Cost benefit analysis of measures to reduce industrial effluent discharges

Åsa Sivard, Tomas Ericsson, Nippe Hylander, Magnus Karlsson and Mikael Malmaeus

ABSTRACT

In an environmentally harmonized society the most cost effective measures to reduce the total effluent discharges should be taken into account. Generalised discharge values are presented for organic material and nutrients in this paper. Depending on conditions in the receiving water any of these parameters can be the determining factor for the eutrophication and oxygen demand. These parameters can be generalized into equivalent loads of TOC, nitrogen or phosphorus by recalculation according to the Redfield ratio. The cost for reduction of organic material and nutrients from a pulp and paper mill is calculated as a cost per unit pollutant (cost equivalent). This cost equivalent is compared with alternative costs, expressed in the same way, for reduction of organic material and nutrients in adjacent industries, municipal treatment plants, impact from transportation, farming, air deposits etc. In order to find where the most cost efficient measures for the society should be taken the cost equivalent for the mill is compared with the alternative measures and their equivalent costs.

Key words | cost benefit analysis, discharges, effluent, nitrogen, phosphorus, TOC

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BACKGROUND

Sweden and the other Nordic countries have a long tradition of unique permits, negotiated at each industry. The discharge limit values and the parameters differ between different mills. They also differ if they are production based or given as tons or kg per day. Limit values given as concentrations, such as mg/l, are rare in Sweden and should also, from an environmental point of view, be avoided if not combined with a maximum flow.

As Sweden is a member of the European Union since 1995, the negotiation processes and new given limits are also strongly influenced by the IPPC BREF directive for Best Available Technique (BAT) for different types of industries. Recommended BAT discharge levels for integrated and non integrated Kraft Pulp mills are presented in Table 1 (IPPC 2001).

The BAT levels in the table should be seen as discharge levels during normal operation and margins should be added to discharge limits. The IPPC directive and the BAT levels are currently under revision. According to the draft version of the new directive, the BAT values will more often be seen as discharge limits. The mill standards vary in Europe and there are few newly constructed mills, but the BAT levels are discussed as goals in most environmental negotiations.

Stricter limits for pulp and paper mills regarding nitrogen and phosphorus will also be initiated with reference to the Baltic Sea Action Plan (BSAP) proposed by Helcom (Helsinki Commission) to combat eutrophication in the Baltic Sea.

Cost benefit analyses have met a growing interest by governments and authorities for example when deciding on measures to reduce phosphorus and nitrogen discharges in order to fulfil goals in the BSAP (Gren 2008).

A way of comparing costs for discharge reducing measures from pulp and paper mills with costs for other

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Table 1 | BAT levels for discharge levels at non integrated/integrated bleached pulp mills

	(kg/ADt)
COD	8–23
Total nitrogen (N_{tot})	0.1–0.2*
Total phosphorus (P_{tot})	0.01–0.03†

*Any nitrogen discharge associated with the use of chelating agents should be added to the figure.
†Due to the higher content of phosphorus in the pulp wood some eucalyptus pulp mills cannot achieve these values if P is in surplus compared to what the biological treatment plant needs. Emission will be determined by P-content of the wood. No phosphorus has to be added to the wastewater treatment plant.

possible measures to reduce the same amount of discharged organic material or nutrients to the actual receiving water is described in this paper. The examples are based on studies for Nordic pulp and paper mills in probationary studies before negotiations with the environmental court. However, the mill case studies and discharge figures are not actual figures for a specific mill.

Some examples of alternative methods relevant for the local situations in parts of Sweden are discussed in the studies performed. Local discharge sources must be investigated and valued if this type of study is to be made for another mill. This article points out a method but the given figures cannot generally be used for a local case.

ENVIRONMENTAL CONDITIONS IN THE RECEIVING WATER

As a first stage the conditions in the receiving water have to be studied, e.g. where depth, type of bottoms, water exchange, trophic status and other important conditions are evaluated in order to determine the sensitivity to eutrophicating substances in the actual water body. In every specific case the local situation in the receiving water has to be considered. However, in this paper a more general situation is examined.

MILL CASE

As case study a bleached Kraft pulp mill with an annual production of 400,000 ADt has been chosen. High TOC effluents are treated in an activated sludge plant with a separate selector stage. High solids effluent streams are led to a primary clarifier and some low contaminated effluent streams are led directly to the receiving water, Figure 1. The effluent in this case is piped into a deeper area off-shore.

TOC is used as parameter for organic material amount. The TOC/COD-ratio varies depending on effluent characteristics, but is often approximately 1/3 (Wilander 1988).

Actual discharges and discharge goals are presented in Table 2. The discharge goals are within the recommended range for BAT according to the IPPC BREF document.

COST CALCULATION OF DISCHARGE REDUCING MEASURES AT MILL

For cost calculation of discharge reducing measures at the mill the investment and operating costs for internal and external measures have been calculated. From the investment a capital cost has been calculated based on 6% interest rate and 10 years depreciation time, which will give an annual instalment of 13.6%. Operating costs are electricity, chemical costs and transport costs for chemicals, personnel costs, maintenance costs, costs for handling of sludge and

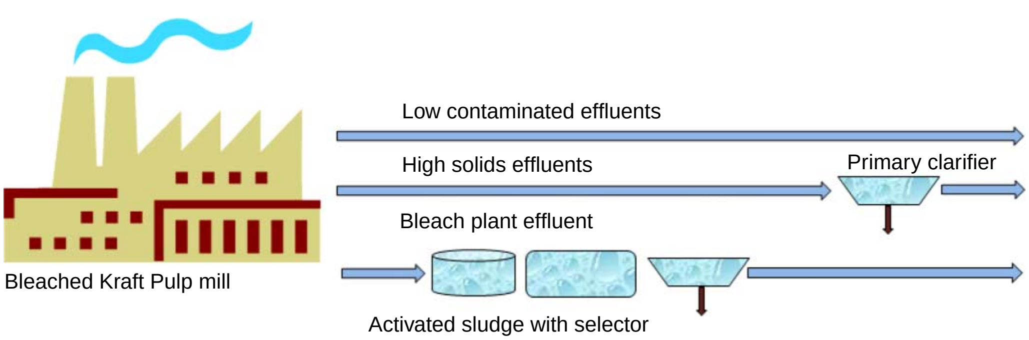

Figure 1 | Mill case, showing a bleached Kraft Pulp mill with a production of 400,000 ADt/year.

Table 2 | Mill case, discharge figures and discharge goals

		From biological treatment	Total discharge	Discharge goal
Flow	m^3/d	20,000	110,000	–
	m^3/t	18	98	–
TOC	kg/t	4	7	5
N_{tot}	kg/t	0.16	0.45	0.2
P_{tot}	kg/t	0.01	0.04	0.02

increased costs for NO_x and SO_x discharges to air in alternatives where sludge is incinerated.

Possible measures to reduce discharge limits from the mill are identified. The measures could be:

1. Improvement of the biological treatment and sand filtration of biologically treated effluent. The calculated cost is 1.5 MUSD/year. (Investment 7.5 MUSD and Operating costs 0.5 MUSD/year). This alternative does not fully reach the TOC goal.
2. Biological treatment of total effluent and sand filtration of biologically treated effluent. The calculated cost is 3.5 MUSD/year. (Investment 17 MUSD and Operating costs 1 MUSD/year). This alternative does not fully reach the TOC goal.
3. Improvement of the biological treatment and sand filtration of biologically treated effluent as in alternative 1 together with internal measures in the bleach plant. The calculated cost is 2.5 MUSD/year (Investment 13 MUSD and Operating costs 0.7 MUSD/year).

With the measures in Alternative 3 the treatment goals are reached and this alternative is chosen for the reduction of organic material and nutrients.

NUTRIENT AND CARBON EQUIVALENTS

An additional supply of nutrients to a water body often results in an increased primary production of algae. The decay of the algae consumes oxygen and may lead to a depletion of the oxygen store in the water column especially along the bottoms (hypoxia). A similar effect may occur when effluents rich in organic matter are being mineralised. Principally, if the non-desired ecological effect is the oxygen consumption, it is therefore possible to compare a discharge of organic matter (TOC) with a discharge of nitrogen or phosphorus.

The Redfield ratio, based on the weight of carbon, nitrogen and phosphorus in phytoplankton, may be used for calculation of TOC, nitrogen and phosphorus equivalents. The Redfield ratio varies depending on type of biomass. In this article we have used the Redfield ratio C:N:P 41:7:1 (Wetzel 2001), which is a general assumption for aquatic systems. Hence the possible production of organic material is about 6 kg TOC/kg nitrogen and 40 kg TOC/kg phosphorus.

CASE STUDY OF NITROGEN REMOVAL

Whether nitrogen or phosphorus alone or both substances control eutrophication is highly debated among scientists; see e.g. Bryhn & Håkanson (2008), Schindler *et al.* (2008) and Conley *et al.* (2009). It is beyond the scope of this paper to contribute to this discussion but from a management and legislative perspective clearly under certain circumstances; nitrogen removal is prioritised whereas in other situations phosphorus removal may be more important.

If the discharge of organic material (TOC) is the critical issue and nitrogen is considered as the most limiting nutrient for production of organic material in the receiving water the sum of nitrogen and TOC discharges can be expressed as nitrogen equivalents and the phosphorus discharge does not lead to any additional primary production.

In the mill case an N_{tot} discharge reduction by 0.25 kg/t (from 0.45 kg/t to 0.2 kg/t) has to be reached. A TOC reduction by 2 kg/t (from 7 kg/t to 5 kg/t) also has to be reached.

As the annual production is 400,000 t, an annual N_{tot} reduction of 100 t and an annual TOC reduction of 800 t have to be achieved. According to the Redfield ratio, the TOC reduction can be expressed as 133 t N equivalents ($800/6 \approx 133$). The total N_{eq} reduction will then be 233 t/year. As the annual cost to reach this discharge level was 2.5 MUSD, the cost will be 11 USD/kg N_{eq} reduced.

COMPARISONS WITH COSTS FOR OTHER NITROGEN REDUCING MEASURES

In order to evaluate the most cost effective measures for reduction of nitrogen, costs for alterative nitrogen reducing measures have been examined and some examples are given in this paper.

Nitrogen discharges to the receiving waters can be diminished by reducing discharges from incineration plants and traffic. The cost for nitrogen reduction in receiving waters if NO_x catalysts are used in all cars has been calculated at 12 USD/kg N_{eq} reduced. A difficulty when calculating on NO_x reductions is that there are multiple benefits (acidification, human toxicity, ozone formation and eutrophication in lakes and seas), so a suggestion is to be more accurate in allocating the cost to different areas (Elofsson & Gren 2004).

Another possibility for nitrogen reductions is to take additional measures in municipal effluent treatment plants. The cost interval for reduction of nitrogen in sewage works, designed for very high TOC and phosphorus reductions is in the range 4–8 USD/kg N_{eq} reduced (Olshammar *et al.* 2003). Those figures are well founded as during the last 15 years the expansion with nitrogen removal has been performed in all coastal based sewage treatment plants in the south of Sweden. If a further reduction of nitrogen of 5 mg/l can be performed in a sewage treatment work for 500,000 pe (personal equivalents, i.e. a flow of about 140,000 m^3/d) the nitrogen discharge from this source will be reduced by about 250 t/year.

The Agricultural sector is potentially discharging high quantities of nitrogen. One assumption is that approximately 15% of the nitrogen in industrially produced fertilizers leaches to the receiving waters (Finnveden *et al.* 2006). As a rule of thumb, about 25% of the run off nitrogen is eliminated by retention before entering the receiving water (Brandt & Ejhed 2002). From a study by the Swedish Government Agriculture Department (2000) the costs for a number of nitrogen reducing measures have been calculated; wetlands and fallow fields 6–10 USD/kg N_{eq} reduced and improved manure handling 1 USD/kg N_{eq} reduced. As an example the potential for reduction of nitrogen discharge from agriculture in south west Sweden by wetlands, fallow fields and optimised manure handling is about 1,000 t/year.

Costs of different NO_x reduction measures for merchant shipping have been taken from public Swedish (Kågeson 2000) and EU studies (EU 2005). These measures are very cost effective, 0.1–0.3 USD/kg N_{eq} reduced, but since shipping is international it has proven difficult to reach agreements on measures in this area. A big cruise ship, with modern NO_x minimising equipment (Direct Water injection), has a nitrogen discharge of about 350 t N/year. With NO_x catalysts the discharge can be reduced to below 100 t N/year.

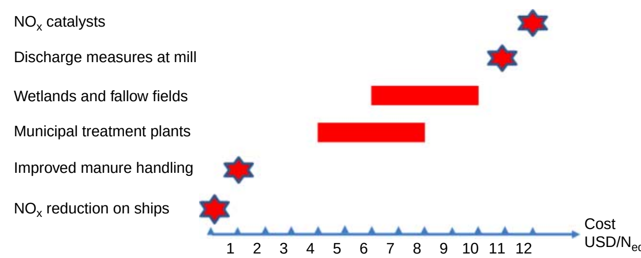

Figure 2 | Costs for N_{eq} reduction by different methods.

The costs for nitrogen reducing measures in some different areas are compared with the cost for nitrogen reduction in the mill case in Figure 2.

CASE STUDY OF PHOSPHORUS REMOVAL

If the overall algae growth in the mill recipient is considered to be limited by the availability of phosphorus the discharges of TOC and nutrients could be calculated as phosphorus equivalents (see the previous section about nitrogen removal).

In the mill case a P_{tot} discharge reduction by 0.02 kg/t (from 0.04 kg/t to 0.02 kg/t) has to be achieved. Also a TOC reduction by 2 kg/t (from 7 kg/t to 5 kg/t) has to be reached.

As the annual production is 400,000 t, an annual P_{tot} reduction of 8 t and an annual TOC reduction of 800 t have to be achieved. According to the Redfield ratio, the TOC reduction can be expressed as 20 t P equivalents ($800/40 = 20$). The total P_{eq} reduction will then be 28 t/year. As the annual cost to reach this discharge level was 2.5 MUSD, the cost will be 89 USD/kg P_{eq} reduced.

COMPARISONS WITH COSTS FOR OTHER PHOSPHORUS REDUCING MEASURES

In order to evaluate the most cost effective measures for reduction of phosphorus, costs for alterative phosphorus reducing measures have been examined and some examples are given in this paper.

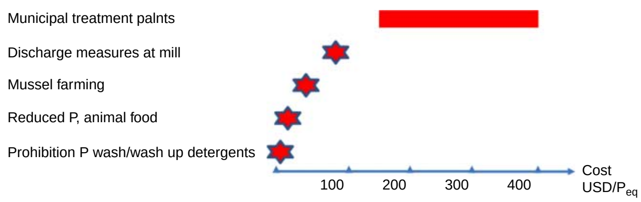

Figure 3 | Costs for P_{eq} reduction by different methods.

One possibility for phosphorus reductions is to take measures in municipal effluent treatment plants. The cost interval for reduction of phosphorus in sewage works, already designed for high TOC and phosphorus reductions is in the range 150–400 USD/kg P_{eq} reduced, calculated from public Swedish statistics (SCB 2007). Swedish sewage works have already been built for very high reduction rates of phosphorus, and hence the additional cost for further phosphorus removal is high. Discharge limits for phosphorus from sewage works in Sweden is normally in the range 0.3–0.5 mg/l. If measures to reduce phosphorus discharge to a value below 0.3 mg/l are implemented at all sewage treatment plants with higher discharges (about 100–150 treatment plants) a total phosphorus discharge reduction of about 120 t/year can be attained. The average investment is estimated to cost up to 2 MUSD per plant.

Mussels can be used as food and as animal food. As mussels live from filtration of water they thereby have an uptake of nitrogen and phosphorus, which will be taken away from the receiving water if the mussels are harvested. Mussels can thereby be used as a method to reduce nutrients in the water and further as a food source. The cost for phosphorus reduction by this method has been calculated at 40–50 USD/kg P_{eq} reduced (NV 2008). The potential for phosphorus reduction by mussel farming in Sweden is calculated at 35 t/year.

Agriculture is an area from which a lot of phosphorus can be discharged. In a study by the Swedish Board of Agriculture costs for different phosphorus reducing measures have been taken; as an example reduced P in animal food 6–10 USD/kg P_{eq} reduced, (Greppa Näringen 2007). In a Swedish project a reduction of 50% of phosphorus discharge from pig farms was attained after information about animal food with lower phosphorus content. The national potential of phosphorus reduction by this method has been calculated at approximately 75 t/year.

A prohibition against the use of phosphates in washing machine detergents and washing up liquids has been performed in Sweden. The phosphorus discharge reduction by this prohibition was mainly performed in small effluents not discharged to sewage treatment and was calculated to 50 t/year. The Swedish Chemicals Agency also recommends a prohibition against phosphates in all washing up detergents. A low cost of 0.5 USD/kg P_{eq} reduced has been calculated, which includes information to different companies; (Kemikalieinspektionen 2006, 2007).

The costs for phosphorus reducing measures in some different areas are compared with the cost for phosphorus reduction in the mill case in Figure 3.

CONCLUSIONS

There are a lot of possibilities to reduce both nitrogen and phosphorus in a more cost effective way than in the Mill Case. For society at large it may sometimes be more cost-efficient to reduce nitrogen and phosphorus from other sources in society than to push for BAT at each mill.

This is an approach similar to the discussion behind the introduction of tradable emission permits for carbon dioxide. Adopting such an approach however makes it necessary to reconsider the prevalent environmental permitting procedure and goals for determining discharge limits for the individual parameters which is in principle based on applying BAT as long as the investment cost is "reasonable".

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