to negatively affect growth of phytoplankton and invertebrates in the near shore zone of the Howe Sound (Levings et al. 2004, 2005), with knock-on effects for availability of safe

food resources for salmonid fish. The Britannia Mine Water Treatment Plant was required to meet the following discharge consent criteria: Al 1.0 mg/L; Cu 0.1 mg/L; Fe 0.1 mg/L; Zn 0.2 mg/L; Mn 0.4 mg/L; Cd 0.01 mg/L; and suspended solids 30 mg/L.

It is notable that the permit concentration for Fe is lower than that for Zn—a completely non-sensical provision from any ecological perspective, given the much greater toxicity of Zn. By contrast, the Al concentration is surprisingly lax, since it is known to be ecotoxic at such concentrations; however, in achieving 0.1 mg/L Fe, it is virtually impossible that Al could exceed 0.1 mg/L after having passed through the same water treatment plant.

## Coal Mines

1. *East Fife Coalfield, Scotland*. During active mining in the East Fife coalfield, which definitively ended with the cessation of pumping in 1995, ferruginous mine water was pumped directly into the sea (without prior treatment) from two shafts:

- Michael Shaft: 278 L/s at an average of 34 mg/L Fe, corresponding to a loading of 816 kg Fe/day.
- Frances Shaft: 104 L/s at an average of 12 mg/L Fe, corresponding to a loading of 108 kg Fe/day.

The Michael discharge gave rise to a visible plume over an area of some 4,000 $m^2$, whereas the Frances discharge caused no visible plume.

After rebound of mine water in the East Fife Coalfield, pumping was restarted from the Frances Shaft. Water quality had deteriorated dramatically in the interim (Nuttall and Younger 2004) and intensive treatment was required before the mine water could be released. At present, no final consent limit has been set for this site, as trials with the treatment system continue. However, a limit of 10 mg/L Fe is likely to be agreed to, as this level can readily be attained by the current treatment plant. At current pumping rates (averaging 83 L/s), this equates to a maximum Fe loading of 72 kg/day—which would be erring very much on the side of caution given the lack of any plume associated with the former loading of 924 kg Fe/day released without treatment from the Frances and Michael shafts during the period of active mining.

2. *Bates Colliery, Northumberland* (*England*). This pump-and-treat system controls water in most of the now-abandoned Northumberland Coalfield. The consent specifies a total flow rate of up to 200 L/s at up to 10 mg/L Fe (equivalent to a loading of 173 kg Fe/day). In meeting this consent, no plume is visible in the receiving marine water.
3. *Horden Colliery, County Durham* (*England*). This pump-and-treat system controls water in most of the eastern portion of the now-abandoned Durham Coalfield. The consent specifies a total flow rate of up to 116 L/s at up to 10 mg/L Fe (equivalent to a loading of 100 kg Fe/day). In meeting this consent, no plume is visible in the receiving marine water. On a number of short-lived occasions in which discharge occurred without treatment, a loading of up to 400 kg Fe/day locally entered the sea; this caused only a highly localised visible plume in the sea.
4. *Gardanne Coal Basin, Provence* (*France*). Agreement has been reached to discharge the entire post-rebound water make of this coalfield to the sea without treatment, via a long outfall debouching up to 160 L/s of untreated mine water more than 300 m beyond the low-tide line. With peak iron concentrations anticipated to reach as much as 100 mg/L, the permit envisages a peak loading of 1,400 kg Fe/day. At such a high loading, localised discolouration of sea water is accepted to be inevitable, though this will be located too far from the shore to be an eyesore from that vantage point.

## Precedents of Mine Water Consent Limits for Marine Discharges

It is notable that in all of the coal mine cases mentioned above, discharge consents specify only total Fe, pH (6–8.5), and suspended solids: none of them set specific limits on Al or any other metals. It should also be noted that the non-coal mine cases are principally regulated relative to Cu, Zn, and other ecotoxic metals. As in the coal mine cases, the regulation of Fe is approached solely from the point of view of visible nuisance (except in the case of the extremely low concentration specified at Britannia, which is indefensible on ecological grounds).

Table 1 below summarises the key findings from the reviewed case studies, arranged in order to illuminate key issues in consent limit-setting and loadings thresholds. As the table reveals, there are no known cases in which a Fe loading less than 200 kg Fe/day has given rise to an unsightly ochreous plume in the sea around a mine water discharge. Consent limits for Fe in marine discharges of mine waters range from an extreme low of 0.1 mg/L (which is not defensible on any grounds) to a very liberal 100 mg/L, with most permits permitting 10–15 mg/L.

**Table 1** Summary of consent limits for Fe from case studies of discharges of mine water to the sea

| Mine | Location | Type of mine | Consent limit for Fe (mg/L) | Permitted loading of Fe to sea (kg/day) | Fe loading (kg/day) to sea that caused a plume here |
|---|---|---|---|---|---|
| Wheal Jane | Cornwall (UK) | Tin/zinc | 10 | 151 | 3,000 |
| Skinningrove | Cleveland (UK) | Iron | 17[a] | 70[a] | 600 |
| Stratoni | Greece | Gold | 15 | 90 | 60,000 |
| Britannia | Canada (BC) | Copper | 0.1 | N/A | N/A |
| Frances | Fife (UK) | Coal | 10[b] | 72[b] | 816 |
| Bates | Northumberland (UK) | Coal | 10 | 173 | 400[b] |
| Horden | County Durham (UK) | Coal | 10 | 100 | 400[c] |
| Gardanne | Near Marseille (France) | Coal | 100 | 1,400 | 1,400[d] |

[a] No formal permits

[b] Not yet finalized

[c] Imprecise estimate

[d] Tracer tests in container port harbour

## Towards Site-specific Criteria for Mine Water Discharge to Marine Environments

It is generally accepted that, to be meaningful and effective, discharge consent criteria for marine systems need to be site-specific and season-specific (e.g. Johnston and Keough 2005). For mine effluent disposal to marine ecosystems, relevant issues include the vigour of marine dispersion and the toxicity of some metals towards "model" marine species appropriate to the region (Marín-Guirao et al. 2005). Evaluations also need to take into account societal acceptability (e.g. Osborn and Datta 2006), particularly with respect to unsightly plumes of ochre, which are actually ecologically innocuous (Younger et al. 2005). Development of site-specific criteria for individual mine complexes will therefore require consideration of a range of factors. However, avoiding visual intrusion by unsightly plumes emerges as the principal driver in the vast majority of cases worldwide.

With regard to avoiding unsightly ochreous plumes, it is clear from the case studies summarised above that there exists a threshold of iron loading below which no visible plume would be expected (even where the mine water is discharged to relatively calm, barely tidal seas, such as the Mediterranean). This threshold appears (from scrutiny of Table 1) to approximate 200 kg Fe/day. Given that the *quantity* of water yielded by a given body of workings is generally beyond control (at least once reasonable steps have been taken to limit excessive indirect recharge), maintenance of iron loadings beyond this critical threshold can be applied by calculating a target maximum iron concentration (post-treatment, where necessary) using the following formula:

$$Fe_{MAX} = 2,314.8/Q_{MAX}$$

where: $Fe_{MAX}$ is the maximum iron concentration to be permitted in the final effluent to the sea, and $Q_{MAX}$ is the maximum anticipated flow rate (either to be pumped or anticipated gravity flow rate from an adit)

Example: for a mine water with a total flow rate of 116 L/s ($\approx$1,845 U.S. gpm), to avoid having a discharge into the sea possibly causing a visible plume, one would target a post-treatment Fe concentration of 2,314.8/116 = 20 mg/L.

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