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Implications for forestry of stream water chemical demands – an introductory study

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Foreword

This report is the result of a project partly financed by the Kempe Foundations. Issues relating forest management and water quality have received increased attention, not the least because of the EU water directive. The quantitative results presented here should be interpreted with great care as there are big uncertainties regarding the consequences of forest management on water quality. This study serves as a first assessment of the possible weight these issues may have on the background of available knowledge.

We would like to thank Jakob Schelker to supply material from the Balån watershed and Anu Hankala for preparations of the maps.

Umeå, February 2010.

Content

Background

Forestry influences the water quality in streams and lakes. Hydrological, biological and chemical processes are influenced by activities such as harvesting and fertilization. These ordinary forest operations tend to affect the water quality negatively compared with the status of non-managed forests. However, the extent of these effects are related to the share of the catchment affected by the forestry operations and how they are performed (Ring et al. 2009) According to the EU water framework directive (WFD, 2000/60/EC), the water quality in pristine areas, unaffected by human activities, should act as reference for determining the surface water status. The vision is to achieve good ecological and chemical status of lakes and streams in Europe by 2015. Thus, it is likely that the WFD will have consequences for how forestry can and should be conducted on stand lever as well as on catchment level.

The implementation of the WFD is in Sweden led by five water authorities. It is their responsibility to propose management plans to enhance water quality, where needed. This also includes the effects caused by forestry. As part of the work of evaluating the status of waters the Swedish Environmental Protection Agency (SEPA) has developed a classification system, which includes biological, chemical and hydro-morphological variables (SEPA 2007, 2008). It can thus be assumed that the way forestry affects the value on these parameters is central to an understanding of how forestry needs to adapt in order to fulfill the stipulations commanded by the water directive as interpreted by the water authority.

Guidelines for mitigation the negative effects of forest operations on water quality have been issued (Swedish Forest Agency 2000, Swedish Forest Stewardship Council 1998). However, how severe the limitations on forestry will be in order to maintain or achieve a certain water quality is rarely studied under Swedish conditions. There are indications, however, that the SEPA classification system will classify the ecological status in many Swedish forest streams less than good (Löfgren et al. 2009a). Neither has the question of how forestry could adapt optimally to water quality requirements been inspected; it is not obvious that rules of thumb, like that not more than 30% of the area of a watershed should be harvested, are neither optimal nor sufficient. One of few studies under boreal conditions was conducted by Öhman et al. (2009), showing that in order for the concentration of dissolved organic carbon (DOC) to be below a 10% increase above the reference value the economic loss could be in the range of 5-30% depending on assumed values for the cause and effect relationships.

A more comprehensive grip of the relation between water quality and forestry than Öhman et al. (2009) will be taken here by allowing several parameters to be simultaneously affected by forest operations. However, limitations in data on the initial status of the water and knowledge of the response function of forestry effects on water quality preclude some quality variables to be analyzed. Biological status is inherently difficult to assess, not the least because the initial organism status is unknown. Hydro-morphological variables are less related to present forestry (see below). The parameters that will be analyzed in this report all have to do with the chemical status of the water. Given the study area, it is possible to estimate the initial chemical status and also to make a reasonable quantification of the response of these values to forest activities.

The focus is here on forestry as a large scale and long-term activity, i.e. the perspective is strategic. This means that some aspects on how water quality is influenced by forestry will not be covered as they are of a more operational nature, such as how the harvesting operation is planned in the stand as regards water crossings. These aspects, important as they may be (Ring et al. 2009), are assumed to be accounted for in consistency with the values assigned by the water quality models used in this study. The strategic perspective on forestry also makes hydro-morphological parameters less at focus as they relate more to measures directed towards improving the water quality as such rather than being a normal forest operation (restoration of rafting channels as an example). Exceptions to this exist, like the prevalence of large woody debris in streams.

The purpose of this study is to assess, in a strategic setting, the implications for forestry of limiting the concentrations of some chemical substances below certain values. The planning horizon will be 100 years divided into 5-years periods. The water quality variables are related to nitrogen (N), phosphorus (P), methylmercury (MeHg) and dissolved organic carbon (DOC). The results of the study pertain to financial values, forest management activities and concentrations of the aforementioned substances. The analysis is conducted on three sub-catchment areas of Balån in the county of Västerbotten (Löfgren et al. 2009b). These areas have for several years been subject to extensive studies and have delivered data difficult to find elsewhere. Since water quality, like most ecological phenomena, is dependent on spatial scale, two different geographical scales are defined; one on sub-catchment level and one where the three sub-catchments are considered as a unit.

Material and methods

Study area

The Balån study area is situated about 60 km from the coast in the county of Västerbotten. The area was chosen since it has been supervised since 2004 and much of the needed data is available from the area (see articles in Ambio Vol. 38, No. 7, Nov. 2009). The area is distributed on three sub-catchments – I, II and III – consisting of a total of 66 stands (Fig. 1). Areas I and II contain stands that on average are considerably older than area III whereas all together they have a fairly even age distribution (Fig. 2). Dominated by pine (*Pinus sylvestris*) and spruce (*Picea abies*) the area also contains limited amounts of other species, mostly birch (*Betula* spp.) (Tab. 1). The forest data for the area was estimated by the k nearest neighbor method (*k*NN) (Reese et al. 2003) with stands delineated with the algorithm developed by Hagner (1990). (Note: The description of the area given by Löfgren et al. (2009b) is based on other forest data, implying that they do not completely agree. This refers, for instance, to the site index, which is on average lower in this data, and the area of sub-catchment III, which is smaller here.)

Tab. 1. Forest data for the three sub-watersheds

Sub-catch	Area (ha)	Volume (m3 ha^{-1})	Spruce (%)	Pine (%)	Other (%)	SI (H100 m)
I	37	163	50	40	9	17.4
II	45	158	38	53	9	16.9
III	156	74	41	36	24	18.6
Sum	238	104	42	42	16	18.0

Fig 1. The three sub-watersheds – I, II and III – in the Balån watershed.

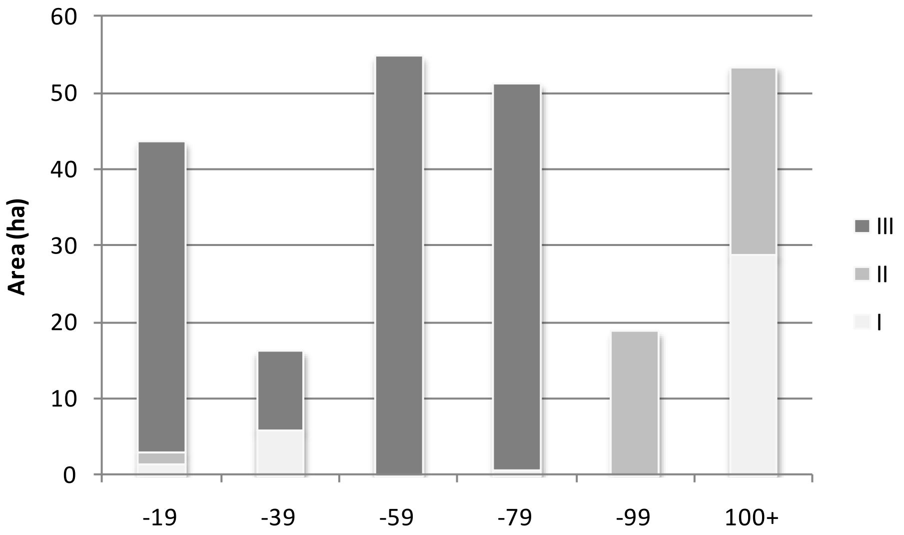


Fig 2. The age structure of the three sub-watersheds.

Water quality indicators

Long-term forest management planning under boreal conditions refers to decades and centuries. In order to simulate the forest dynamics, and its reaction to different forest operations, it is customary to use growth and yield functions with time steps of several years. Swedish growth functions typically operate with a time step of 5 years. Thus, the description of the effects on water quality needs to be given as averages for 5-years periods. It is here assumed that the consequences of a forest activity last in at most two 5-years periods, i.e. 10 years.

In describing the consequences of forest operations on the concentration of a substance dissolved in water one option is to predict the concentration directly. Another option is to predict the transport of the substance and water, respectively, and combine the two by dividing the substance flux with run off. The latter procedure has been followed here as the data in most cases is given in the annual substance losses per hectare.

Tab. 2. Annual unit area transport for undisturbed conditions (base level), at the first 5-years period after the forestry operation (1st period) and 6-10 years after the forestry operation (2nd period) and concentrations under undisturbed conditions

	W (clear-felling) L m^{-2} y^{-1}	N (clear-felling) kg ha^{-1} y^{-1}	N (N-fertilization) kg ha^{-1} y^{-1}	P (clear-felling) kg ha^{-1} y^{-1}	MeHg (clear-felling and thinning) mg ha^{-1} y^{-1}	DOC (clear-felling) kg ha^{-1} y^{-1}
Base level	400	1.5	0	0.060	0.3	50
1st period	560	3.0	1.5	0.096	0.9[a]	87
2nd period	500	3.0	0	0.060	0.9[a]	72
Base level concentrations		mg L^{-1}	-	µg L^{-1}	ng L^{-1}	mg L^{-1}
		0.375	-	15.0	0.075	12.5

Tab. 2 summarizes the average effect per year of different forest operations on different substances as well as the base level in non-managed forests. The motivation for the figures is given below. It can be noted that the increased flux in all cases except fertilization is due to the final felling of one hectare. In the case of methylmercury the effect also follows from thinning one hectare. In the case of fertilization the effect is from fertilizing one hectare.

Water flow (W): The base level is set to 400 mm y^{-1} following data from Balån presented by Löfgren et al. (2009b; Table 3). The increase from final felling is estimated with the model presented by Öhman et al. (2009; Table 1, Case 1a), resulting in an increase in the first 5-years period of 40% and in the second 5-years period of 25% over the base level.

Nitrogen (N) and clear-felling: The data given by Löfgren and Olsson (1990) indicate an increase from about 1.5 to 3.0 kg N ha^{-1} y^{-1} on average for an entire period of 10 years for the Bottnia Bay region. These figures describe the total transport, i.e. they include increased concentration as well as increased runoff thus motivating the procedure stated above of separating the two effects in the calculations.

Nitrogen (N) and N-fertilization: It is assumed that 5% of the nitrogen in the fertilizer is emitted to streams; resulting in 1% y^{-1} the 5-years period the fertilizer is applied (Löfgren 2007). Fertilization is here done with a standard dosage of 150 N ha^{-1}.

Phosphorus (P): The response is based on the data in Löfgren and Olsson (1990). The base level is set to 0.06 kg ha^{-1} y^{-1}. It is assumed that the export doubles during 3 years following final felling, resulting in an average export of 0.096 kg ha^{-1} y^{-1}during the first 5-years period [(0.06·2.0*3+0.06·2)/5].

Methylmercury (MeHg): The base level is set to 0.3 mg ha^{-1} y^{-1} following data from Balån presented by Sørensen et al. (2009; Table 2). The increase in total export is assumed to follow from both final felling and thinning, to be 3 times larger than that from an undisturbed, growing forest, and to persist for 10 years, which is in consistency with the assumptions given by Bishop et al. (2009).

Dissolved Organic Carbon (DOC): The base level of 50 kg ha^{-1} y^{-1} was set based on data from Balån presented by Laudon et al. (2009). The increase from final felling is estimated with the model presented by Öhman et al. (2009; Table 1, Case 1a), resulting in an increase in the first 5-years period of 24% and in the second 5-years period of 15% over the base level. Adding the effect of increased water flow according to the model presented above it will be 87 and 72 kg ha^{-1} y^{-1} for period 1 and 2, respectively [1.24·1.40·50, 1.15·1.25·50].

Forest management problem and data

The management problem consists of maximizing the economic interests of the forest owner while at the same time satisfying requirements of low concentrations of substances in the water. The economic objective to be maximized is here stated as the net present value (NPV) of all timber revenues net of harvesting and silvicultural costs over the 100 year planning horizon. The constraint on concentration in run-off is expressed as a level set for all periods and each substance in each sub-catchment I-III (case WsSep) or aggregated for the sum of the three sub-catchments (case WsAll). That means that for a certain acceptable relative increase of the concentration over the base level, for instance 25%, this increase should be obeyed in each period for each substance. This requirement is applied either on sub-catchment level or for the whole area as one unit, depending on what analysis is conducted.

The increase in concentration of a substance in a specific 5-year period is, as explained above, a function of the area of final felling – and thinning and fertilization for some substances – in that or the previous period. Thus, the treatment schedule that is chosen for each stand of the area will determine the concentrations. This will of course also determine the economic outcome. With a treatment schedule is here meant a sequence of harvesting and silvicultural treatments over the entire planning horizon for a particular stand. The combination of such schedules for the stands constitutes a solution to the forest management problem.

Since we do not know what treatment schedule is optimal for each stand we will supply each stand with a large set of schedules to choose from. The schedules will differ in terms of, for instance, the timing of thinning and final harvest. Optimal schedules, constituting the optimal solution, are established by solving the mathematical problem that is specified in the next section.

Treatment schedules were simulated using the GAYA stand simulation system (Eriksson 1983, Hoen and Eid 1990). Standard treatments included stand establishment, precommercial thinning of young forest, thinning, fertilization, and final felling. The minimum age for final felling for each stand was set according to the forestry act of Sweden regarding corresponding site productivity (SNBF 1994). Thinning treatments had an intensity of 30 percent removal of the basal area. Fertilization carried a dosage of 150 kg of nitrogen ha^{-1}.

The GAYA simulator used growth functions by Ekö (1985). Revenues were computed with functions from Ollas (1980) and with timber prices according to the forest owner organization Norra skogsägarna for region Umeå valid from August 2007. The quality distribution of logs of pine and spruce is weighted with data from SOU (2007). Harvesting costs was computed based on functions by Nurminen et al. (2006) with the cost per hour set to 750 and 650 SEK for harvester and forwarder, respectively. Fertilization cost was set to 2,300 SEK ha^{-1}. Cost of silvicultural activities were taken from SOU (2009) for the year 2007 average figure amounting to 7,600 SKE ha^{-1} for site preparation and planting and 2,300 SEK ha^{-1} for precommercial thinning. The discount rate was set to a real rate of 3% y^{-1}.

All permissible programs within given specifications were generated for each stand, resulting in 31,038 schedules, corresponding to an average of 470 schedules per stand.

Mathematical model

The management problem described above was formulated as a linear programming (LP) model. An optimal solution to the problem, i.e. a solution that maximizes the NPV and satisfies the requirements on concentrations, is a combination of treatment schedules (as outlined above) for each and every stand in the watersheds. This combination determines the output values over time for the entire area. In order to control the state of the forest after 100 years it is also required that the average stocking should be 100 m^3 ha^{-1} (this is slightly lower than at present, cf. Tab. 1, but is motivated by the fact that non-established forest carries no volume in the model). The model formulation is known as a Model I formulation (Johnson and Scheurman 1977). In technical terms, a solution consists of an allocation of a treatment schedule j, $j \in \{1,..., J_i\}$, to each stand i, $i \in \{1,..., I\}$.

There are T periods and $t \in \{1,...,T\}$. Associated with each treatment schedule j for each stand i is the NPV, R_{ij}, an indicator C_{ijt} set to 1 if the stand is clear felled in period t, where otherwise 0, an indicator T_{ijt} set to 1 if the stand is thinned in period t, otherwise 0, an indicator F_{ijt} set to 1 if the stand is fertilized in period t, otherwise 0, and finally the volume V_{ij} ha^{-1} after harvest in the last period. D_{ij}, is here the sum over period 1 to T of discounted revenues at road side and costs for harvesting. Each stand belongs to one of three sets, $S(r)$, $s \in \{1,2,3\}$ corresponding to the sub-watersheds. Given that the decision variable x_{ij} signifies the number of hectares that treatment schedule j of stand i is allocated to, the area of final harvest, thinning and fertilization in period t in sub-watershed r – c_{tr}, t_{tr}, and f_{tr}, respectively – are given by

$$\sum_{i \in S(r)} \sum_{j=1}^{J_i} C_{ijt} \cdot x_{ij} = c_{tr} \qquad t = 1...,T;\ r = 1,...3 \qquad (1)$$

$$\sum_{i \in S(r)} \sum_{j=1}^{J_i} T_{ijt} \cdot x_{ij} = t_{tr} \qquad t = 1...,T;\ r = 1,...3 \qquad (2)$$

$$\sum_{i \in S(r)} \sum_{j=1}^{J_i} F_{ijt} \cdot x_{ij} = f_{tr} \qquad t = 1...,T;\ r = 1,...3 \qquad (3)$$

That means that the transport in period t in sub-watershed r of water, w_{tr}, N, n_{tr}, P, p_{tr}, MeHg, m_{tr}, and DOC, d_{tr}, is given by

$$w_{tr} = (FW^0 - FW^B) \cdot c_{tr} + (FW^1 - FW^B) \cdot c_{(t-1)r} + BW_r$$

$$t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (4)$$

$$n_{tr} = (FN^0 - FN^B) \cdot c_{tr} + (FN^1 - FN^B) \cdot c_{(t-1)r} + FE \cdot f_{tr} + BN_r$$

$$t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (5)$$

$$p_{tr} = (FP^0 - FP^B) \cdot c_{tr} + (FP^1 - FP^B) \cdot c_{(t-1)r} + BP_r$$

$$t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (6)$$

$$m_{tr} = (FM^0 - FM^B) \cdot c_{tr} + (FM^1 - FM^B) \cdot c_{(t-1)r} +$$
$$(FM^0 - FM^B) \cdot t_{tr} + (FM^1 - FM^B) \cdot t_{(t-1)r} + BM_r$$

$$t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (7)$$

$$d_{tr} = (FD^0 - FD^B) \cdot c_{tr} + (FD^1 - FD^B) \cdot c_{(t-1)r} + BD_r$$

$$t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (8)$$

where FX^0 , FX^1 , and FX^B is the flux ha^{-1} at the period of the forest management activity, one period after the activity and the base level transport, respectively, for substance X. Thus, Eq. (4)-(8) computes the total flux from the sub-watershed by adding the increased transport of forest management activities to the total flux under undisturbed conditions, BX_r,. The constraint on concentration is then formulated for N, P, MeHG, and DOC as

$$n_{tr} / w_{tr} \le (1+\delta) \cdot BN_{tr} / BW_{tr} \qquad t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (9)$$

$$p_{tr} / w_{tr} \le (1+\delta) \cdot BP_{tr} / BW_{tr} \qquad t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (10)$$

$$m_{tr} / w_{tr} \le (1+\delta) \cdot BM_{tr} / BW_{tr} \qquad t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (11)$$

$$d_{tr} / w_{tr} \le (1+\delta) \cdot BD_{tr} / BW_{tr} \qquad t = 1\ldots,T;\ r = 1,\ldots 3 \qquad (12)$$

where δ is the allowed relative increase in concentration. (A slight transformation of Eq. (9)-(12) will yield a linear relation.) The given formulation is for the case where the requirement is for each region. When the concentration levels should only be respect the for the whole area the transports of substances are simply summarized over the sub-watersheds.

Finally, we will also require that ending volume from the whole watershed is high enough, i.e.

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} V_{ij} x_{ij} \geq 100 \cdot A \tag{13}$$

where A is the total forest area; that programs are allocated to the whole area of each stand, i.e.

$$\sum_{j=1}^{J_i} x_{ij} = A_i \qquad i = 1\ldots, I \tag{14}$$

where A_i is the area of stand i; that the NPV is maximized, i.e.

$$\text{Max} \quad Z_1 = \sum_{i=1}^{I}\sum_{j=1}^{J_i} R_{ij} x_{ij} \tag{15}$$

and that the x-variables are non-negative, i.e.

$$x_{ij} \geq 0 \qquad i = 1\ldots, I,\ j = 1\ldots, J_i \tag{16}$$

Results

The model was run with different values for δ, i.e. the maximum allowed increase in concentration for any substance above the reference level in any period. The requirement was either applied for each sub-watershed, here denoted as case WsSep, or to the entire area, here denoted as case WsAll. The value of δ was reduced in steps by starting with an allowed increase of 100% and then reducing it to 50%, 25%, 12.5%, 6.25%, 3.125% and 0%. The solutions for δ equal to 100%, 12.5% and 6.25% will here be analyzed more closely.

Economic implications

Fig. 3 shows that the economic loss increases rapidly with stricter concentration limitations and if very small concentration increases are allowed, below around 15% of the normal level, the economic effects are tangible. With restriction levels of 10% and 6% for WsSep or WsAll, respectively, less than half the economic value of the forest remains. The loss for case WsSep is greater than for case WsAll, as expected, but the difference in economic loss never exceeds 20%.

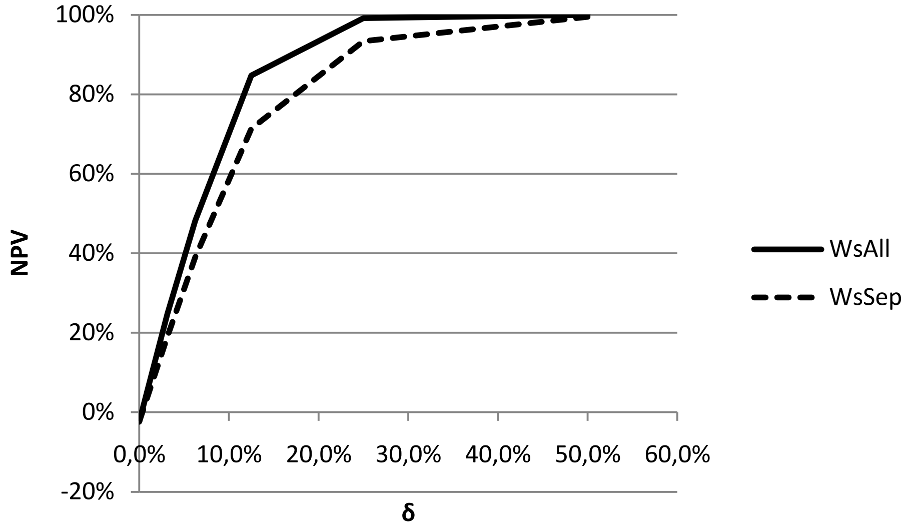


Fig. 3. The NPV relative to its maximum value for different maximum allowed relative concentration levels (δ) and cases WsAll and WsSep.

Concentrations

With δ equal to 100% there is in reality no limitation on concentrations and cases WsSep and WsAll give equal solutions. The concentrations of MeHg increase considerably in all watersheds with δ equal to 100% (Tab. 3). The other substances in order of decreasing level of excess concentrations are N, DOC and P. Since the relative levels of N, DOC and P generally, and not surprisingly, are lower than for MeHg the presentation below will focus on this substance. It is also obvious that MeHg is the limiting factor in all analyses where the concentrations are constrained. Reference will also be made to N as it in certain cases also reaches fairly high levels above the reference. Fig. 4 shows the relative increase over time for MeHg and N in the case of no restrictions (period 20 excluded as it exhibit "end of the planning horizon" characteristics).

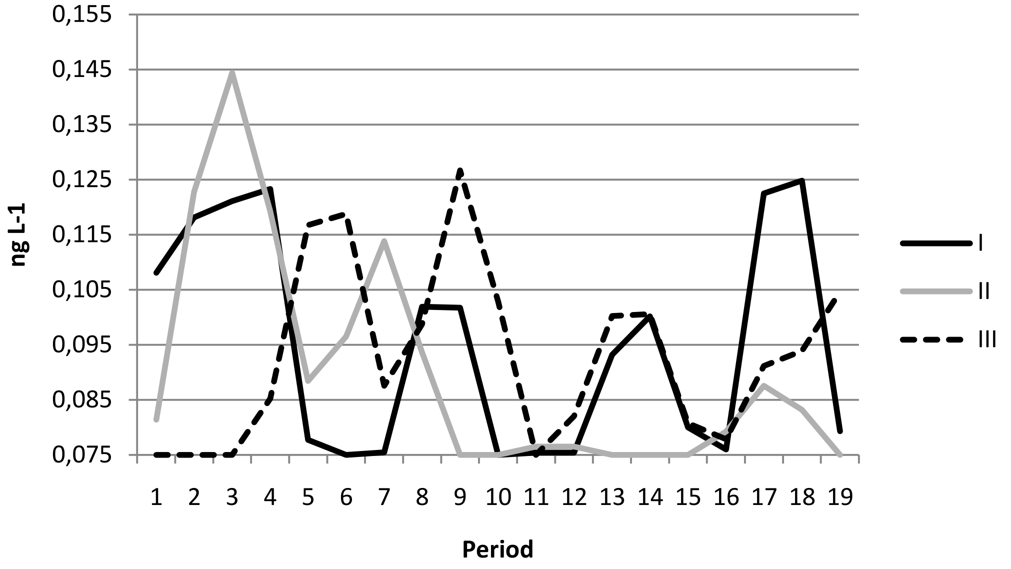
In case WsSep, the simulations indicate that the MeHg concentrations are not only at the maximum values 12.5% and 6.25%, respectively, for all the three sub-catchments but they are also at the maximum value for all periods except the first one. In case WsAll the concentration of MeHg is at its maximum value for all periods except the first one. The reason for this exception is probably that you have a lagged effect, i.e. you have the same increase in flux from harvesting in the second period as in the first, meaning that maximum concentrations the first period would preclude any harvests in period 2. However, the first period concentration is only about 5% below the maximum value in all cases.

As indicated in Tab. 3 case WsAll, in contrast to case WsSep, will cause concentrations in certain sub-catchments to be above the maximum value for the entire area for MeHg. Also N concentrations could reach fairly high relative values. This applies even though the whole area requirement is 6.25% (Fig. 5).

Tab. 3. Concentrations of substances above the base level (%) for the cases WsSep and WsAll under different maximum allowed relative concentration levels (δ)

			Sub-watershed			
Substance	Case	δ	I-III	I	II	III
N		100%	18.5%	35.4%	41.8%	24.9%
	WsSep	12.5%	8.3%	5.4%	5.4%	10.1%
		6.25%	4.1%	2.7%	2.7%	5.0%
	WsAll	12.5%	9.9%	23.6%	28.5%	8.4%
		6.25%	2.7%	15.6%	13.0%	4.1%
P		100%	0.8%	2.2%	1.1%	1.0%
	WsSep	12.5%	1.6%	1.6%	1.6%	1.6%
		6.25%	0.8%	0.8%	0.8%	0.8%
	WsAll	12.5%	1.6%	3.4%	2.4%	1.8%
		6.25%	0.8%	2.2%	1.1%	1.0%
MeHg		100%	80.0%	100.0%	100.0%	68.9%
	WsSep	12.5%	12.5%	12.5%	12.5%	12.5%
		6.25%	6.3%	6.3%	6.3%	6.3%
	WsAll	12.5%	12.5%	58.7%	58.5%	18.9%
		6.25%	6.3%	37.7%	31.6%	9.5%
DOC		100%	6.0%	12.2%	11.3%	6.1%
	WsSep	12.5%	2.7%	2.7%	2.7%	2.7%
		6.25%	1.3%	1.3%	1.3%	1.3%
	WsAll	12.5%	2.7%	9.4%	9.8%	3.6%
		6.25%	1.3%	6.3%	5.4%	1.9%

(a)



(b)

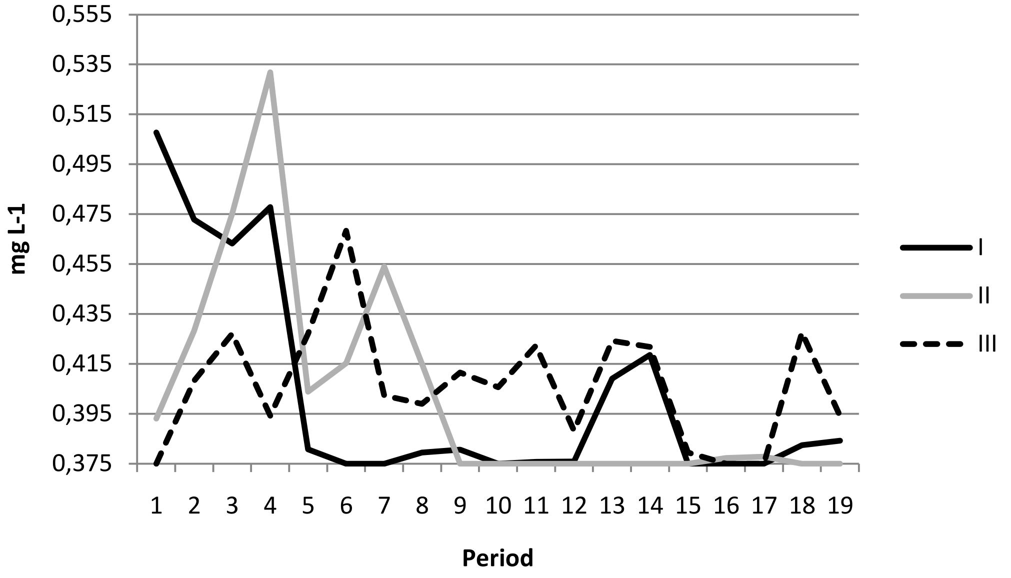
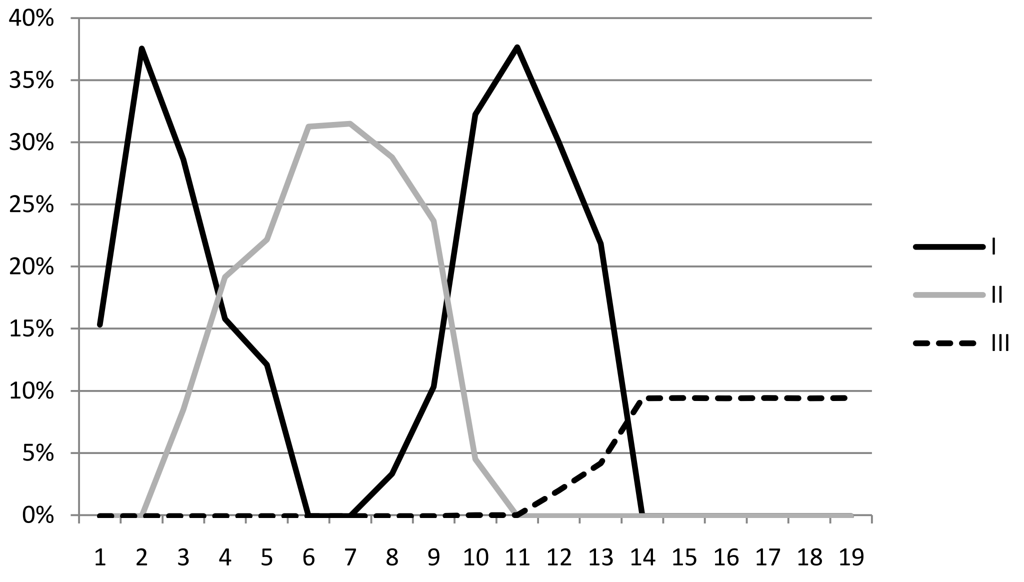


Fig 4. (a) MeHg concentrations and (b) N concentrations over time for the three sub-catchment areas with no constraint on relative concentrations. In both cases the y-axis minimum corresponds to the base level concentration.

(a)



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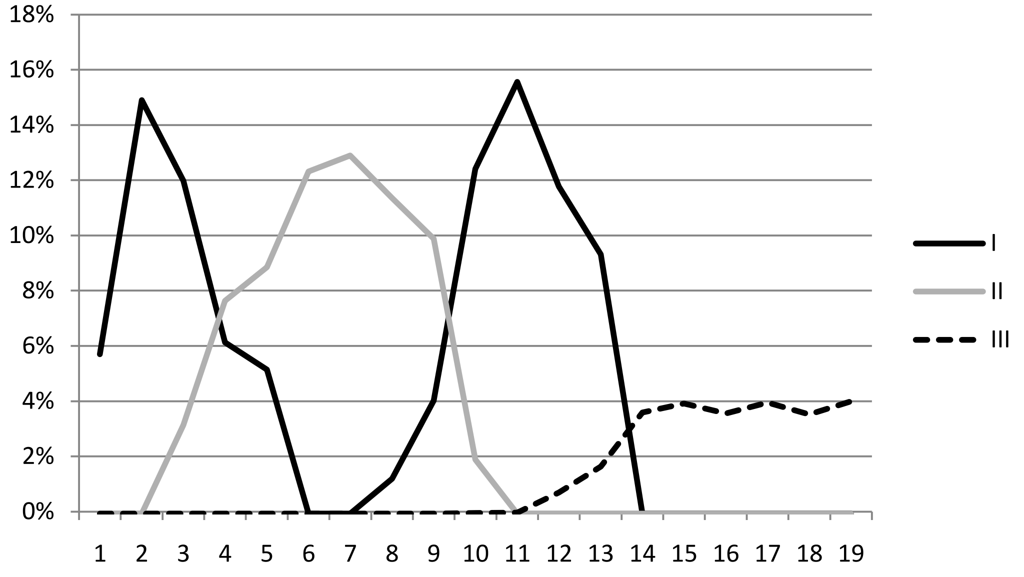

Fig 5. Relative increase above reference level concentrations for (a) MeHg and (b) N over time for the three sub-catchments when the maximum allowed relative concentration above the base level is set to 6.25% for the whole area (case WsAll).

Forest management

The comparatively low site index of the area is reflected in the average activity of the 100% solution. Final felling has a rotation of about 100 years and thinning is not made more than once over a rotation (cf. 2.1 ha of final felling with 1.3 ha of thinning y^{-1}; Tab. 4). The activity drops as a result of stricter concentration level demands. Fertilization decreases even more than final felling although it is only related to N concentrations, which is not limiting. It may have to do with the linkage to decreased harvest activities due the age structure. Thinning is reduced even further and it is almost absent already at the 12.5% level.

Tab. 4. The extent of forest operations (ha) for the cases WsSep and WsAll under different maximum allowed relative concentration levels (δ)

			Operation	
Case	δ	Final felling	Fertilization	Thinning
	100%	2.1	1.3	1.3
WsSep	12.5%	1.7	0.5	0.1
	6.25%	0.8	0.2	0.0
WsAll	12.5%	1.8	0.4	0.0
	6.25%	0.9	0.0	0.0

Fig. 6 shows for one case (WsAll) how thinning are phased out and fertilization is reduced at the end of the horizon. Final felling activity attains a cyclical nature.

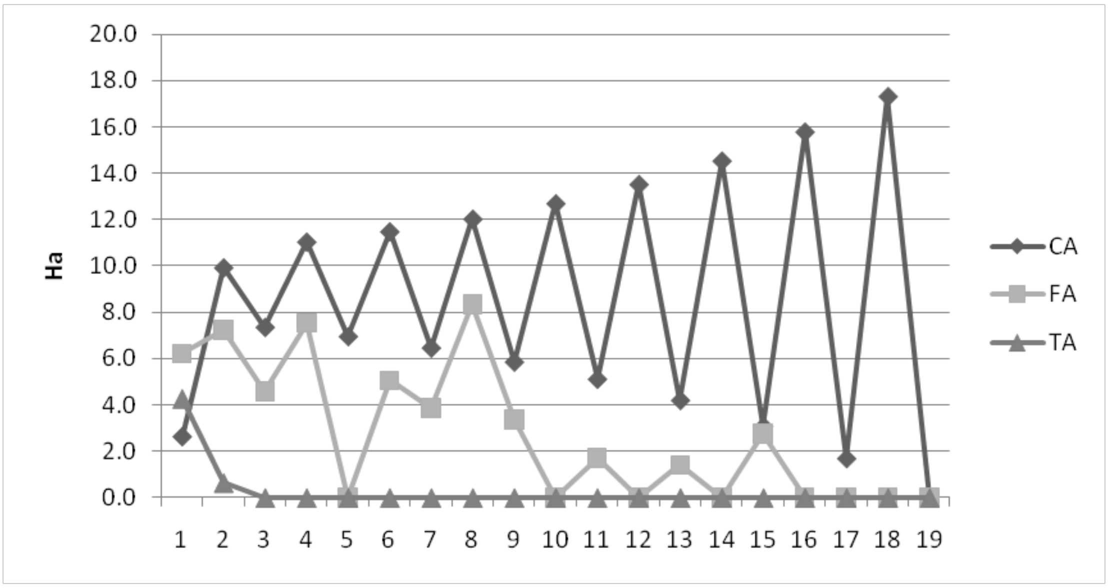

Fig 6. The area of final felling (CA), fertilization (FA), and thinning (TA) over time for the whole area when the maximum allowed relative concentration above the base level is set to 12.5% for each sub-catchment (case WsSep).

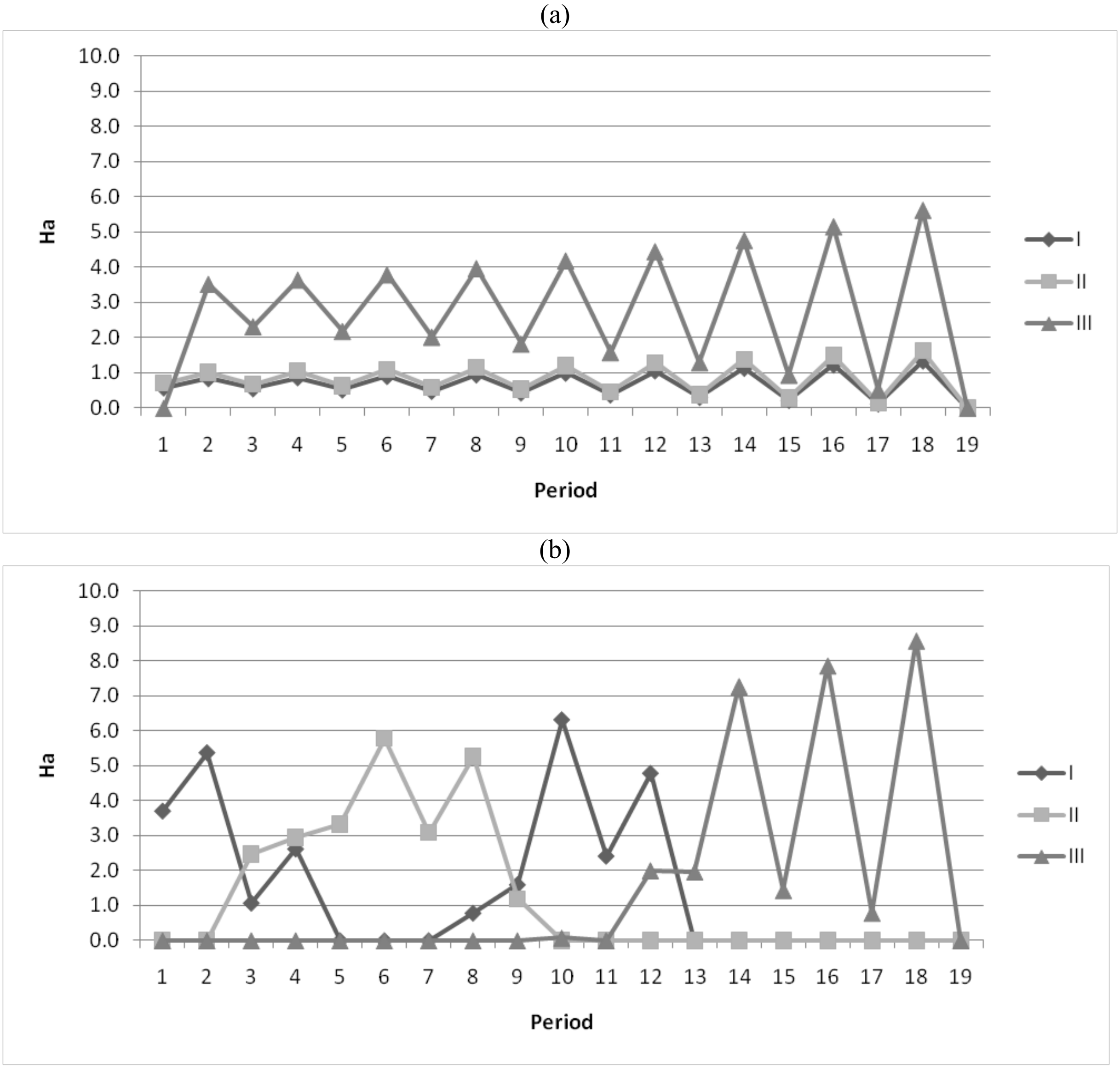

Fig 7. The final felling area over time when the maximum allowed relative concentration above the base level is set to 6.25% for (a) each sub-catchment (case WsSep) and (b) for the whole area (case WsAll).

The drop in final felling area roughly agrees with the drop in economic value for case WsAll; about 20% loss for 12.5% and 60% for the 6.25% case. The greater loss in case WsSep is evidently due to the fact that final harvests can be allocated in time in a more profitable way in WsAll than in WsSep; Fig. 7 show markedly different patterns of harvest area allocation in this respect.

Discussion

The results indicate that the requirements to enhance water quality stipulated by the EU water framework directive goals may influence forest management, both on how the forest is managed and the economic consequences. The results agree on a general level with Öhman et al. (2009) in that water quality issues may have a noteworthy affect on the economic outcome of forestry. The consequences on forest management are here a reduction of final felling. Thinning disappears as a management activity after a couple of periods, or 10 years. Fertilization is also reduced, although this activity is not constrained; fertilization only affects nitrogen and does never approach the set values. The explanation may be that as thinning stops the diameter development of the stands to be harvested in final felling they have too poor a diameter to make fertilization profitable.

The results also confirm that there is a scale effect. This is to be expected for a case like this, where the age structure is very different in the sub-watersheds and there is much to gain from allocating the forest operations differently over time. However, in case it is motivated to set criteria for water quality for small sub-watersheds, this will not be an uncommon situation. The results thus indicates that it is important to identify the critical points in the stream system and then formulate restrictions on concentrations on those target points, a procedure suggested by Öhman et al. (2009).

The results are highly dependent on the assumptions of how the export of MeHg responds to forest management. Firstly, harvesting increases transport 3 times, as compared with, for instance, N that only increases 2 times, secondly, the effect remains for two 5-year periods, and thirdly, it is also inflicted by thinning. This explains not only the fact that methylmercury is generally the limiting substance, but also the cyclical pattern in harvests and the elimination of thinning as a forest operation. One could especially note that thinning does not increase water flow, only transport, thus contributing even more than final felling to the concentration.

MeHg concentrations with the given assumptions are 2 to 6 times lower than measured in Balån (Sörensen et al. 2009). However, as constraints are formulated as relative concentrations this does not affect the results. It could, though, be of importance if consideration is given to the absolute value of different concentration levels, for instance in terms of thresholds. It should also be noted that the concentration levels are low compared with what has been found in 109 randomly selected headwater forest streams in the river Dalälven catchment. The quartile distance in that sub-population was 0.16-0.49 ng L^{-1} (Löfgren, unpublished data).

For all those reasons it would be valuable to further elaborate and to make sensitivity analyses on the assumptions concerning MeHg.

Some of the data used for assumptions on forestry effects on nitrogen and phosphorus refers back to the early 1990’s. Since then water quality has been identified as a vital issue and recommendations concerning proper harvesting operations have been issued. It is thus possible that on average the export of these two substances are overestimated.

In the management model used here it is implicitly assumed that all forest operations take place in the beginning of the 5-year period. If instead it is assumed to take place evenly over the entire period the effects would be distributed over a slightly longer period, which in turn may make it slightly easier to avoid peaks of concentration. Still, it is unlikely that this would have any greater influence on the results.

All substances have here been assumed to have the same value and the same threshold have been set for all. It would be interesting to have expert judgment of the severity of the concentrations of each substance expressed as value functions and also to weight the different substances against each other. This means that the problem is dealt with as a multiple criteria problem. This is not without reason as there are so many uncertainties and subjective judgments that have to be made also in cases where the scientific data is insufficient.

The selected concentration restrictions in this study are not connected to the Swedish surface water classification system (SEPA 2007), but are used as examples on the principle of using concentration restrictions as supplementary input variable to forest management. In fact and with the exception of DOC, the assumed concentration restrictions of 12.5% and 6.25%, respectively, are low compared to the normal variation of these substances in pristine forests. Based on the annual mean concentrations from 1996-2008 at the three non-managed integrated monitoring sites Aneboda, Kindla and Gammtratten, the coefficient of variation (CV) varies between 16-35%, 31-38%, 9-12% and 17-37% for nitrogen, phosphorus, DOC and Hg (note not Me-Hg), respectively (Löfgren unpublished data). Hence, it seems unlikely that the water authorities would use the simulated concentration increases in order to put restrictions on the forest management in the studied sub-catchments.

The main conclusion from this study is that forestry indeed can be affected as a consequence of the EU water directive if the forestry effects on water quality are large enough. The more quantitative results must, however, be interpreted with the utmost caution. This is just a first attempt at analyzing the many different dimensions of water quality that are affected by forest management and great uncertainties still remain as to the cause-effect relationships. We also need to bring in other dimensions than those treated here, like sedimentation and fish biology. One should also not forget that the final result not the least hinges on how well the harvests are planned and carried out in the field.

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