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Economic Analysis Of Mine Water Pollution Abatement On A Catchment Scale

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EXECUTIVE SUMMARY

Mine waste deposits from historic and active mining are potential pollution sources for groundwater and surface water within a catchment, as well as for hydrologically connected coastal and marine waters. Water flowing through deposited mine wastes and abandoned mine voids, here referred to as mine water, constitutes an integral part of the hydrological cycle in a catchment and may become polluted, for instance, by sulphate and heavy metals. On its way downstream, through the variable water pathways of the catchment, such polluted mine water will then affect and may also pollute other water environments within the catchment (groundwater, streams, lakes), as well as the coastal and marine waters that are fed by the fresh water outflow from the catchment. The Swedish Dal River catchment, for instance, is considered a 'hotspot' for water pollution by metals, caused by extensive mine waste deposition from historic and ongoing mining activities with regard to local water bodies in the vicinity of mine waste sites, to the Dal River itself and, through the river, also to the Baltic Sea.

Implemented and planned mine waste remediation measures in general, as well as specifically in the Dal River catchment, are based on environmental legislation that handles different sources, in this case the mine waste sites, uniformly. The new EU Water Framework Directive (WFD), however, demands new tools for water quality management and decision-making within a catchment, including quantification of catchment-scale economic efficiency in chosen remediation measures, the allocation of which may then be non-uniform among the different sources of any given water pollutant in a catchment. We provide here a general discussion on the theory and application of economic decision rules for achieving mine waste site remediation and mine water pollution abatement efficiently on a catchment scale

Furthermore, we present a cost-minimization model for determining cost-effective allocation of mine waste remediation and/or mine water pollution abatement measures within the Dal River catchment, in order to achieve targeted zinc, copper and cadmium load reductions to selected recipients, including the Dal River itself. We consider various, practically feasible remediation measures and designs, including soil and water covering of the mine waste deposits, and downstream wetland construction close to, or at compliance boundaries (CBs). We calculate the cost-efficient measure allocation, and associated total and marginal costs for minimum-cost compliance to different environmental targets (ETs; in terms of metal load reduction) and CB locations (recipients), and for different scenarios of technological efficiency, cost and lifetime.

We show that total abatement cost for achieving a certain ET (load reduction) may be as high for a local water environment, as for the Dal River (entire catchment-scale), thus implying much higher marginal costs for the former, local compliance. Furthermore, the cost-efficient abatement measure allocation solution for local compliance may be completely different from that for the Dal River compliance, thus implying additive total costs for both local and regional compliance. The WFD allows for the possibility to use heavily modified waters, for instance close to sources, as pollutant sinks, and focus remediation on achieving good water quality in downstream, more practically restorable water bodies. The active choice of CB location is then of outermost importance for the costs and the cost-efficient allocation of mine waste remediation measures on a catchment scale. Discontinuity in the technical practicability of certain remediation measures (soil and water covers) further implies that relatively low chosen ET levels may not be achievable at a relatively low cost. Wetland construction, or other possible abatement measures in the direct vicinity of CBs, offer an alternative (to the discrete mine waste covering measures) continuous abatement measure possibility, which may be an important part of the cost-efficient solution for abatement measure allocation within a catchment.

As a general conclusion, we identify the following main differences between today's practice in making decisions about mine water pollution abatement options and rational economic approaches consistent with the WFD:

- *Allocation within a catchment of mine water pollution abatement is commonly not quantified in a catchment perspective and thereby not optimised based on net benefits or total costs on the catchment scale.* Our specific case study exemplifies the application of a quantitative hydrologic-economic modelling approach to catchment-scale water quality management with focus on the mine water pollution problem.

- *Cost scenarios for mine water pollution abatement are commonly not estimated with respect to different possible CBs and different possible water quality measures with associated scales of analysis (e.g., locally measured vs. spatially averaged measures) for judging compliance with water quality targets, such as maximum concentration levels (MCLs) or maximum pollution load levels (MPLs).* In our case study, we explicitly quantify abatement cost related to different CBs, each associated with a different water recipient. We use as a relevant water quality measure average annual pollutant mass discharging through the CB, and investigate a wide range of possible water quality improvement, quantified in terms of different reduction levels of the pre-abatement annually discharged pollutant mass. These measures of water quality and its improvement are commonly used in and are suitable for economic analysis of water quality abatement on a catchment scale. For each water recipient, these measures can be related to other water quality measures, for instance average concentration mass discharge values in(to) each considered water recipient, which may be more relevant for judgment of compliance to regulatory standards, for instance, MCLs or MPLs. By providing cost-effective solutions for a wide range of discharge reduction levels in annual pollutant mass, the present case study thus provides a basis for economic analysis of other possible water quality measures, each related to a different reduction level in annual pollutant mass discharge.

- *Estimated costs for mine water pollution abatement do not commonly include cost components associated with measurement/prediction uncertainties, which imply finite risk/probability of abatement measures not achieving their targeted water quality improvements.* This cost aspect is thoroughly addressed in the general discussion of catchment-scale economic analysis provided in this report, but remains yet to be quantified for our specific case study. The site-specific methodology and results already presented for this case study, however, can readily be extended to include uncertainty effects, by use of methods presented earlier in the scientific literature, and will be addressed in forthcoming work.

- *Expected long-term temporal changes in different mine water pollution scenarios are not commonly considered in any dynamic long-term analysis of efficient catchment-scale mine water pollution abatement. There are also commonly no regulatory limits in time explicitly specified for compliance of such abatement with water quality targets, MCLs or MPLs.* This temporal aspect of the mine water pollution abatement problem is also not addressed in our specific case study, which to a large degree deals with water quality management related to old, abandoned mine waste sites. The temporal problem, however, may be highly relevant specifically for the long-term planning and permit requirements for closure of active mines, and generally for efficient catchment-scale water quality management and regulation.

Economic Analysis Of Mine Water Pollution Abatement On A Catchment Scale

List of figures

List of tables

1 INTRODUCTION

The water flowing through deposited mine wastes and abandoned mines, as integral parts of the hydrological cycle in a catchment, may become polluted, for instance, by sulphate and heavy metals. On its way downstream, through the variable water pathways of the catchment, such polluted mine water will then affect and may also pollute other water environments within the catchment (groundwater, streams, lakes), as well as the coastal and marine waters that are fed by the fresh water outflow from the catchment (Figure 1). Implemented and planned measures for water pollution abatement and remediation of contaminated land sites (such as mine waste sites) in a catchment are, so far in many countries, commonly based on environmental legislation that handles different pollution sources (such as different mine waste sites) uniformly. The new EU Water Framework Directive (WFD), however, requires catchment-scale tools for water quality management and decision-making that enable quantitative identification of economically efficient measure allocation for contaminated site remediation and water pollution abatement, which may be highly non-uniform among the different sources of a certain water pollutant within a catchment.

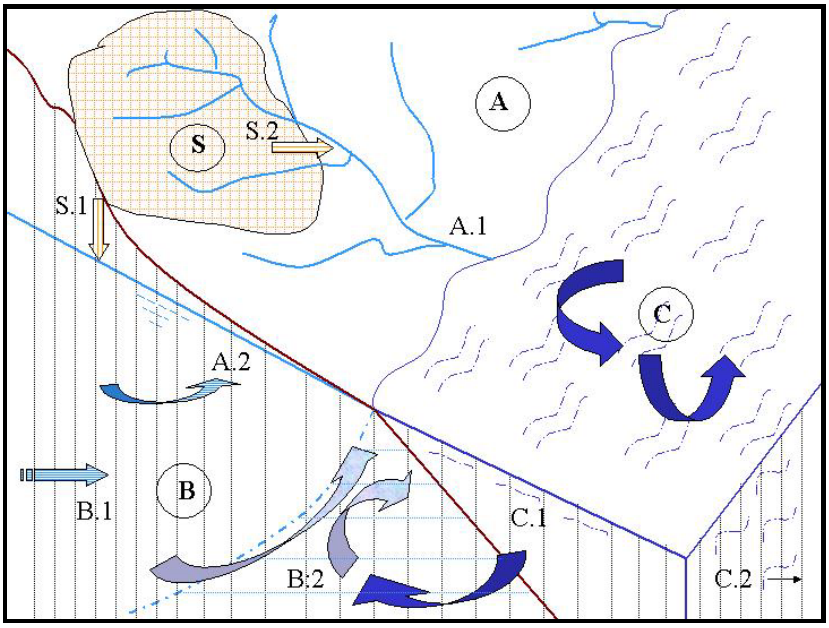

Figure 1. Schematic representation of the different water/pollution sub-systems within, or affected by a catchment

(S: pollution sources; A: stream network; B: subsurface water; C: lake or sea) and the different water-pollutant pathways (S.1: source to subsurface water, S.2: source to stream network; A.1: stream network to lake/coast, A.2: diffuse groundwater flow to stream network; B.1+B.2: total, diffuse and possibly brackish (for coastal aquifers) groundwater flow to lake/sea, with components B.1: fresh groundwater, B.2 re-circulated seawater (for coastal aquifers); C.1: coastal/lake transport pathways; and C.2: marine transport (for sea water)), which are all part of determining the pollutant fate from source to different water quality compliance boundaries and must be accounted for in ecologically and economically efficient water quality management.

In this report, we discuss economic decision rules for choosing mine waste site and mine water remediation measures within a catchment, such that given regulatory targets for water quality and/or pollutant loading are efficiently reached in chosen water recipients and water environments. In principle, there are two types of economic decision rules for water pollution abatement: choosing abatement that maximizes net benefits, or that minimizes costs for achieving pre-specified, for example by law or political decisions, water quality/pollutant load targets. These two economic rules for decision-making are consistent with an environmental regulation framework, such as the WFD, which focuses on water quality standards, for instance given in terms of maximum concentration levels (MCLs), or maximum pollutant loads (MPLs). A rational decision on where, when and which remediation and pollution abatement measures to apply within a catchment can then be based on identifying which measure combination that can practically yield MCLs/MPLs at some compliance boundary (CB; associated with some water recipient) at minimum cost, or maximal net benefit.

In addition to providing a general discussion on the application of economic decision rules for achieving mine waste site remediation and mine water pollution abatement efficiently on a catchment scale, we exemplify in this report also the application of such a rule to a particular case study. Specifically, we develop and apply a cost-minimization model for determining cost-effective abatement solutions within the Swedish Dal River catchment. This catchment is considered a 'hotspot' for water pollution by metals, caused by extensive mine waste deposition from historic and ongoing mining activities (HELCOM 1993). The water pollution of most general public interest is the metal leaching to the Dal River itself (Svensson 1988, Hartlén et al. 1990, Lindeström 1999) and through the river to the Baltic Sea (HELCOM 1993), but also the possible pollution abatement for local water bodies, in the near vicinity of mine waste sites, is interesting to investigate according to the WFD (eg., EU, 2000 par. 13). In our case study, we consider zinc, copper and cadmium loads to different selected recipients (CBs), including the Dal River itself, and various abatement measure practices and designs that may be practically feasible for the (sub)catchments and mine waste sites associated with these recipients; investigated measures include soil and water covers at the source and wetland construction close to the chosen CBs. The main aim of our investigation is to show how different metal load reduction levels at CBs can be achieved at minimum cost; the achievement of a certain load reduction then implies achievement of some related water quality standard, MCL or MPL, in the water recipient that is associated with a given CB.

2 ECONOMIC DECISION RULES ON A CATCHMENT SCALE

The application of the two different economic decision rules to the mine water pollution abatement problem on a catchment scale can be summarised as: a) maximisation of total net benefits of reducing the downstream water pollution by mine waters within the catchment; and b) minimisation of the total costs for achieving pre-specified water quality standards, such as MCLs and MPLs, within the catchment.

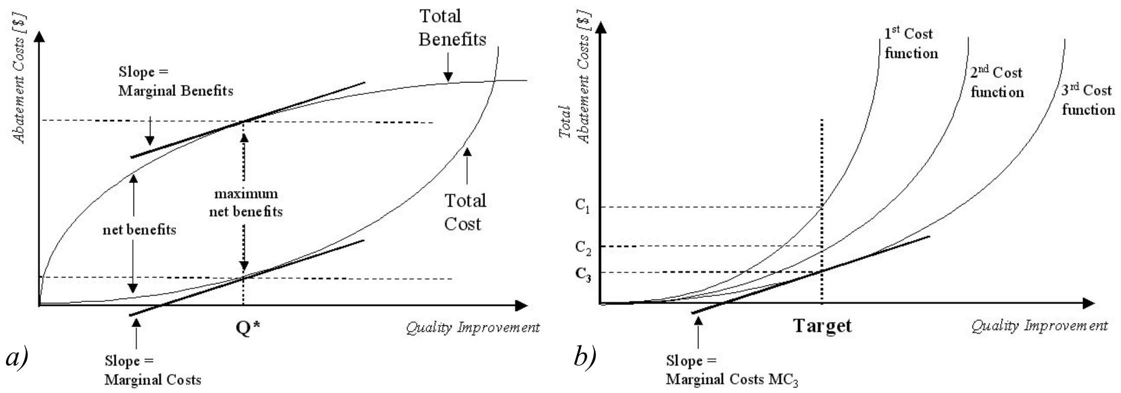

Figure 2. Schematic illustration of the two different economic decision rules: a) Maximisation of total net benefits, and b) Minimisation of the total costs.

Figure 2a shows the maximum benefits at the quality improvement Q*. Any divergences from this level imply a decrease in net benefits. The condition, which is shown in the sequel, is that marginal benefits equals marginal costs. The cost effectiveness rule is illustrated in Figure 2b, where the third cost function shows the minimum cost of achieving the pre specified Target (for instance, given by law or political decision). The relation between Q* and Target is determined by the benefits from water quality in relation to costs. Low marginal benefits implies relatively low Q* and vice versa.

Economic efficiency is then defined from rule a), as the allocation of mine water pollution abatement measures within the catchment that maximises net benefits from pollutant reductions in one or several chosen water recipients, each associated with a CB; reduced damages from metal loading into a recipient may, for instance, yield monetary benefits associated with improved recreational facilities and fishery (Gren et al. 2000c).

Needless to say, environmental improvements are, in practice, far from trivial to measure in monetary terms (Gren et al. 2000a, 2000c). Cost minimisation for reaching pre-specified water quality targets, MCLs or MPLs, in chosen water recipients is then an alternative fruitful approach (Gren et al. 2000a, 2000c) to economic efficiency. In the cost minimisation approach, it is the water quality target, for example given by political processes or by law, rather than the economic efficiency, which determines the required water quality improvement. The aim is then to achieve this targeted improvement at minimum cost.

In this section, we present and explain in simplest possible form, for clarity, the quantitative conditions for net benefit maximisation and cost minimisation of measures for mine water pollution abatement in a catchment. In our specific case study, we further develop and explain the cost minimisation approach and its specific model application to the Dal River catchment (see section 3, Appendices A – C).

Monetary benefits of water quality improvement at some downstream recipient of mine water from different sources (e.g., different mine waste sites) may be expressed as a function of average annual pollutant load decreases, $V(M'-M)$, with M' being the total level of unregulated, pre-abatement average annual pollutant load delivered by mine waters to a downstream CB, M being the achieved total post-abatement load at the same CB, and the function $V(M'-M)$ being decreasing and concave in load M, expressing that the more M is decreased, the smaller will the marginal net benefits be per additional unit load decrease.

Also the cost of reducing pollutants to the water recipient must be accounted for, in both decision rules, including, for example, expenses for soil or water covering of mine waste deposits, or for construction of wetlands downstream of the sources, close or at the CB. A simple cost model may include $i=1,...,N$ different mine waste sites, each associated with three possible mine water abatement measures: soil or water cover of the waste that yields reduced annual average source emissions, M^i_0, or wetland construction that abates the resulting downstream average annual pollutant discharge, M^i, at the CB. Associated cost functions, $C^i_0(M^{i'}_0 - M^i_0)$ and $C^i_{CB}(M^{i'} - M^i)$, where $M^{i'}_0$ and $M^{i'}$ are the unregulated pre-abatement emission level at the source and the resulting (also unregulated, pre-abatement) pollutant load at the CB, respectively. The cost functions may be assumed to be decreasing and convex in load, M, expressing that the more M is decreased, the greater will the marginal costs be per additional unit load decrease.

The maximisation problem is then formulated as choosing that allocation of M^i_0 and M^i_{C0}, which maximises net benefits, according to

$$Max \;\; V(M'-M) - \sum_{i=1}^{N} (C^i{}_0(M_0^{i'} - M_0^i) + C^i{}_{CB}(M_0^{i'} - M_0^i)) \qquad (1)$$

where

$$M = \sum_{i=1}^{N} M^i = \sum_{i=1}^{N} \alpha^i M_0^i \qquad (2)$$

with $0 \leq \alpha^i \leq 1$ are delivery coefficients, accounting for all pollutant retention, mass transfer and transformation processes on the pollutant's pathway from source to CB, which reduce the resulting output load at the CB, M^i, relative to the corresponding source emission M^i_0.
The corresponding cost minimisation problem is defined as

$$Min \quad \sum_{i}^{N} C^i{}_0(M_0^{i'} - M_0^i) + C^i{}_{CB}(M^{i'} - M^i) \qquad (3)$$

subject to

$$M = \sum_{i=1}^{N} \alpha^i M_0^i \leq M^* \qquad (4)$$

where M^* is a pre-specified total maximum annual average load to the recipient through the CB; this maximum load may then correspond directly to a MPL, or to the load level required for achieving MCLs in the considered recipient.

The concavity and convexity assumptions of the benefit and cost functions, respectively, ensure that second-order conditions for an optimum are fulfilled and yield first-order conditions for maximum net benefits as

$$\frac{\partial C^i{}_0}{\partial M^i{}_0} = V_M \alpha^i, \qquad \frac{\partial C^i{}_{CB}}{\partial M^i} = V_M \qquad (5)$$

with V_M being the monetary value of unit improvement in water quality. Equation (5) implies that mine water abatement for each source, with measures taken at the source itself, or at the CB, should be carried out as long as the increase in benefit per unit water quality improvement, V_M, exceeds the associated increase in abatement cost, expressed by terms $\partial C/\partial M$. The corresponding first-order condition for minimum cost is given by $C_0^i = \alpha^i \lambda,\ C_{CB}^i = \lambda$, with λ being the Lagrange multiplier for the target restriction (4), which may also be expressed as

$$\frac{C_0^i}{\alpha^i} = C_{CB}^i \qquad (6)$$

The condition (6) states that, in the optimal abatement solution, the marginal costs of pollutant load reduction at the target CB should be equal for all abatement measures. If this condition were not fulfilled, it would be possible to reduce total cost for the same target, M^*, by reallocating abatement among measures, such that abatement at low cost is increased at some source or at the CB, and high cost abatement measures are decreased.

We emphasise here that for both decision rules (5) and (6), the delivery coefficient values, α^i, with 1-α^i quantifying the natural pollutant attenuation along the different source to CB pathways within a catchment (see Figure 1), are critical in determining the optimal solution for mine water abatement within the catchment. Source abatement costs are higher (equation 6) and benefits are lower (equation 5) for mine water sources emitting pollutants that are subject to low delivery coefficients α^i (i.e., high natural attenuation), relative to sources with high α^i (i.e., low natural attenuation), or to abatement measures at or close to the CB. For both decision rules, inefficiency would occur from erroneous assumptions about and quantification of the delivery coefficients α^i, from the resulting in-optimal allocation of pollutant abatement among sources (such as water or soil covering of mine waste sites) and downstream measures close or at the CB (such as wetland construction). For instance, too much source abatement and too little downstream abatement may be chosen from erroneous α^i quantification, implying resulting inefficiency costs, the magnitude of which depends on the difference in marginal costs between abatement measures at the CB.

The maximisation of net benefits decision rule requires, besides relevant estimates of delivery coefficient values, α^i, and abatement costs, also information on monetary valuation of environmental benefits, associated with the water quality improvement (see, e.g., Gren 1995). The general difficulty of linking water pollutant abatement to, for instance, biological and health impacts measured in monetary terms (Gren et al. 1997) may make the cost-minimisation rule more fruitful than the more elaborate net benefit-maximisation rule, for the yet relatively un-investigated problem of mine water pollution abatement on the catchment scale. Even the cost-minimisation rule is presently at a research stage with regard to this application problem and, in the following, we present and use a methodology for such application to the specific case study of the Dal River catchment in Sweden.

3 COST-EFFECTIVE MINE WATER POLLUTION ABATEMENT IN THE DAL RIVER CATCHMENT

3.1 The Dal River Catchment

The Dal River catchment in the Bergslagen region has an area of 30 000 km^2. While background levels of metal concentrations characterise the upper part of the catchment, where the river is divided into the West and East Dal Rivers, the central, industrialised area of the catchment is affected by mine water pollution, originating from the regions Falun and Garpenberg, two major mining areas of historical and current importance (see Figure 3).

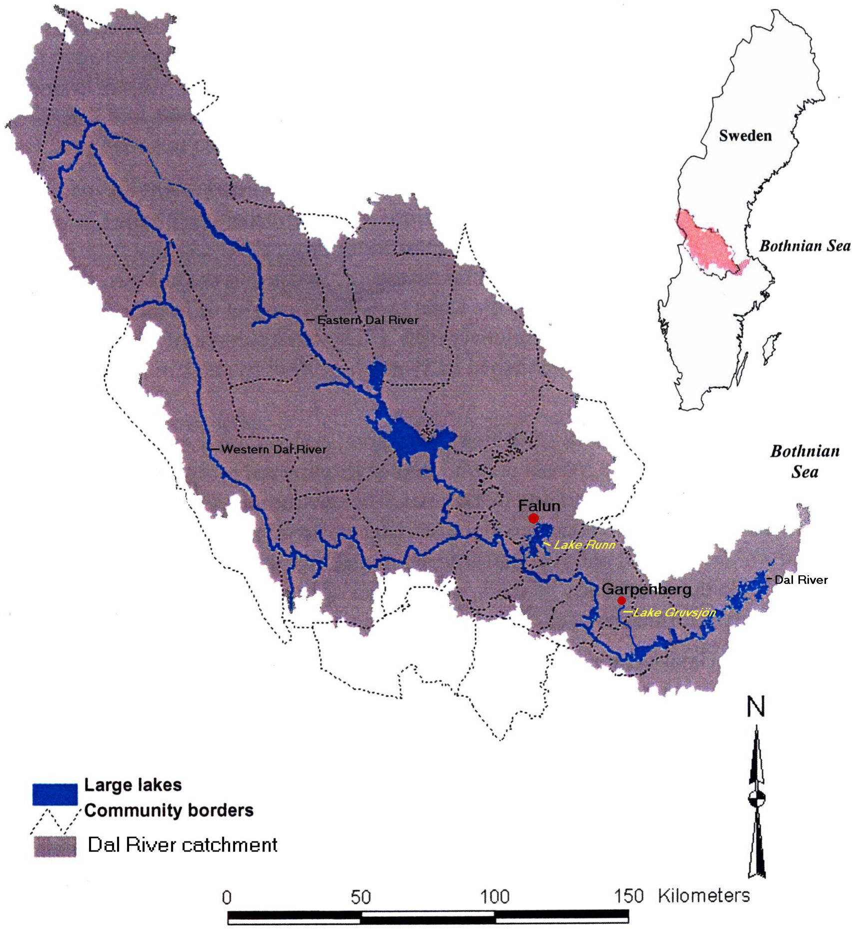

Figure 3. Dal River catchment including the regions Falun with local recipient lake Runn, and Garpenberg with local recipient lake Gruvsjön (for a more detailed map see Appendix A).

The Garpenberg area hosts numerous deposits of mining waste, many of which are protected for their historical value. The city of Falun, with its preserved mining area, has been declared as a Protected Area on the UN World Heritage List.

The exploitation of non-ferrous minerals, like the metals zinc and copper, in these regions created huge environmental problems due to Acid Mine-water Drainage (AMD). Existing deposits around the mines consists mostly of heap and slag in lower and older deposits, and of waste rock and tailings in upper layers. Since mining in the region of Falun approximately started already in year 700, many small and uncharacterized sources of metal leakage can be found within the catchment area. This has influenced the water quality not only in the local recipients Runn and Gruvsjön but also in the catchment's main watercourse, the Dal River (Lindeström 1999). The contribution of zinc and cadmium from the Dal River to the Baltic Sea is estimated to be larger than for any other watercourse in Sweden (Svensson 1988). Therefore, the need of mine water pollution abatement is generally recognized for these regions and various abatement measures are planned or have already been started.

3.2 Catchment-Scale Cost Minimization of Mine Water Pollution Abatement

We have carried out a cost minimisation analysis of the mine water pollution abatement in the Dal River catchment, along the lines of the main concept of cost minimisation (described in section 2, with Appendix C describing the used, site-specific cost-minimisation model in more detail). We then consider as different possible water recipients (CBs) of interest the Dal River on the regional level, and the lake Runn and the lake Gruvsjön on the local level; the two latter are then affected by the sub-catchments of Falun and Garpenberg respectively (Figure 3; Appendix A). We investigate cost-minimisation results, in terms of cost-efficient measure allocation and associated total and marginal costs, for a variety of metal load reduction levels, ranging between 10 and 90 percent of the un-abated (i.e., present) average annual metal loading to each recipient. Present average annual metal loads include leakage from known major mine waste deposits as well as other possible and less known sources of metals leakage (see Appendix A) and we focus here specifically on leakage of the metals zinc, copper and cadmium. Table 1 summarises the different possible abatement scenarios considered in our investigations.

Table 1. Selected scenarios at the regional level, Dal River catchment-scale.

Scenario	***Description***
Base case scenario	▪ Abatement alternatives: soil covering and constructed wetlands ▪ Soil cover efficiency: 98.8 percent reduction of initial metal leakage ▪ Abatement measure lifetimes: 50 yr ▪ Retention of metals (natural attenuation) takes place in surface water sediments (with resulting delivery factors α^i<1 listed in Appendix A, Table A3) ▪ Used measure costs (are listed in Appendix A, Table A6-A8)
Worst case scenario (combination of three different sub-scenarios, the individual results of which are reported in Appendix B?)	▪ Estimated un-abated (present) metal leakage from known mine waste sites reduced by 5 %, and considered instead as originating from unknown diffuse sources (thus increasing source emission uncertainty, for instance, reflecting possible metal leakage from commonly unaccounted for abandoned mine voids) ▪ No retention (natural attenuation) of metals takes place in river and lake sediments (i.e., all delivery factors, for instance in the cost-minimisation equation (6) are α^j=1) ▪ Soil cover efficiency reduced to 85 % of initial metal leakage
Optimistic scenario	▪ Water covering considered hydrologically possible (in addition to the soil cover and wetland construction measures considered in the base case scenario) at selected mine waste sites (see also abatement measure description in Appendix A)
Variable wetland cost scenarios	▪ Lifetime of constructed wetlands may, for instance, be difficult to estimate; reduced wetland lifetime, from some expected value, will then result in higher annual wetland costs (for the same discount rate). Consideration of different possible wetland lifetimes, and other possible reasons for wetland cost variability and uncertainty is the reason for investigating cost-efficient abatement solutions and associated costs for different wetland cost levels ▪ See also Appendix B (Figure B1) for additional results on specific wetland lifetime scenarios

3.2.1 Recipient – Dal River

Reductions of metal loading to the Dal River may be obtained by applying mine water abatement measures both in the Falun and the Garpenberg mine waste sites, as well as by constructing wetlands close to the Dal River CB. Figure 4 then shows the resulting cost-efficient measure allocation solution and associated total annual costs for compliance with three different possible zinc load reduction targets, as function of different possible wetland cost levels. All obtained cost-efficient solutions imply that measures for the Dal River load reduction compliance should only be taken in the Falun area, however with total costs ranging, for example, between 172 000 and 761 000 SEK/yr for a zinc load reduction of 50 percent in different investigated scenarios. For the other investigated metals (copper and cadmium), all cost-efficient solutions involve only wetland construction (results shown in Appendix B, Figure B4). Because only the zinc reduction requires additional mine water abatement measures to wetland construction for achieving cost-efficiency, it may often be the targeted zinc reduction level that dominates the overall measure allocation strategy and associated total costs for reducing also the other metals (since wetland construction requirements in the cost-efficient zinc solution automatically reduces also the loading of other metals considerably.

The results in Figure 4 show that, if water covering is not hydrologically possible (base and worst case scenarios, Table 1; Figures 4a and 4c), wetland construction is the only cost-effective abatement measure to be taken for all targeted zinc reduction levels at relatively low average costs. Soil covering, however, becomes an increasing part of the cost-effective measure allocation solution for increasing wetland cost levels, in particular in combination with increased required zinc load reduction. Furthermore, if water covering is hydrologically possible (optimistic scenario, Table 1; Figure 4b), this particular measure becomes part of the cost-efficient measure allocation solution for all considered wetland cost levels and targeted zinc load reduction levels, thereby also considerably reducing total abatement costs.

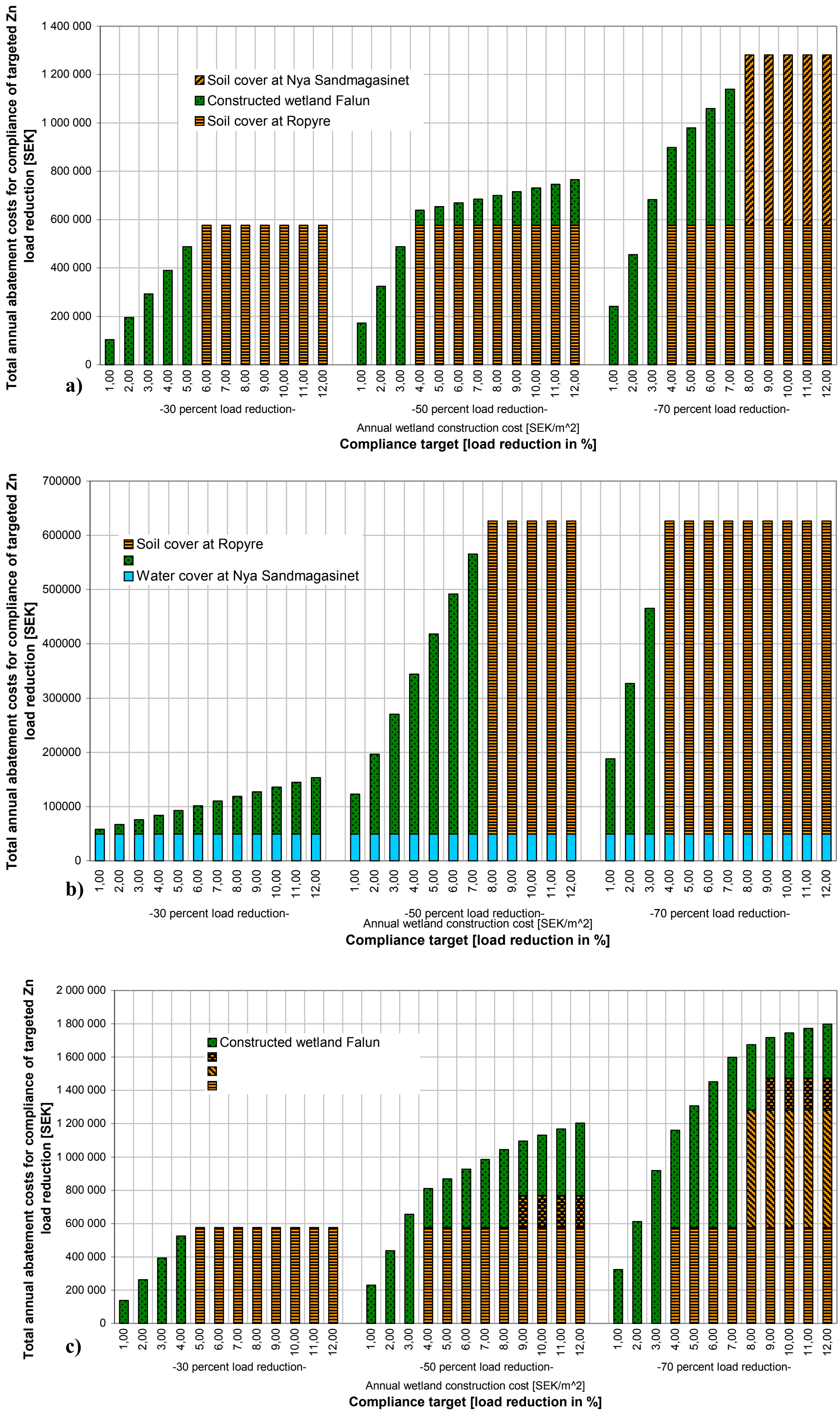

Figure 4. Cost-effective solution and associated total annual abatement costs for compliance to different targets of Zinc load reduction to the Dal River in a) the 'Base case scenario', b) the 'optimistic scenario', and c) the 'Worst case scenario', according to the scenario description in Table 1.

Figure 5 further illustrates resulting marginal costs as functions of targeted metal load reduction level (see also Appendix B, Figure B3, for additional marginal cost results). The marginal costs for compliance to Copper and Cadmium reductions are constant because wetland construction is the only cost-efficient abatement measure over the entire range of investigate wetland cost levels and for all targeted load reduction levels. At an average wetland cost of 1 SEK/m^{2}yr (Larsén, 2002, and references therein) marginal costs are constant also for all Zinc load reduction targets, because also in this case wetlands construction is the only cost-efficient mine water pollution abatement measure. Increasing wetland cost levels, however, imply that also other possible abatement come into play in the cost-efficient measure allocation solution. . Marginal costs for reducing zinc loads to the Dal River then decrease, reaching a minimum somewhere around the 50% reduction level for the 'Base case scenario' considered in Figure 5. The reason for this marginal cost behaviour is that soil and water covering measures, which come increasingly into play for increasing wetland cost and zinc reduction level (Figure 4), are not continuous abatement measures. Specifically, it is not possible to obtain a continuously increasing load reduction level, by increasingly covering a larger part of a mine waste deposit. Each mine waste deposit must be covered entirely to obtain a metal reduction effect, which then yields some discrete effect addition to each water recipient. Otherwise, if only part of a deposit is covered, oxygen diffusion into the mine waste cannot be stopped, oxidation continues and hardly any metal reduction effect is obtained at all. For the Dal River, and for average to relatively high wetland cost, the cost-efficient Zinc load reduction level is thus about 50% for the 'Base case scenario', regardless of whether legal or political reduction targets are be lower than that.

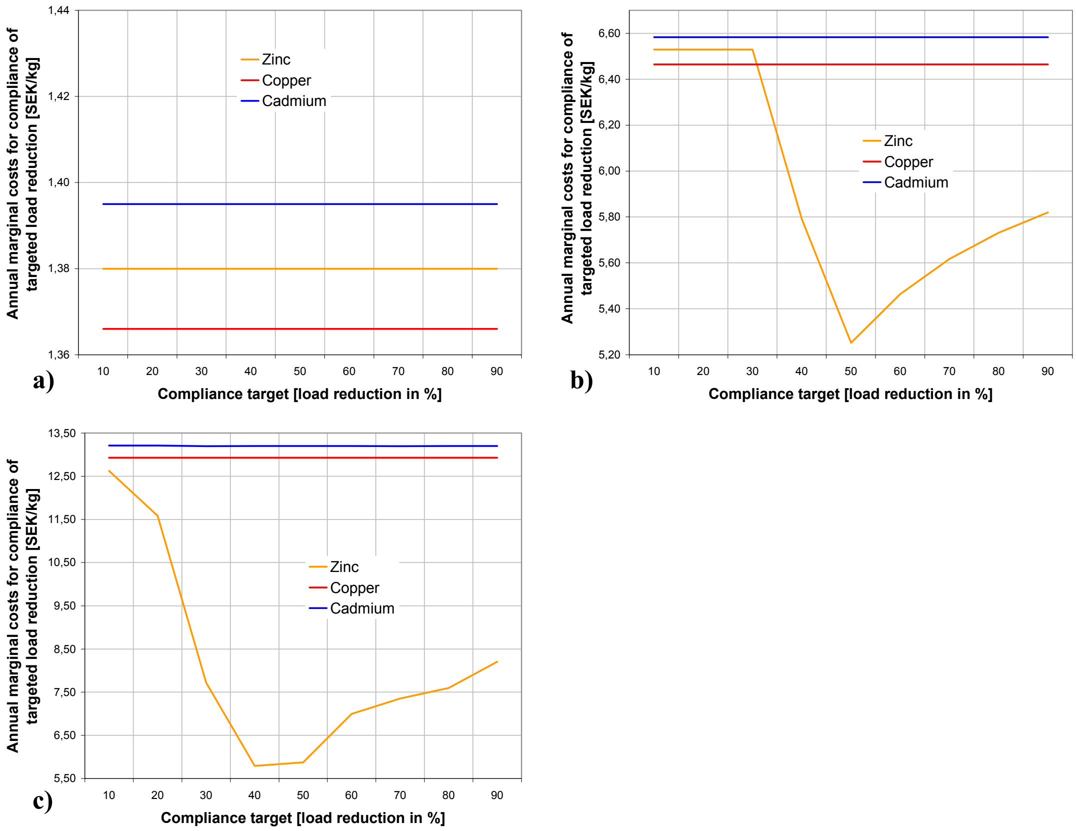

Figure 5. Annual marginal costs for compliance to different targets for reduction of Zn, Cd and Cu loading to the Dal River in the 'base case scenario' (Table 1), for annual wetland cost of a) 1.057 SEK/m^2, b) 5 SEK/m^2, and c) 10 SEK/m^2.

Constant marginal costs, as shown in Figure 5 for Copper and Cadmium (and in some cases also for Zinc), instead imply linearly and continuously increasing total costs with increasing targeted load reduction level. Such a marginal and total cost behaviour is the result of the continuous abatement measure possibility offered by wetland construction, in contrast to the discontinuous mine waste (soil and water) covering methods.

3.2.2 Recipient – Runn (Falun)

Wetland construction is not considered as a possible mine water abatement alternative in the case of the lake Runn due to sub-catchment area limitations; simply, there may not be sufficient space available for relevant wetland construction here. This area limitation implies that some combination of soil and water covering has to be applied for achieving metal load reduction to lake Runn. Figure 6 then shows the resulting cost-efficient abatement measure allocation and associated total costs for compliance to different targeted metal load reduction levels. Zinc is, at this local sub-catchment scale, in contrast to the entire Dal River catchment scale, not longer the metal that dominates the overall mine water abatement solution, requiring most financial input for its abatement. Furthermore, load reduction can only be achieved here up to 70 percent of the pre-abatement (present) loading, with all feasible abatement measures already being used at this reduction level. In general, however, total costs of compliance with different targeted metal load reduction levels, up to the limit of about 70 percent, are in the same range as for the zinc load abatement in the Dal River.

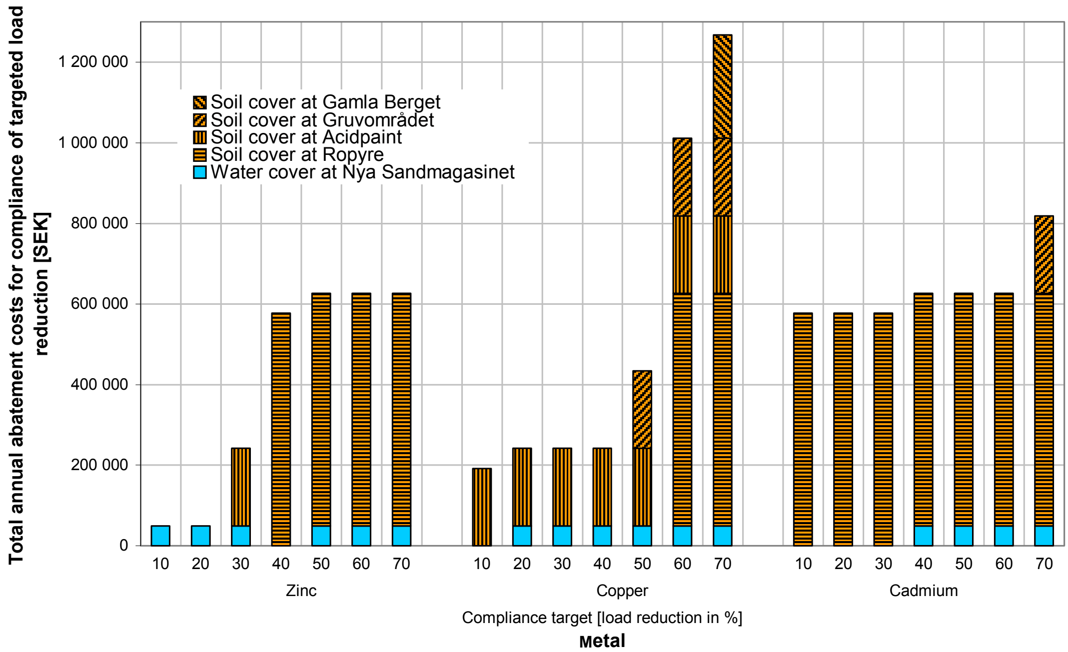

Figure 6. Cost-effective solutions and associated total annual abatement costs for compliance with different targets for reduction of Zn, Cd and Cu loads to the lake Runn.

Figure 7 shows marginal costs of compliance with different metal load reduction levels. The discontinuity effects of soil and water covering, being the only abatement measures considered feasible in the Runn case, are here evident for all investigated metals. Specifically, all marginal cost curves initially decrease with increasing targeted load reductions, until reaching the minimum point that represents a discrete, lowest possible cost-efficient load reduction level. Above this reduction level, marginal costs may increase rapidly, reflecting the required additional discrete mine waste site covering measure that must be implemented in order to get any additional metal load reduction effect at all. Thereafter, marginal costs decrease again until the point of this next, discrete cost-efficient load reduction level is reached (see particularly the Zinc marginal cost curve in Figure 7).

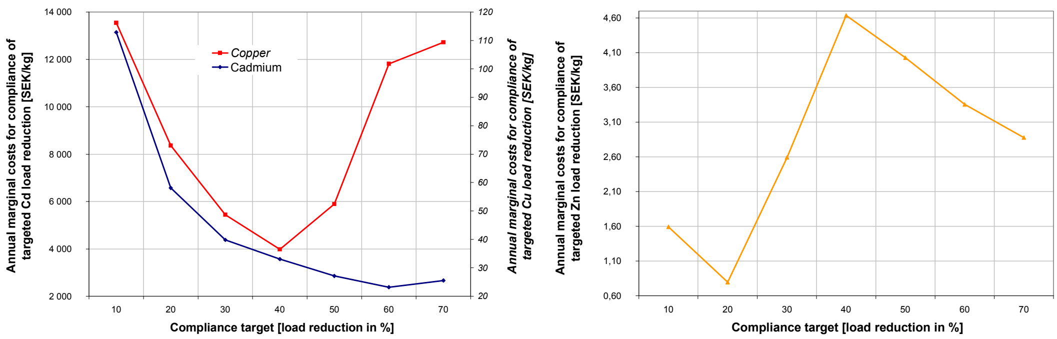

Figure 7. Annual marginal costs for compliance with different targets for reduction of Zn, Cd and Cu loads to the lake Runn.

From comparison of Figure 7 with Figure 5, we also note that marginal costs for compliance with different targeted to Cadmium load reductions are for the lake Runn case at least one, an in most cases more than two orders of magnitude higher than in the Dal River case. Also for Copper and for some conditions even for Zinc, marginal costs of compliance to targeted load reduction levels are here significantly higher than for the Dal River. These results are the direct effect of wetland construction, or any other abatement measure close to the lake Runn CB, not being considered practically feasible in this case.

3.2.3 Recipient – Gruvsjön (Garpenberg)

Pre-abatement (present) metal leakage from mine waste sites in the Garpenberg sub-catchment are estimated to account for only 1-2 percent of the total metal discharges into the Dal River (see Appendix A, Table A2). Nevertheless, metal discharges into the local lake Gruvsjön may be considerable and require mine water pollution abatement, with Figure 8 illustrating results for cost-efficient allocation of abatement measures and associated total costs in this case. We can then see that already at a targeted 20 percent load reduction to the lake Gruvsjön, total abatement costs are comparable to those for the Dal River at a 70 percent reduction target, without any of the cost-efficient abatement measures for Garpenberg being included in the cost-efficient abatement allocation solution for the Dal River. As Figure 8 shows, total costs of metal reduction compliance are already at their highest level at load reductions of 20 percent for Copper and Cadmium. At the 10 percent targeted reduction level, both total (Figure 8) and marginal (Figure 9) costs for Copper and Cadmium abatement are relatively low, due to the possibility of water covering at four mine waste sites. In analogy with the case of Lake Runn, also in the case of lake Gruvsjön there is an upper limit in possible load reduction; above load reductions of 50 percent, no additional abatement measure alternatives are available for further load reduction, within the chosen set of measures investigated in this report.

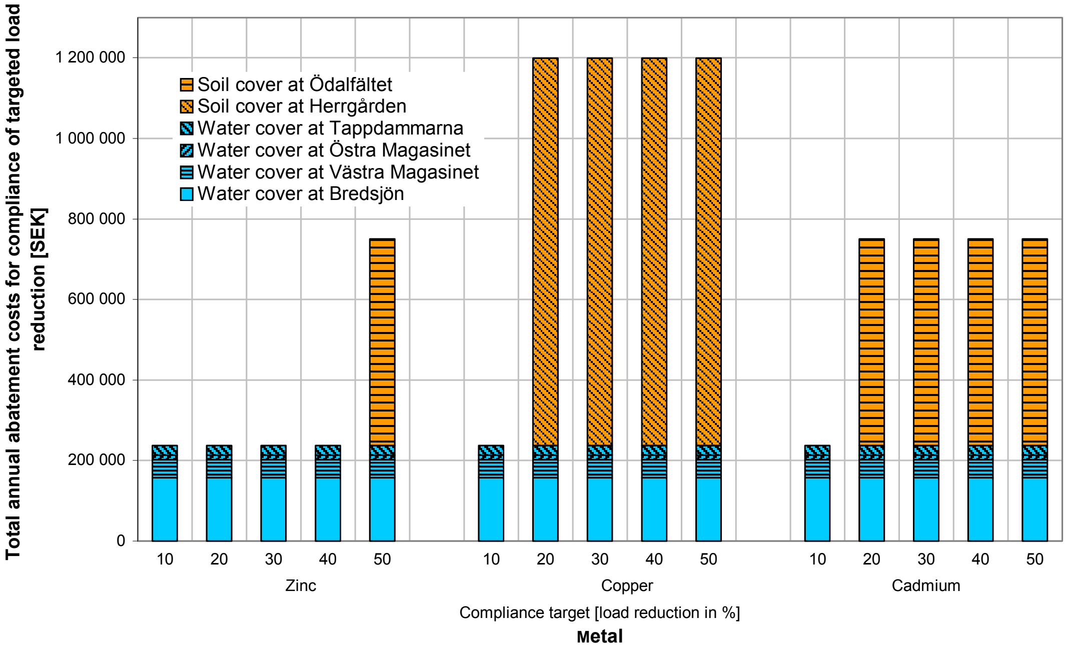

Figure 8. Cost-effective solution and associated total annual abatement costs for compliance to different targeted load reduction of Zn, Cd and Cu to the lake Gruvsjön.

Marginal abatement costs for Copper and Cadmium load abatement are here much higher than in both the lake Runn and the Dal River cases, abatement of one kg of Cadmium may here cost more than 350 000 SEK annually. Also in this case, marginal costs of compliance decrease as long as the cost-efficient abatement solution remains the same (Figure 8) due to the waste covering discontinuity effect; only at reduction level points where additional discrete measures must be applied do marginal costs rapidly increase and thereafter decrease again, until the next need of additional discrete abatement measures.

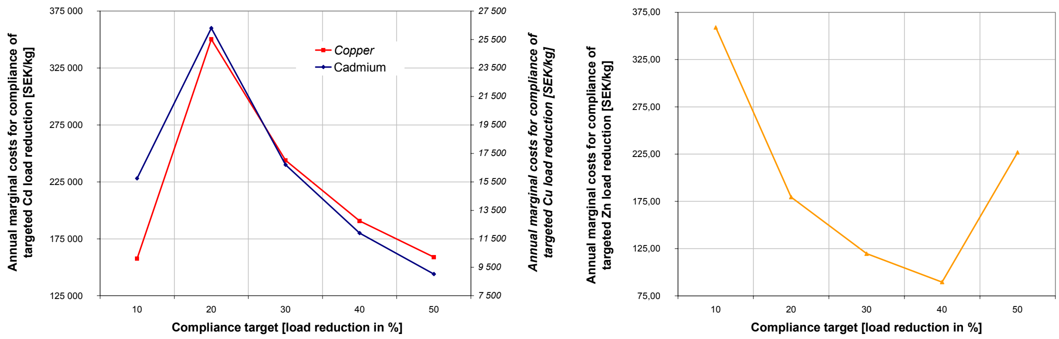

Figure 9. Annual marginal costs for compliance with different targeted reductions of Zn, Cd and Cu loads to the lake Gruvsjön.

3.2.4 Case study conclusions

We have presented here results from a site-specific cost-minimization model applied to the determination of cost-effective allocation of mine waste remediation and/or mine water pollution abatement measures within the Dal River catchment, in order to achieve targeted zinc, copper and cadmium load reductions to the Dal River itself and to selected local mine water recipients. We have considered various, practically feasible remediation measures and designs, including soil and water covering of the mine waste deposits, and downstream wetland construction close to the compliance boundaries (CBs) associated with the different investigated mine water recipients. We calculate the cost-efficient measure allocation, and associated total and marginal costs for compliance to different environmental targets (ETs; in terms of metal load reduction) and CB locations (mine water recipients), and for different scenarios of technological efficiency, cost and lifetime.

We show that total abatement cost for achieving a certain ET (load reduction) may be as high for a local water environment, as for the Dal River (entire catchment-scale), thus implying much higher marginal costs for the former, local compliance. Furthermore, the cost-efficient abatment measure allocation solution for local compliance (here particularly for the Garpenberg – lake Gruvsjön - sub-catchment) may be completely different from that for the entire catchment-scale (here the Dal River catchment). We note here that the EU Water Framework Directive allows for the possibility to use heavily modified waters, for instance close to sources, as pollutant sinks, and focus remediation on achieving good water quality in downstream, more practically restorable water bodies. The active choice of CB location is then of outermost importance for the costs and the cost-efficient allocation of mine waste remediation measures on a catchment scale.

Our site-specific results also show that discontinuity in the technical feasibility of certain remediation measures (here soil and water covers of mine waste sites) implies that relatively low chosen ET levels may not be achievable at relatively low cost. In general, local minima in costs may then occur only at certain, discrete ET levels, which must be identified and quantified for achieving economic efficiency. Wetland construction, or other possible abatement measures in the direct vicinity of CBs, may offer an alternative (to the discrete mine waste covering measures) continuous abatement measure possibility, which may be an important (or even the only, as shown here for Copper and Cadmium load abatement for the Dal River) part of the cost-efficient solution for abatement measure allocation within a catchment.

4 GENERAL DISCUSSION

The case study application described in section 3 shows that and how it may be possible to identify cost-effective (i.e., minimal cost) solutions for mine water pollution abatement in a given catchment on basis of clearly formulated water quality targets. The necessary pre-specified water quality target formulation for identifying a minimal-cost solution, however, requires, besides MCLs/MPLs and associated required pollution discharge reductions, clear specification also of compliance boundaries/limits/scales in space and in time. In addition, due to practical, as well as inherent uncertainties in predicting pollutant loads and concentrations in natural hydrological systems (Cvetkovic et al. 1992, Destouni 1992, Destouni et al. 1997, Graham et al. 1998, Foussereau et al. 2000, 2001), there is also a need to specify a level of acceptable risk (probability) of exceeding (or, conversely, probability of meeting) targeted water quality standards in terms of MCLs or MPLs. Total costs for achieving these targets are namely strongly affected by and must account for this uncertainty, in particular for relatively high probability requirements (, Andersson et al. 2001, Bayer et al. 2001, 2002, Gren et al. 2000b, 2002). The cost-effect of quantifiable uncertainty may, or may not differ between different possible types of measures/technologies for mine water pollution abatement, yielding the following different possibilities for the cost-effective abatement solution:

a) *Remaining quantifiable uncertainty in measured/predicted water quality at the CB **differs** between different types of measures.* This differing uncertainty effect is then clearly a factor that, for any given required probability of target achievement, may discriminate among the different possible abatement measures, thus changing the cost-effective measure allocation solution relative to one neglecting uncertainty effects (, Bayer et al. 2001, 2002, Gren et al. 2000b, 2002). This is an additional effect to the following one.

b) *Remaining quantifiable uncertainty in measured/predicted water quality at the CB **does not differ** between different types of measures.* The uncertainty effect may in this case not affect the cost-effective measure allocation solution for a given required target achievement probability, but may add greatly to the magnitude of total minimum costs for high requirements of target achievement probability (Gren et al. 2000b, Andersson et al. 2001, Bayer et al. 2001, 2002). The target formulation in terms of required probability is therefore also in this case an important decision variable.

In general, different possible target scenarios are possible and need to be explicitly formulated and analysed, in order to identify one or more relevant target formulations that are technically possible to achieve at acceptable cost. One target interpretation for MCL/MPL compliance may, for instance, be that MCLs/MPLs should be achieved everywhere concentrations, or pollutant discharges are measured, regardless of how they are measured, and almost immediately or soon after abatement measures are applied. With such an extremely narrow interpretation of required target compliance, in terms of CB position (water quality ≤ MCLs/MPLs everywhere), temporal compliance limits (water quality ≤ MCLs/MPLs achieved very soon), risk/probability of failure (zero risk of water quality > MCLs/MPLs) and observation scale/method (water quality ≤ MCLs/MPLs regardless of measurement method/scale), target achievement is generally likely to be both technically and economically impossible. If the combined regulatory target formulation is instead sufficiently flexible to render technical/economic practicability to target compliance, then all these different spatial, temporal, risk/probability and observation method aspects of the water quality target formulation represent important decision variables that need to be explicitly considered, quantified and investigated.

Besides the different possible CB choices, exemplified in our case study of the Dal River catchment (section 3) by different water recipients, there are also alternative measures of water quality/pollutant loading, associated with different water quality targets, for instance in terms of MCLs or MPLs. These water quality measures may be directly measured local/point concentration or mass flux values, flux-averaged concentrations or mass flow rates that are integrated over larger cross-sectional areas of the considered CB, or cumulative contaminant mass leaving those control planes; in the Dal River case study we chose the latter type of measure, in terms of average annually accumulated pollutant mass discharged through the CB. In any case, it must be realised that several different water quality/pollutant loading measures are possible to use, each being associated with some observation scale and resulting quantifiable uncertainty (Cvetkovic et al. 1992, Destouni 1992, Destouni et al. 1997, Graham et al. 1998, Foussereau et al. 2000, 2001). Noting the above-discussed, possibly major uncertainty effect on total costs and cost-effective abatement measure allocation, as well as the technical/economic impracticability that may be implied by using some of these measures (local/point concentration/flux values, for instance, are inherently highly variable in natural hydrologic systems), the regulatory framework should also specify the range of acceptable choices among these different possibilities of quantifying and measuring water quality. Otherwise, different measures and observation methods may be used arbitrarily to show compliance or not compliance to water quality standards, according to subjective wish.

Furthermore, the costs for each possible abatement technology/measure must in principle include three different components:

1. Costs for all technological measures that need to be taken for achieving a regulatory target by some given abatement technology/measure. The target formulation must then include the required probability for the chosen measure of water quality/pollutant loading to meet the associated regulation standard, thereby incorporating the uncertainty cost effects discussed above. Costs in this category must also include technological monitoring and compliance control costs, the requirement for which may differ between different source (for instance, water or soil cover of mine wastes) and CB (for instance, wetland, or reactive barrier construction) abatement measures.
2. Costs caused by side effects from each technology/measure, for instance negative or positive cost for increased or decreased, respectively, land and/or groundwater value, which may possibly be implied by different mine water pollution abatement measures.
3. Transaction costs associated with planning, implementing and managing a given abatement technology/measure, such as all non-technological costs for effect establishment, monitoring and compliance control (with associated technological costs included in 1). Also here there may be uncertainty costs to pay, which may or may not differ between different technologies. For instance, existence of asymmetric information among the regulator, liable parties and other stakeholders is likely to increase total costs, because the regulator may have to pay so called informational rents (i.e., pay for receiving more valid information from involved parties. Different measures/technologies may differ with regard to such informational uncertainty and associated cost, which could thereby provide an important discrimination factor in a rational choice among different measures.

In addition, it must be noted that the time scales involved in mine water pollution and abatement problems may be very long; metal turn-over times in mine wastes, for instance, may be on the order of hundreds or thousands of years, with the time scale being prolonged by remediation measures, such as water and soil covering. Decision-making based on a single minimum-cost solution for short-term environmental quality target fulfilment may generally be too narrow a policy criterion for far-reaching environmental problems, which may even affect the entire economy over long time-scales. Such problems are generally best tackled in a dynamic economic framework, which should then ideally include models of both technological change and economic growth (Hart 2002). For possibly less far-reaching problems, and as intermediate analysis steps, important insights may be gained also by dynamic economic modelling that ignores growth and technological change (e.g., Hart et al. 2002). For instance, a dynamic cost-effective path for water pollution abatement may involve combinations of pollution abatement measures that change in time, such that a downstream containment strategy may be appropriate initially, to be increasingly replaced by source abatement as time passes. The decision problem of catchment-scale mine water pollution abatement could, in principle, also be analysed by such dynamic economic modelling, however, application of static cost-minimization analysis for multi-target formulation (investigating the cost-efficient target fulfilment in several water recipients/CBs, rather than in only one of them) under uncertainty should first be attempted as natural next steps to the basic cost-minimisation analysis exemplified by our case study (section 3), for gaining necessary basic insights to guide further steps in the direction of dynamic economic analysis. A static cost-minimisation approach is certainly justified if the temporal compliance limit chosen by the regulator is small (MCLs/MPLs must be achieved soon) and all considered abatement measures must yield quick responses in water quality.

Finally, the economic decision rules discussed here do not answer the question on how total abatement costs and benefits should optimally be divided among different stakeholders (liable parties, regulators, tax payers). This is an important clarification to make, because a stakeholder-specific benefit-maximisation or cost-minimisation analysis, for instance, may tacitly or explicitly, exclude some of the cost components and effects that may be important to include in the identification and quantification of efficient mine water abatement solutions for different possible target formulations on a catchment scale. Furthermore, the answer to the question how all these costs and benefits should efficiently be shared among the different stakeholders depends on the choice between various possible policy instruments (Gren et al. 2000a, 2002). A discussion on the scientific basis for making this type choice rationally is outside the scope of this report, but will be discussed in forthcoming work.

5 GENERAL CONCLUSIONS

As a general conclusion from the present economic analysis overview and specific case study, we identify the following main differences between today's practice in making decisions about mine water pollution abatement options and the rational economic approaches discussed above:

- *Allocation within a catchment of mine water pollution abatement is commonly not quantified in a catchment perspective and thereby not optimised based on economic efficiency on the catchment scale.* The specific case study in this report exemplifies the application of a quantitative hydrologic-economic modelling approach to catchment-scale water quality management with focus on the mine water pollution problem.

- *Cost scenarios for mine water pollution abatement are commonly not estimated with respect to different possible CBs and different possible water quality measures with associated scales of analysis (e.g., locally measured vs. spatially averaged measures) for judging compliance with water quality targets, such as MCLs or MPLs.* In the case study of this report, we explicitly quantify abatement cost related to different CBs, each associated with a different water recipient. We use as a relevant water quality measure average annual pollutant mass discharging through the CB, and investigate a wide range of possible water quality improvement, quantified in terms of different reduction levels of the pre-abatement annually discharged pollutant mass. These measures of water quality and its improvement are common in and suitable for economic analysis of water quality abatement on a catchment scale (e.g., Gren et al., 2000a, 2002). For each water recipient, these measures can be related to other water quality measures, for instance average concentration or mass discharge values in(to) each considered water recipient, which may be more relevant for judgment of compliance to regulator standards, for instance, MCLs or MPLs. By providing cost-effective solutions for a wide range of discharge reduction levels in annual pollutant mass, the present case study thus provides a basis for economic analysis of also other possible water quality measures, each related to a different reduction level in annual pollutant mass discharge.

- *Estimated costs for mine water pollution abatement do not commonly include cost components associated with measurement/prediction uncertainties, which imply finite risk/probability of abatement measures not achieving their targeted water quality improvements.* This cost aspect has been thoroughly discussed in the general discussion section of this report, but remains yet to be quantified for our specific case study. The methodology and results already presented here for this case study, however, can readily be extended to include uncertainty effects, by use of methods presented by Gren et al. (2000a, 2002) and will be addressed in forthcoming work.

- *Expected long-term temporal changes in different mine water pollution scenarios are not commonly considered in any dynamic long-term analysis of efficient catchment-scale mine water pollution abatement. There are also commonly no regulatory limits in time explicitly specified for compliance of such abatement with water quality targets, MCLs or MPLs.* This temporal aspect of the mine water pollution abatement problem is also not discussed in our specific case study, which to a large degree deals with water quality management related to old, abandoned mine waste sites. The temporal problem, however, may be highly relevant for the long-term planning and permit requirements for closure of active mines; it will therefore be addressed in forthcoming work and discussed in the final WP4 report of the ERMITE project.

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APPENDICES

A. Mine Water Pollution Sources and Abatement Alternatives in the Dal River Catchment

Table A1. Surface water observation locations in the Dal River catchment (Lindeström 2000).

No	Name of station	Sub-catchment area (km^2)
2	Fulan	883
5	Yttermalung	3968
7	Dala Järna	7245
8	Mockfjärd	8543
13	Rotälven	888
16	Mora	9962
17	Oreälven	2278
18	Gråda	12271
19	Forshuvud	21282
22	Tunaån	585
23	Torsång	21919
25	Varpan, utlopp	527
26	Slussen	559
27	Sundbornsån	2110
29	Långhag	25057
30	Långshytteån	25465
34a	Herrgårdsdammen	47.8
34	Forsån	126
35	Näs bruk	26888
37	Gysinge	28049
38	Älvkarleby	28919

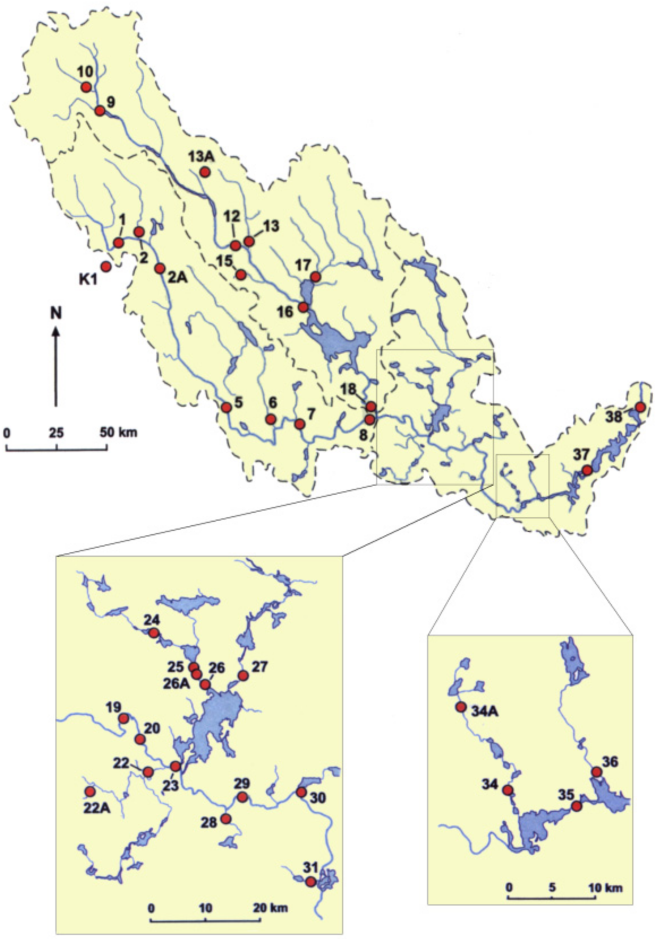

Figure A1. Surface water observation locations, zoomed areas = Falun region left, Garpenberg right, (Lindeström 2000).

Table A2. Primary leakage distribution of metals, describing the distribution of Zinc, Copper and Cadmium sources within the Dal River catchment, (Hartlén et al. 1990).

Area	Zinc	Copper	Cadmium
Falun	95%	87%	90%
Garpenberg	2%	1%	2%
Other	3%	3%	8%

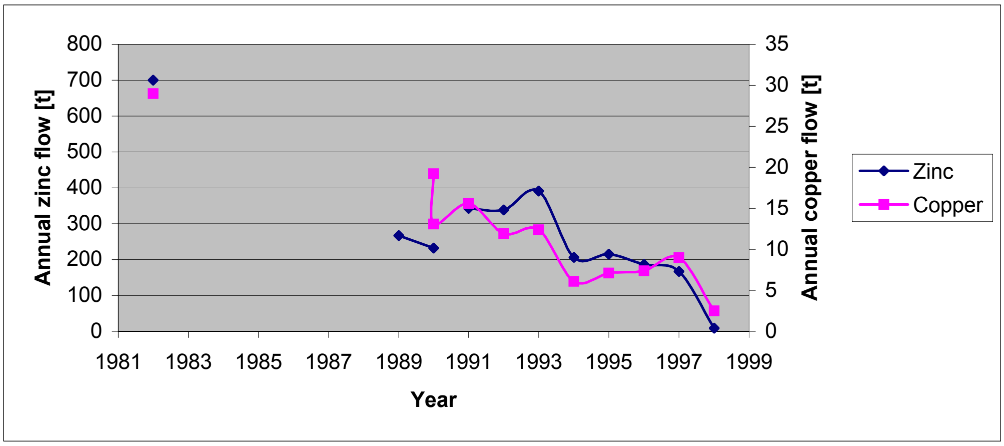

Figure A2. Metal release history in Falun, indicating reduced leakage rates after closure of mining activities in 1992 at Falun, derived from *(Sandberg 1999)*.

Table A3. Retention rates of Zinc, Copper and Cadmium in main surface waters (Hartlén et al. 1990, Lindeström 1999).

	Zinc	Copper	Cadmium
Runn	25%	45%	49%
Gruvsjön and Garpenbergsån - Forsån	37%	91%	71%

.

Table A4. Total metal release from different sources in Falun.

Mine waste deposit[1]	Area [m²]	Release [kg/yr]		
		Zn	*Cd*	*Cu*
Roasted pyrite residues (Kiesbränder)	90 000	145 000	160.0	2 100
The northern industry area, slag	110 000	7 000	1.5	1 000
Slag fills	550 000	2 600	1.6	320
Slag heaps	200 000	3 000	4.0	500
Slag in Korsgården[2] (incl. Vallean)	250 000	2 000	0.1	300
Nya Sandmagasinet tailing dam	110 000	87 400	148.0	6 100
Heap in Gruvområdet	30 000	10 000	19.0	1 500
Raw material for manufacturing oxide paint (heap)	30 000	20 000	10.0	2 000
Gamla Berget	40 000	2 600	1.8	900
Galbergsmagasinet	100 000	10 000	17.0	1 000
Sum mine waste deposit leakage		***289 600***	***363.0***	***15 720***[3]
Total metal release from Mining waste[4]		308 750	441.0	13 920
➔ spread sources mining waste (I)		19 150	78.0	0
Total metal release from other sources[5] (II)		12 100	14.7	1 820
Total diffuse metal leakage in Falun I +II		***31 250***	***92.7***	***1 820***

[1] Areas and leakage amounts from Hartlén J. and Lundgren T. (1990). Gruvavfall i Dalälvens Avrinningsområde - Metallutsläpp och åtgärdsmöjligheter. Linköping, Statens Geotekniska Insitut.
[2] Area estimation since direct related data is not available, leakage amount subtracted from Nya Sandmagasinet since both share the same recipient
[3] Inconsistency of pages 14 and 64 in Hartlén J. and Lundgren T. (1990). Gruvavfall i Dalälvens Avrinningsområde - Metallutsläpp och åtgärdsmöjligheter. Linköping, Statens Geotekniska Insitut.
[4] Hartlén J. and Lundgren T. (1990). Gruvavfall i Dalälvens Avrinningsområde - Metallutsläpp och åtgärdsmöjligheter. Linköping, Statens Geotekniska Insitut.
[5] Lindeström L. (1999). Dalälvens Vattenvårdsförening DVVF - Metaller i Dalälven. Fryksta, Miljöforskargruppen; includes inflow from station 25 & 27, Främbyverket, deposition on Runn, soil loads etc.

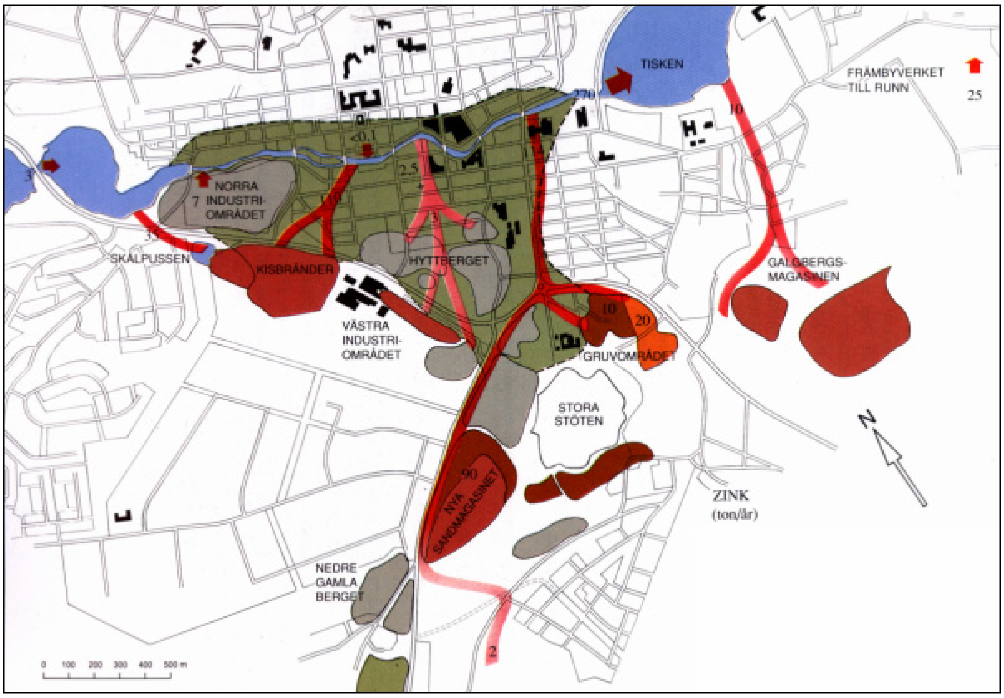

Figure A3. Map showing total metal zinc release from different sources in Falun (Hartlén et al. 1990).

Table A5. Total metal release from different sources in Garpenberg.

Mine waste deposit	Area[1] [m^2]	Release [kg/yr][1]		
		Zn	*Cd*	*Cu*
Herrgården, slag	150 000	2 000	2.6	92.0
Järnvägsbanken, slag	64 000	2	-	0.2
Odalfältet, heap	80 000	1 000	3.7	10.0
Tappdammarna, tailings	54 000	46	0.13	-
Östra magasinen, tailings	24 000	23	0.04	7.2
Västra sandmagasinen, tailing dam (2 magasines)	100 000	960	1.2	10.0
Lilla Bredssjön, tailing dam	350 000	2 000	0.37	19.0
Ryllshyttemagasinet (still in use)	-	-	-	-
Sum mine waste deposit leakage		***6 031***	***8.04***	***138.4***
Total metal release from Mining waste[2]		6 500	10.0	200.0
➔ spread sources mining waste (I)		469	1.96	61.6
Total metal release from other sources[3] (II)		118	0.42	35.0
Total diffuse metal leakage in Garpenberg I +II		***587***	***2.38***	***96.6***

[1] leakage amounts are averaged; Fällman A.-M. and Quarfort U. (1990). Teknisk Kartläggning av Gruvavfall i Garpenberg. Linköping, Statens Geotekniska Institut.
[2] Hartlén J. and Lundgren T. (1990). Gruvavfall i Dalälvens Avrinningsområde - Metallutsläpp och åtgärdsmöjligheter. Linköping, Statens Geotekniska Insitut.
[3] Lindeström L. (1999). Dalälvens Vattenvårdsförening DVVF - Metaller i Dalälven. Fryksta, Miljöforskargruppen; includes wastewater treatment plant, deposition on lakes, soil loads, storm water etc.

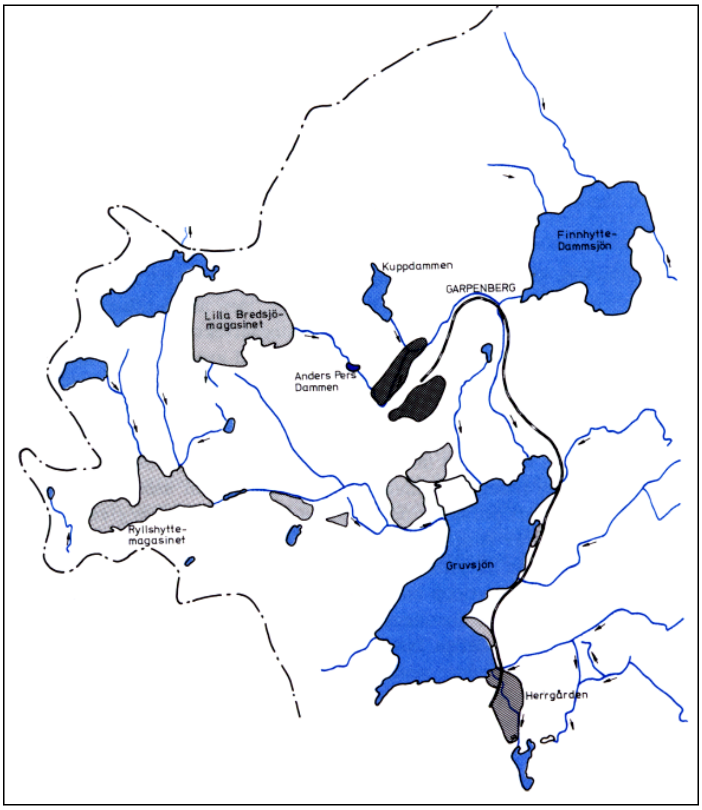

Figure A4. Map showing mining waste deposits and surface waters in the Garpenberg region (Hartlén et al. 1990).

Table A6. Soil covering projects and their costs in Sweden (Gustafsson et al. 1999).

Location	Year of rehabilitation	Area (ha)	Total cost (Million US$)	Cost per m^2 (US$)
Bersbo	1987-1990	5.7	5.0	28
Ranstad	1990-1993	25	7.7	31
Falun	1990-1996	20	2.3	11.5
Saxberget	1994-1996	50	4.2	12

Table A7. Costs of constructed wetlands.

Capital costs [m^2]	Operational costs [m^2]	Total cost [m^2]	Source
5 – 32 US$	0.5 – 3.2 US$	5.5 – 35 US$	MEND 1996
20 SEK	0.7 + 0.21 SEK/yr	-	Larsén 2002 and references therein (opportunity costs = 0.21 SEK/m^2yr)
60 – 360 SEK	negligible	60 – 360 SEK	Sauer et al. 2001
23.67 US$	-	23.67 US$	Marcus Jerrold 1997

Table A8. Costs of water covering.

Capital costs [m^2]	Operational costs [m^2]	Total cost [m^2]	Source
1.5 US$	unknown	1.5 US$	Gustafsson et al. 1999
~20 US$	unknown	~20 US$	MEND 1995

Table A9. Considered abatement measures and their characteristics used for the economic evaluation of mine water pollution abatement in the Dal River catchment.

Constructed wetlands	▪ Can be located at the inflow of the Falun respectively Garpenberg sub-catchment into the Dal River. ▪ Construction costs vary between 1.057 and 12 SEK/m^{2}yr including operational costs (Table A7). ▪ Efficiency in reducing metals is 2 g/m^{2}d for all three metals in acid waters (Larsén, 2002, and references therein). ▪ Lifetime of 50 years, by this annual costs determined using an annuity factor of 0.039.
Soil covering	▪ Can theoretically be located at all mine waste sites but must cover the whole site. ▪ Construction costs of 6.41 SEK/m^{2}yr (Gustafsson et al 1998) ▪ Efficiency in reducing initial metal leakage is 98.8 percent (MEND 1994; Larsén, 2002, and references therein). ▪ Measure lifetime of 50 years assumed, by this annual costs were determined using an annuity factor of 0.039.
Water covering	▪ Cannot be applied at some mine waste sites namely: Herrgården (residential area), Järnvägsbanken (railway), Odalfältet (caving area) and at all sites in Falun except Nya Sandmagasinet. ▪ Deposits consisting of older already weathered materials may leak after this kind of abatement however. ▪ Construction costs of 0.45 SEK/m^{2}yr are derived from Sekkenjokk (Gustaffsson et al 1998), which was covered in 1992 to costs of 1.5$/m^2. However, the costs of water covering are to a great extent site depending and can exceed costs for soil covering as mentioned in an earlier investigation (Hartlén et al. 1990). ▪ Efficiency in reducing metal leakage by preventing oxygen inflow is 99 percent (Larsén, 2002, and references therein) ▪ Measure lifetime of 50 years was assumed, by this annual costs were determined using an annuity factor of 0.039

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B. Background Information and Detailed Results related to section 3 (Cost-Effective Mine Water Pollution Abatement in the Dal River Catchment)

Table B1. 'Lifetime scenario' and sub-scenarios of the 'worst case scenario' as mentioned in Section 3.2, Table 1.

Scenario	*Description*
Lifetime scenario	▪ Lifetime of constructed wetlands is reduced to 25, or 12.5 years, to be compared with assumed 50 years in the base case scenario; reduce wetland lifetime results in higher annual construction costs (same interest rate used)
Cover efficiency scenario	▪ Soil cover efficiency reduced to 85 % of initial metal leakage
Diffuse leakage scenario	▪ Estimated un-abated (present) metal leakage from known mine waste sites reduced by 5 %, and considered instead as originating from unknown diffuse sources (thus increasing source emission uncertainty, for instance, reflecting possible metal leakage from commonly unaccounted for abandoned mine voids)
No retention scenario	▪ No retention (natural attenuation) of metals takes place in river and lake sediments (i.e., all delivery factors, for instance in the cost-minimisation equation (6) are α^{i}=1)

Figure B1 presents cost-effective abatement measures and total annual costs for the 'Lifetime scenario' described in Table B1. Maximum total costs are as high as in the 'Base case scenario' and cost-effective measures for reduction of Zinc loads to the Dal River remain almost the same with increasing annual wetland construction costs. Soil covering becomes the only cost-effective measure above certain wetland cost levels.

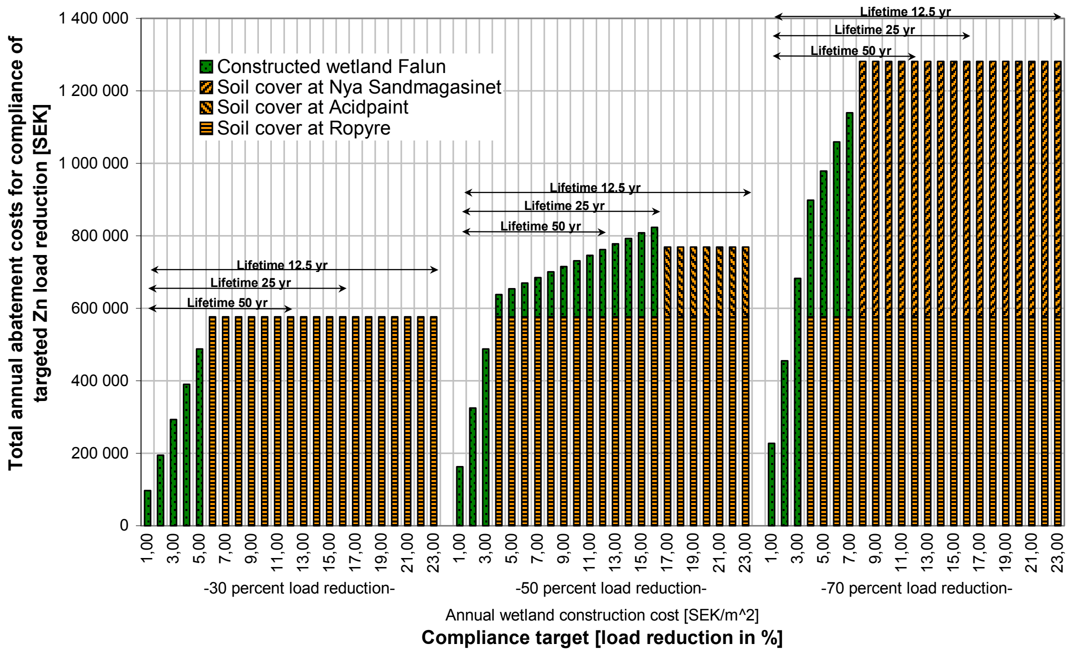
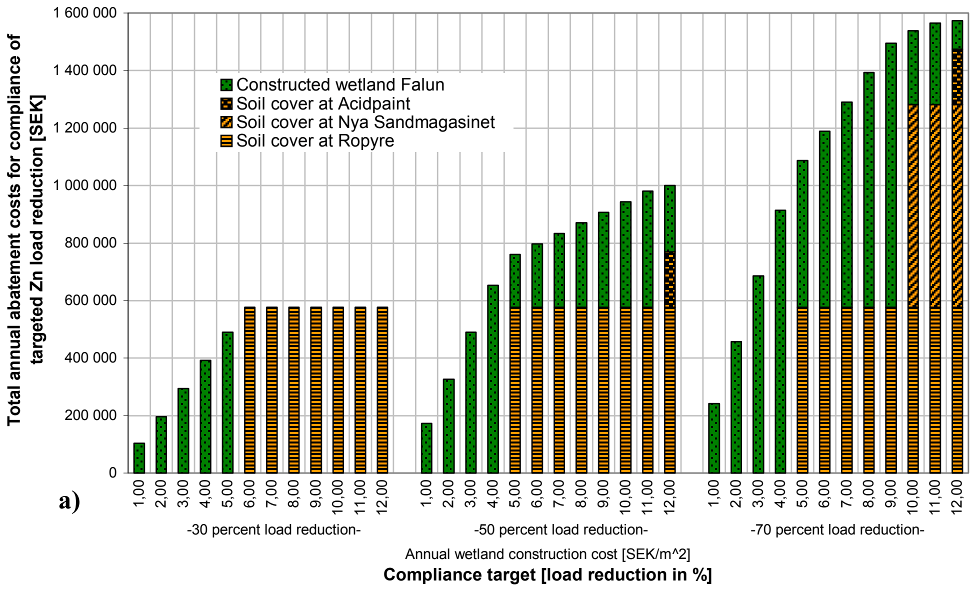
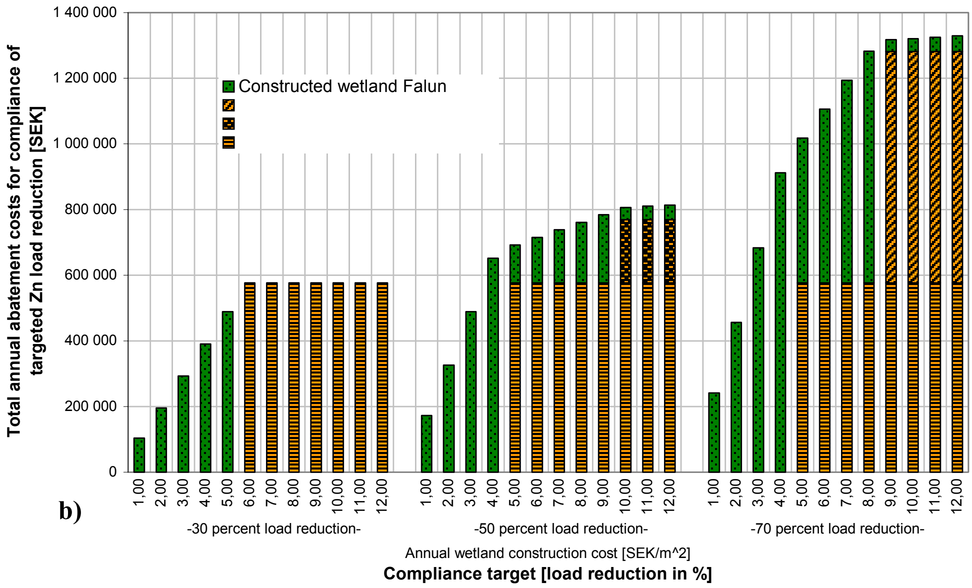


Figure B1. Cost-effective solution and associated total annual abatement costs for compliance to different targets for reduction of Zinc load to the Dal River in the 'Lifetime scenario ', according to the scenario description in Table B1.

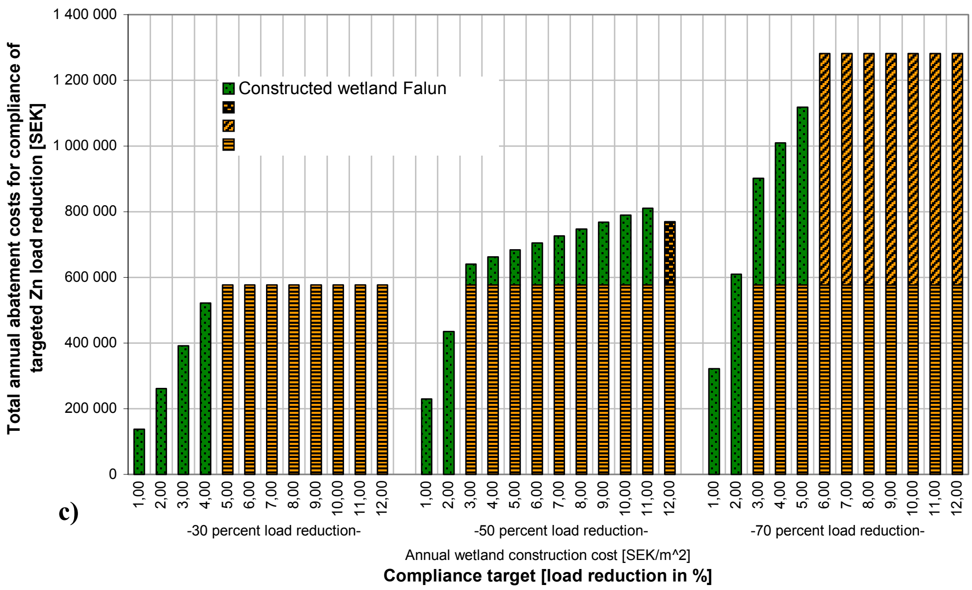
Figures B2a-c show results for the economic evaluation of the three sub-scenarios, as described in table B1, forming the 'Worst case scenario' (section 3.2, Figure 4c). Reduced soil cover efficiency in terms of initial metal leakage reduction has the most significant effect on total abatement costs; however, all three sub-scenarios cause an increase in total abatement costs for compliance of targeted load reductions of Zinc and steeper cost functions because more abatement measures are required to comply set reduction targets.



a)



b)



c)

Figure B2. Cost-effective solution and associated total annual abatement costs for compliance to different targets for reduction of Zinc load to the Dal River in a) the 'Cover efficiency scenario', b) the 'Diffuse leakage scenario', and c) the 'No retention scenario' according to the scenario description in Table B1.

As Figure B6 illustrates are marginal costs for compliance to different targets for reduction of Zinc loads increasing or, at higher annual wetland construction costs, constant. The figure shows only results for the four main scenarios, marginal costs for the three sub-scenarios are included in results for the 'Worst case scenario'

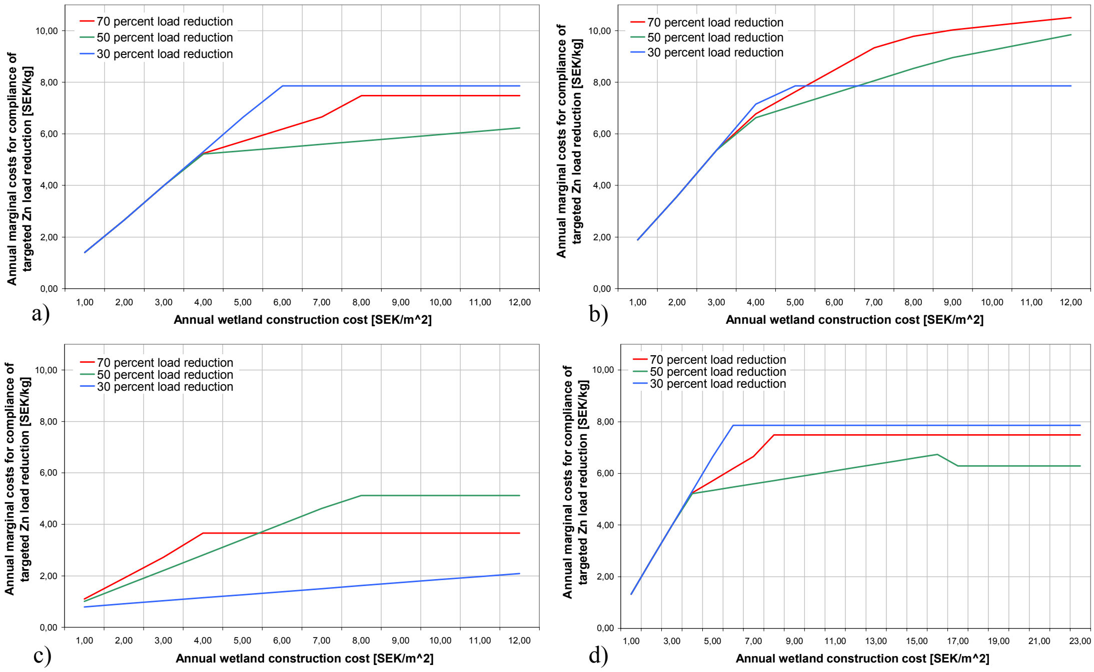


Figure B3. Annual marginal costs for compliance to different targets for reduction of Zn load to the Dal River for a) the 'Base case scenario', b) the 'Worst case scenario', c) the 'optimistic scenario' and d) the 'Variable lifetime scenario '.

Total abatement costs for compliance for load reductions of Copper and Cadmium to the Dal River are presented in Figure B4. Abatement strategies consist of constructed wetlands, only for annual wetland construction cost above 11 SEK/m^2*yr, water covers become part of the cost-efficient measure allocation solution.

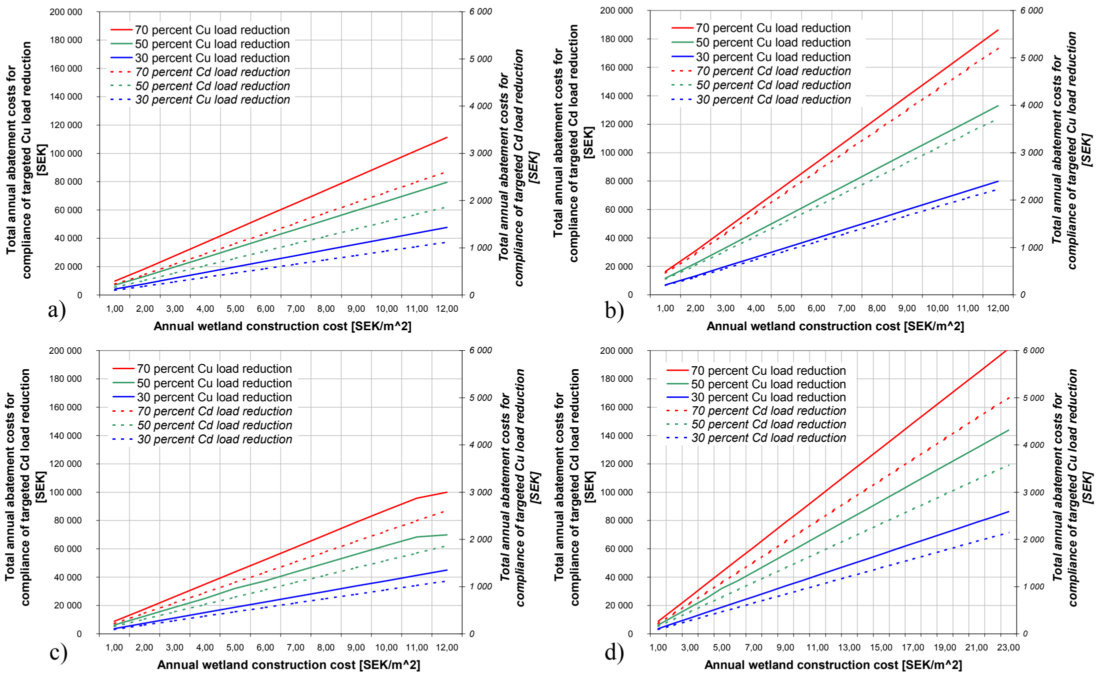


Figure B4. Total annual abatement costs for compliance to different targets for reduction of Cd and Cu loads to the Dal River for a) the 'Base case scenario', b) the 'Worst case scenario', c) the 'optimistic scenario' and d) the 'Variable lifetime scenario '.

C. A Cost Minimisation Model for Catchment-Scale Mine Water Pollution Abatement

To reduce total and marginal abatement costs to different targeted load reduction of metals, i.e. a certain amount of AMD reduction at a given recipient, information about cost functions and effects of abatement measures must be expressed in a cost minimization model as presented in section 2. Several different methods of reducing the metal leakage exist (Appendix A, Table A9 describes selected abatement measures); some, which are applied at mine waste deposits (e.g. soil and water covering) and others that are applied at some distance from leakage sources (e.g. constructed wetlands). The cost minimization problem must therefore be defined in a way that different abatement measures at different mine waste deposits and remote sites can be combined but that similar measures, as for example water and soil covers, cannot be considered in measure allocation solutions simultaneously. In addition, natural attenuation, distribution of leakage sources and various recipients within a catchment must be taken into account.

- **Basic model**

To reduce the total abatement costs, the cost of reducing the metal leakage from various mine waste deposits using different abatement measures (e.g. water and soil covering and constructed wetlands) must be compared. As a result, the basic cost minimization problem can be written as:

$$\min \sum_{A} \left(\sum_{i \in A} C_i \left(X_i \right) + C_R \left(X_R \right) \right) \qquad \textbf{(C1)}$$

where

A	set of sub-regions or sub-catchments
R	set of recipients within the investigation area
$C_i \left(X_i \right)$	cost of reducing X_i units of metal load at mine waste deposit *i* in the area *A*
$C_R \left(X_R \right)$	cost of reducing X_R units of metal load at the recipient *R*

The cost functions are increasing and convex in X_i and X_R respectively. The variable *A* is used to consider different sub-catchments; in such sub-catchments several onsite measures (measures applied at mine waste deposits) can be included but remote measures (measures applied at recipients within the sub-catchment but at some distance from leakage sources) will have an effect on metal releases from all of the area, i.e. sub-catchment outflow.

The amount of metal leakage from all mine waste deposits in a specific area *A*, L_A, can be obtained by subtracting the sum of all leakage reductions by onsite actions from the total initial leakage of metals from the mine waste deposits in the region *A*, L_{initA}:

$$L_A = L_{initA} - \sum_{i \in A} X_i \qquad \textbf{(C2)}$$

The total amount of metals that reach the recipient, L_R, is

$$L_R = \sum_{A} \left(\left(L_A + L_{OA} \right) - X_R \right) \qquad \textbf{(C3)}$$

where

L_{OA}	sum of other, known or unknown, sources of metal leakage in the region *A*

The maximum amount of metals that can be removed at the recipient is then defined by:

$$X_R \leq \sum_A \left(\left(L_{initA} + L_{OA} \right) - \sum_{i \in A} X_i \right) \tag{C4}$$

Defining a maximum load as the environmental targets ($\overline{L}$) at a certain recipient, following restriction must be satisfied:

$$\overline{L} \geq \sum_A \left(\left(L_{initA} + L_{OA} \right) - \sum_{i \in A} X_i - X_R \right) \tag{C5}$$

Using all this definitions, the objective function can be written as a Lagrangian function.

$$\begin{aligned} L = & \sum_A \sum_{i \in A} C_i \left(X_i \right) + C_R \left(X_R \right) \\ & + \lambda \left(\overline{L} - \sum_A \left(\left(L_{initA} + L_{OA} \right) - \sum_{i \in A} X_i - X_R \right) \right) \\ & + \alpha \left(\sum_A \left(\left(L_{initA} + L_{OA} \right) - \sum_{i \in A} X_i - X_R \right) \right) \end{aligned} \tag{C6}$$

subject to

$$\frac{\partial C_i}{\partial X_i} + \lambda - \alpha = 0 \qquad i \in A \tag{C7}$$

$$\frac{\partial C_R}{\partial X_R} + \lambda - \alpha = 0 \tag{C8}$$

These expressions lead to the conclusion that marginal costs of metal load reduction at the mine waste deposits are equal to marginal costs of load reduction at the recipient, assumed that used cost functions are continuous.

$$\frac{\partial C_i}{\partial X_i} = \frac{\partial C_R}{\partial X_R} \tag{C9}$$

- **Enhanced model**

Considering effects of abatement measure localization and choice of abatement measure will considerably affect the cost minimization model. While, for example, covering methods must be applied at mine waste disposal sites, remote actions as constructed wetlands can benefit from natural retentions in upstream waters. Furthermore, measure combinations might lower abatement costs significantly compared to single actions.

- **Localization of abatement measure**

Taking into account that metals are accumulated in the bottom sediments of waters, abatement measures located downstream of leakage sources have to reduce a fraction of the original metal load only. Retentions rates (or delivery coefficients α^i as defined in section 2) range between *0* and *1* but differ much among different and within single waters. However, assuming that r_A is the averaged retention rate within a specific sub-catchment, the metal load fraction reaching the outlet of this sun-catchment is $(1- r_A)$. Locating, e.g., constructed wetlands nearby the sub-catchment outlet takes maximum advantage of retention rates, while on the other hand, less total metal loads can be reduced due to retention.

The maximum amount of metals that can be abated at the recipient is then

$$X_R \leq \sum_A (1-r_A)\left((L_{initA} + L_{OA}) - \sum_{i \in A} X_i \right) \qquad \textbf{(C10)}$$

considering all abatement measures taken at the mine waste deposits.
The environmental targets ($\overline{L}$) must be satisfied and equation C5 becomes:

$$\overline{L} \geq \sum_A \left((1-r_A)\left((L_{initA} + L_{OA}) - \sum_{i \in A} X_i \right) - X_R \right) \qquad \textbf{(C11)}$$

Reformulating the objective function as a Lagrangian gives:

$$\begin{aligned} L = & \sum_A \left(\sum_{i \in A} C_i(X_i) + C_R(X_R) \right) \\ & + \lambda \left(\overline{L} - \sum_A \left((1-r_A)\left((L_{initA} + L_{OA}) - \sum_{i \in A} X_i \right) - X_R \right) \right) \\ & + \alpha \left(\sum_A \left((1-r_A)\left((L_{initA} + L_{OA}) - \sum_{i \in A} X_i \right) - X_R \right) \right) \end{aligned} \qquad \textbf{(C12)}$$

subject to

$$\frac{\partial C_i}{\partial X_i} + (1-r_A)(\lambda - \alpha) = 0 \qquad i \in A \qquad \textbf{(C13)}$$

$$\frac{\partial C_R}{\partial X_R} + \lambda - \alpha = 0 \qquad \textbf{(C14)}$$

Therefore, marginal costs of metal load reduction at the mine waste deposits are not longer equal to marginal costs of load reduction at the recipient; instead, retention factors link marginal costs. High retention rates increase relative marginal costs of onsite measures compared with e.g. constructed wetlands.

$$\frac{\partial C_i}{\partial X_i}(1-r_A)^{-1} = \frac{\partial C_R}{\partial X_R} \qquad \textbf{(C15)}$$

- **Choice of abatement measure**

The model we have so far does only include one possible abatement measure, which is certainly insufficiently. Therefore, the approach must be extended to include different abatement measures *j* at selected sites *i* (e.g. waste separation and covering) as well as different abatement measures *k* at the recipient *R* in region *A* (e.g. constructed wetlands and pump-and-treat).

Previous equations have to be extended as shown below:

$$X_R \leq \sum_A (1-r_A)\left(\left(L_{initA} + L_{OA}\right) - \sum_{j\in J}\sum_{i\in A} X_{ji} \right) \qquad \textbf{(C16)}$$

with

J set of onsite measurements

$$\overline{L} \geq \sum_A \left(\left(1-r_A\right)\left(\left(L_{initA} + L_{OA}\right) - \sum_{j\in J}\sum_{i\in A} X_{ji} \right) - \sum_{k\in K} X_{kR} \right) \qquad \textbf{(C17)}$$

with

K set of measurements at recipient *R*

With those changes, the minimization problem in Lagrangian notation is given as:

$$\begin{aligned} L = & \sum_A \left(\sum_{j\in J}\sum_{i\in A} C_{ji}\left(X_{ji}\right) + \sum_{k\in K} C_{kR}\left(X_{kR}\right) \right) \\ & + \lambda\left(\overline{L} - \sum_A \left(\left(1-r_A\right)\left(\left(L_{initA} + L_{OA}\right) - \sum_{j\in J}\sum_{i\in A} X_{ji} \right) - \sum_{k\in K} X_{kR} \right) \right) \\ & + \alpha\left(\sum_A \left(\left(1-r_A\right)\left(\left(L_{initA} + L_{OA}\right) - \sum_{j\in J}\sum_{i\in A} X_{ji} \right) - \sum_{k\in K} X_{kR} \right) \right) \end{aligned} \qquad \textbf{(C18)}$$

subject to

$$\frac{\partial C_{ji}}{\partial X_{ji}} + \left(1-r_A\right)\left(\lambda - \alpha\right) = 0 \qquad i\in A \qquad j\in J \qquad \textbf{(C19)}$$

$$\frac{\partial C_{kR}}{\partial X_{kR}} + \lambda - \alpha = 0 \qquad \textbf{(C20)}$$