Cost-effective abatement of stochastic metal loading to water recipients

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Abstract

Relevant implementation of the EU Water Framework Directive with regard to mine water pollution of downstream water bodies requires pressure-impact assessment and catchment-scale economic optimisation of abatement measures. However, pressure-impact assessment is bound to be uncertain. This is because mine water pollution is often an unknown combination of pollution loads, from both known mine waste sites (point sources) and diffuse mine water sources, such as old mine wastes, abandoned mine voids and/or desorbing pollutants from immobile water zones and solid aquifer/sediment material. We investigate and quantify the influence of such pressure-impact assessment uncertainty on the allocation of cost-effective measures for targeted mitigation of mine water pollution loading. We use a stochastic description of total pollution loading from different possible polluted mine water sources and quantify the effect of random load variance on minimum abatement costs for a targeted 50 percent Zinc load reduction to the Swedish Dal River. Consideration of stochastic mine water pollution loading implies that cost-efficient abatement measures and associated minimum total costs within the Dal River Basin increase considerably with increasing load variance and desired probability to reach the targeted load reduction. However, this increase is only step-wise continuous because the cost-efficient abatement solutions include both continuous (e.g. constructed wetlands) and discrete (e.g. soil covers) abatement measures.

1 Introduction

Mine water, here defined as water flowing through mine waste deposits and abandoned mine voids, constitutes a pollution source for various water environments within a catchment (groundwater, streams, lakes), as well as for hydrologically connected coastal and marine waters. In the Swedish Dal River catchment, for instance, heavy metals from extensive historic and ongoing mining activities are considered to be major pollution sources, not just to the Dal River, but also to the Baltic Sea (Hartlén and Lundgren 1990; HELCOM 1993; Lindeström 1999; Svensson 1988).

The impact of all significant water pollutants, including pollution of downstream water bodies by heavy metals, acidity and sulphate from mine water, has to be investigated according to the EU Water Framework Directive. Efficient abatement of such downstream water pollution also requires a catchment-scale economic optimisation of several different possible abatement measures (Baresel et al. 2003, 2004; ERMITE Consortium 2004). The required pressure-impact and economic abatement efficiency assessment, however, will commonly have to include consideration of uncertain pollution loads. These uncertainties principally arise from diffuse sources, which may include abandoned mine wastes and voids (e.g., Wood et al. 1999; Younger, 2003; Younger et al. 1997), and also slowly-released pollution from previously sorbed metals on aquifers / sediment material and relatively immobile groundwater zones (e.g., Berglund et al. 2003; Malmström et al. 2000, 2004).

As a consequence of uncertain stochastic pollution loads, catchment-scale economic optimisation of abatement measures for water pollution also becomes uncertain. Both optimal measure allocation and associated minimum abatement costs may change considerably for different desired probabilities of abatement success (e.g., Gren et al. 2000, 2002). In this paper we therefore investigate and quantify the influence of stochastic mine water pollution loads and pressure-impact assessments on cost-effective abatement measure allocation on catchment scales. We use a stochastic description of total pollution loading from different possible sources of polluted mine water, and quantify the effect of random load variance on minimum abatement costs for a targeted 50-percent Zinc load reduction to the Dal River, Sweden.

2 Materials and methods

The Dal River catchment, with an area of 30 000 km^2, is located in the Bergslagen region of Sweden. Extensive historic and ongoing mining activities are primarily associated with the Falun and Garpenberg regions (Fig. 1). As a consequence there is considerable leaching of metals to the Dal River (Lindeström 1999; Hartlén and Lundgren 1990; Svensson 1988) and through the river to the Baltic Sea (HELCOM 1993).

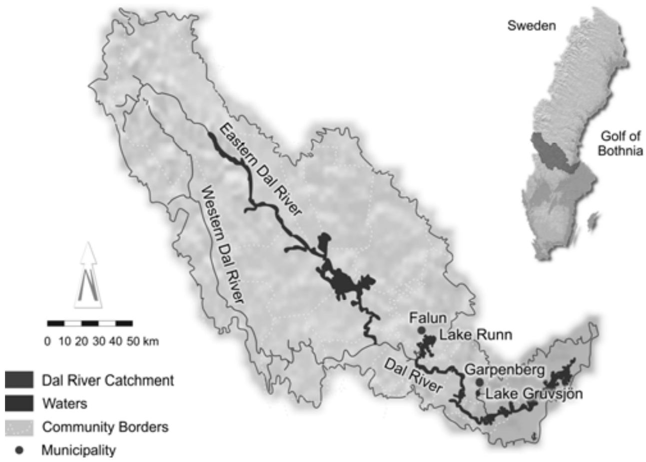

Fig. 1. Location map of the Dal River catchment.

Specific deterministic studies of the cost-efficient allocation of abatement measures and associated minimum total costs for targeted heavy metal load reductions to the Dal River have been carried out by Baresel et al. (2003, 2004) and ERMITE Consortium (2004). These studies have been based on quantitative estimates of metalliferous discharges from assumed deterministically known mine waste deposits and diffuse sources within the Dal River catchment (Fällman and Qvarfort 1990; Lindeström 1999; Hartlén and Lundgren 1990), and natural attenuation of metals loads within each sub-catchment (see Table 1). These studies used hypothetical abatement techniques (e.g. soil and water covers, constructed wetlands) in an economic model to determine how water quality objectives (i.e. 50% Zn load reductions) could be met cost effectively in the Dal River. In this article we extend this modeling approach by also considering the possible stochastic (i.e. not deterministically known or fully understood) contributions to the Dal River metal load, both in the current and in future post-abatement scenarios.

Table 1. Estimates of main sources of metal loads into the Dal River for the two considered dominating sub-catchments, Falun and Garpenberg, in terms of estimated total leakage from known mine waste sites (referred to as point leakage, L_{Pm}), and estimated leakage from unknown sources and loading from upstream areas (referred to as diffuse leakage, L_{Dm}). Furthermore, the table lists reported estimates of the natural attenuation of metal loads within each sub-catchment ($1\text{-}\alpha_m$).

	Parameter	Metal		
		Zn	Cd	Cu
Sub-catchment Falun, m = 1				
Leakage from known mine waste deposits [kg yr^{-1}] (a)	L_{P1}	289 600	363.0	15 720
Diffuse metal leakage [kg yr^{-1}] (a) (b)	L_{D1}	31 250	92.7	1820
Natural attenuation factor [%] (c)	$1 - \alpha_1$	25	49	45
Sub-catchment Garpenberg, m = 2				
Leakage from known mine waste deposits [kg yr^{-1}] (d)	L_{P2}	6031	8.04	138.4
Diffuse metal leakage [kg yr^{-1}] (e) (b)	L_{D2}	587	2.38	96.6
Natural attenuation factor [%] (c)	$1 - \alpha_2$	37	71	91

(a) From Hartlén and Lundgren (1990), including the sites Kiesbränder, North Industry, Slag fills and heaps, Korsgården, Nya Sandmagasinet, Oxide paint materials, Gruvområdet, Gamla Berget and Galbergsmagasinet (covered)
(b) From Lindeström (1999), including upstream sources, natural depositions, soil loads, water treatment plants
(c) From Hartlén and Lundgren (1990), and Lindeström (1999)
(d) From Fällman and Qvarfort (1990); Länsstyrelsen Dalarna Län (2001), including the sites Herrgården, Järnvägsbanken, Odalfältet, Tappdammarna, Östra magasin, Västra Sandmagasin and Lilla Bredsjön
(e) From Hartlén and Lundgren (1990)

The basic modeling approach of Baresel et al. (2003, 2004) and ERMITE Consortium (2004) considers i=1,…,I different mine waste sites located within sub-catchments m=1,…,M of an entire main river basin. For each mine waste site, there are j=1,…,J different possible site-specific measures for water pollution abatement, yielding a pollutant emission reduction by X_m^{ij} at the considered mine waste site at a cost of

$\sum_{ij} C_m^{ij}(X_m^{ij})$. Additionally, possible downstream-located abatement measures, such as wetland construction, for instance, directly at the Dal River compliance boundary, may yield a pollutant load decrease $\tilde{X}_m$, at a cost that depends on the constructed wetland area A_m, $C_m(A_m)$, at that compliance boundary (water recipient).

Total pre- and post-abatement pollutant load, L'_m, in each sub-catchment m is determined partly from source emissions L'_{Pm} that originate from known mine waste sites i, and partly from source emissions L'_{Dm} from diffuse pollution sources within a sub-catchment and upstream sub-catchments. Furthermore, natural pollution attenuation that may occur along pollutant transport paths from source to compliance boundary is also used to determine L'_m and L_m, and is quantified by sub-catchment-specific delivery coefficients α_m based on reported estimates (Table 1).

The deterministic cost-minimization problem for going from pre- to post-abatement pollution loads that achieve regulatory compliance is then given as:

$$\mathrm{Min}_{X_m^{ij} A_m} \sum_m \left[\sum_{ij} C_m^{ij}\left(X_m^{ij}\right) + C_m\left(A_m\right) \right] \tag{1}$$

subject to

$$L = \sum_m \left[\alpha_m \left(L'_{Pm} + L'_{Dm} - \sum_{ij} X_m^{ij} \right) - \tilde{X}_m \right] = \sum_m L_m \le L^* \tag{2}$$

with L and L_m being total and sub-catchment-specific post-abatement load, respectively, from all sub-catchments m and L^* being the regulatory compliance target. However, uncertain pollution loads from both point and diffuse mine water sources are more rationally described by stochastic pollution loads, not least due to the uncertain, stochastic nature of pollution delivery coefficient, α_m. Assuming such stochastic delivery coefficients α_m leads to that resulting pre- and post-abatement pollutant loads, L'_m and L_m, from each sub-catchment m are also stochastic and defined by their expected values $E(L'_m) = E(\alpha_m) \times (L'_{Pm} + L'_{Dm})$ and $E(L_m) = E(\alpha_m) \times (L'_{Pm} + L'_{Dm} - \sum_{ij} X_m^{ij}) - \tilde{X}_m$, respectively.

The cost minimization model (1) is then stochastically expressed as:

$$\mathrm{Prob}\left(\sum_m L_m \le L^* \right) \ge \beta \tag{3}$$

with β being the desired/required probability to reach the targeted load L^*. This stochastic constraint may be replaced by a deterministic equivalent, as described by Charnes and Cooper (1964), for example:

$$\sum_m \mu(L_m) + K^{\beta}\sqrt{\operatorname{Var}\sum_m (L_m)} \le L^* \tag{4}$$

This consists of expected values and variances of post-abatement pollutant loads, $\mu(L_m)$ and $\operatorname{Var}\sum_m(L_m)$, respectively. It is then assumed that co-variances between different sub-catchments m can be disregarded. The second term in (4) is expressed by the expected load $\mu(L_m)$ multiplied by the coefficient of variation $CV(L_m)$. K^{β} is a parameter for the assumed normal distribution of stochastic loads, which is tabulated for various standard normal probability distribution and probabilities β.

In our specific case study of the two Dal River sub-catchments ($m = 1, 2$), Falun and Garpenberg (Fig. 1), we investigate abatement costs for different load variances by using CV values of 0.25, 0.5, 0.75 and 1.0. The desired probability β to reach a target of a 50-percent Zinc load reduction is investigated for values of $\beta = 0.8$, 0.95 and 0.99. Abatement measure costs and other abatement characteristics remain the same as used in Baresel et al. (2003, 2004) and ERMITE Consortium (2004). However, Table 1 lists the main model parameterization (including considered mine waste sites, i, in the notes to Table 1).

3 Results

Fig. 2 and 3 show total annual abatement costs for compliance of a targeted 50-percent Zinc load reduction from the Falun and Garpenberg sub-catchments of the Dal River for different variances CV of the hypothetical normal load distribution and compliance probability β. The resulting minimum total costs for cost-efficient allocation of abatement measures in the catchment increase significantly with increasing load variance (CV) and desired probability (β) to reach the target. Moreover, compared to the deterministic results of Baresel et al. (2004), which is approximately 250 000 SEK per year, the stochastic results obtained indicate much higher minimum abatement costs for regulatory compliance with high probability.

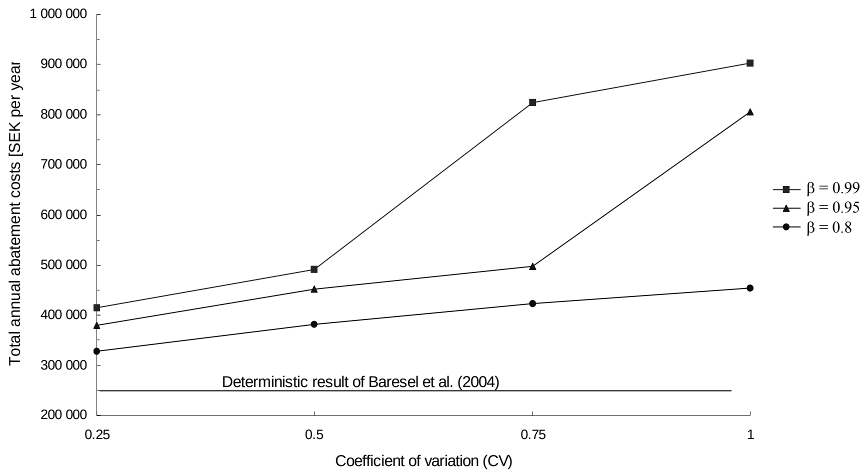

Fig. 2. Total annual abatement costs for compliance to a targeted 50 percent Zinc load reduction from the sub-catchments Falun and Garpenberg of the Dal River, for different coefficients of variation CV of the assumed normal load distribution and probabilities β to reach the targeted Zinc load reduction.

The increase of abatement costs with increasing coefficient of variation, CV, (Fig. 2) has a stepwise continuous pattern due to the requirement for discrete cost-intensive abatement measures, such as soil covers at specific mine waste deposits. At a compliance probability of 0.8, and for low CVs at higher probabilities, the cost-efficient abatement solutions consist of the same measure of allocation as in the deterministic solution (water covering of one mine waste site and constructed wetlands in both sub-catchments Falun and Garpenberg). For greater CV and/or β values, however, additional mine waste covering becomes necessary, which results in the illustrated step-wise cost behavior in Fig. 2.

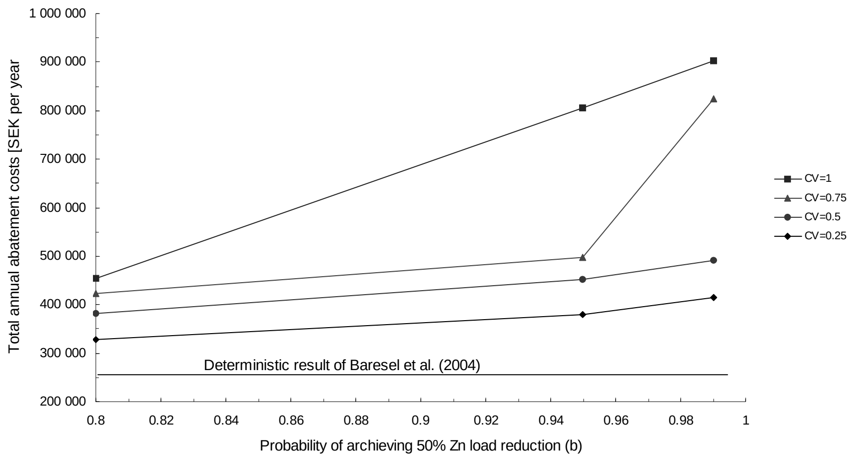

Fig. 3. Total annual abatement costs for compliance to a targeted 50 percent Zinc load reduction from the two sub-catchments Falun and Garpenberg to the Dal River for different probabilities β to reach the targeted Zinc load reduction and variances CV of the hypothetical normal load distribution.

Fig. 3 further illustrates minimum total cost for cost-efficient allocation of abatement measures in the Dal River catchment as a function of compliance probability β. This exhibits a smoother, more convex, behaviour than the function of CV in Fig. 2. This is because higher β values at constant CVs cause no change in measure allocation, except for the probability β = 0.99 at CV 0.75, which leads to a significant cost step increase in Fig. 3. In all other illustrated cases the size of downstream constructed wetlands, as preferred abatement measures, increases continuously and smoothly with increasing compliance probability β.

4 Conclusions and discussion

We have used a stochastic description of total pollution loading from both known mine waste sites (point sources) and diffuse mine water sources, to quantify minimum abatement costs for a targeted 50 percent Zinc load reduction to the Dal River, Sweden. Consideration of stochastic mine water pollution loading implies that cost-efficient abatement measures and associated minimum total costs increase considerably with increasing load variance and desired probability to comply with the targeted load reduction. This increase, however, may be step-wise continuous because the possible cost-efficient abatement solutions include both continuous (such as constructed wetlands) and discrete (such as soil and water covers) measures.

Catchment-scale economic optimisation, as shown in this paper, may generally have to consider deterministically unknown combinations of pollution loads from different mine water sources. The present results therefore imply that high priority should be given to reducing the uncertainty in the quantification of pollutant delivery coefficients, which are in turn determined by the physical transport and biogeochemical reaction processes along the pollutant pathways from source to water recipient.

Our specific case study considers only a limited number of possible abatement measures for mine water pollution, fixed costs for such measures, and the Dal River as the only water recipient of interest. Consideration of alternative abatement measures, associated costs, water recipients, and other possible restrictions will considerably influence site-specific results of cost-effectiveness. Nevertheless, the more general result aspects and implications of our study show clearly that consideration of the stochastic nature of metal loading to water recipients is important for relevant estimates of total abatement costs and efficient abatement measure allocation. The uncertainty related to such stochastic loading should be as far as possible reduced by site-specific investigations and be considered in decision-making.

5 References

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