AMBIO 2014, 43:352–360
DOI 10.1007/s13280-013-0435-1

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

REPORT

Nutrient Abatement Potential and Abatement Costs of Waste Water Treatment Plants in the Baltic Sea Region

Sami Hautakangas, Markku Ollikainen, Kari Aarnos, Pirjo Rantanen

Received: 25 January 2013 / Revised: 15 May 2013 / Accepted: 31 July 2013 / Published online: 31 August 2013

Abstract We assess the physical potential to reduce nutrient loads from waste water treatment plants in the Baltic Sea region and determine the costs of abating nutrients based on the estimated potential. We take a sample of waste water treatment plants of different size classes and generalize its properties to the whole population of waste water treatment plants. Based on a detailed investment and operational cost data on actual plants, we develop the total and marginal abatement cost functions for both nutrients. To our knowledge, our study is the first of its kind; there is no other study on this issue which would take advantage of detailed data on waste water treatment plants at this extent. We demonstrate that the reduction potential of nutrients is huge in waste water treatment plants. Increasing the abatement in waste water treatment plants can result in 70 % of the Baltic Sea Action Plan nitrogen reduction target and 80 % of the Baltic Sea Action Plan phosphorus reduction target. Another good finding is that the costs of reducing both nutrients are much lower than previously thought. The large reduction of nitrogen would cost 670 million euros and of phosphorus 150 million euros. We show that especially for phosphorus the abatement costs in agriculture would be much higher than in waste water treatment plants.

Keywords Nutrients · Abatement potential · Abatement costs

Electronic supplementary material The online version of this article (doi:10.1007/s13280-013-0435-1) contains supplementary material, which is available to authorized users.

INTRODUCTION

Eutrophication is a persistent environmental problem in the Baltic Sea and combating it requires large reductions in nutrient loads (HELCOM 2007). The principle of cost-efficient environmental policy requires that reduction targets to countries, polluting sectors, and polluting installations should be allocated so that their marginal abatement costs are equalized. Thus, a sound environmental policy requires that decisions are based both on the abatement potential and abatement costs of units.

Agriculture and municipal waste waters are the two main polluting sectors of the Baltic Sea (HELCOM 2009b). Thus, they have the greatest reduction potential, i.e., the largest amount of nutrient loads could be removed by reducing loads from these two particular sectors. But how big this potential actually is, and how great the costs are, need to be assessed. There has been much discussion on the role and costs of agriculture but it is in contrast, surprising how little we actually know about the abatement potential and costs of waste water treatment plants (WWTP). So far the discussion has been based on rude cost estimates that are made at high aggregate level.[1] Also data on actual loads of waste water treatment plants is scarce and for many countries unreliable.[2] Lack of this much needed information is a serious drawback in designing efficient policies against eutrophication.

Previous studies on the abatement costs of nutrients in urban waste water treatment plants have not utilized as

[1] The basic source used in many policy papers is COWI (2007).

[2] For instance, Helsinki Commission (HELCOM) provides a comprehensive list of WWTP plants but detailed information on effluents and abatement is either missing or outdated. The same holds true for the European Union.

comprehensive data and updated as our study. So far most of the literature has utilized costs reported in COWI (2007) (see e.g., Gren 2008a) which draws, however, heavily Schou et al. (2006) which in turn is based on Winther et al. (2004) and Krüger International Consult A/S and Karpuhin (2001). In all the studies we had access to the focus is not on the WWTPs but to provide a view on the different sectors' nutrient loads to the Baltic Sea and to estimate the costs of reducing these loads. This is done by using the information already available.

This paper makes a major effort to develop this information. Our research goals are the following. First, we assess the current abatement level and loads from urban waste water treatment plants in all Baltic Sea countries and examine the physical potential for further reductions. Second, we determine the costs of abating nutrients, nitrogen (N) and phosphorus (P), from sewage water and derive total abatement cost functions. Third, we assess the level of marginal costs at various levels of abatement. To our knowledge, our study is the first of its kind; there is no other study on this issue which would take advantage of this large detailed data on the WWTP's financial and physical operations.

MATERIALS AND METHODS

Waste water treatment plants are designed to remove harmful substances from the waste waters of households and enterprises and also from urban runoff. These harmful substances include, e.g., nutrients, organic matter, pollutants, microorganisms, and heavy metals. We will concentrate on nutrients. There is a large variety of different sized WWTPs around the Baltic Sea littoral countries. Some of them treat only hundreds of people's waste waters while some of them treat waste waters of a big city. Also their performances vary a lot. Some plants can remove less than 30 % of the nutrients from the incoming water while some are pursuing to remove almost 100 % of the nutrients. The composition of the inflow water itself differs depending on the units connected to the WWTP and for one's part affects the performance of a WWTP.

In order to be able to find out the nutrient reduction potential and the costs of reduction we have to find out capacities and technologies of the waste water treatment plants in the Baltic Sea riparian countries. We concentrate on the WWTPs of at least 10 000 Person equivalent (PE)[3] of their size because the European Union (EU) and Helsinki Commission (HELCOM) requirements involve particularly those.

[3] 1 PE = 70 g/day of BOD_7 (the organic biodegradable load having a 7-day biochemical oxygen demand of 70 g of oxygen per day).

Data Collection Process

There exist two main databases from which data was collected at first; the EU and HELCOM. According to HELCOM (2006) database there are over 700 municipal wastewater treatment plants in the Baltic Sea catchment area with PE higher than 10 000, yet excluding Russia of this number. As a sampling method we used a random sample for Denmark, Finland, Germany, Russia, and Sweden. This procedure was chosen because the data of the WWTPs in those countries was comprehensive and reliable enough. As for other countries, we were compelled to use the data that was available on the whole. Therefore, for Estonia, Latvia, Lithuania, and Poland the sample was considered to have a self-selection bias: sample consists of the most advanced treatment plants.

We derived the size distribution of the PE loads of the WWTPs drawing on the HELCOM (2006) database. The minimum of the PE load was set to 10 000 PE and maximum originally to less than 1 000 000 PE. The maximum excludes two plants located in Poland and two in Russia. To the final data we added those two Russian plants. We used this data which consisted of estimated figures of 2015 based on the ongoing projects instead of using outdated data from 2004. Without these additional plants the data on Russia would have been too exiguous.[4]

The data was originally collected in five size classes and transferred later to four classes. The target was to find treatment plants from every country to each category. If the category originally contained eight or more WWTPs, the amount of treatment plants selected was ca. 20 % from the total number. Otherwise at least one treatment plant was selected.

The selection consists altogether of 182 WWTPs in the Baltic Sea drainage basin. The number of the selected plants represents approximately 25 % of all the WWTPs in the region. The size distribution of the treatment plants is shown in Table 1. The number of wastewater treatment plants in Poland represents almost 50 % of the total number in the drainage basin. More on data collection and WWTP technologies in Electronic Supplementary Material (ESM) A.

[4] There are similar improvement projects in progress in Poland as in Russia. The goal of the Polish project has been set to reach 80 % reduction level for nitrogen and 85 % level for phosphorus in agglomerations from 15 000 PE to 99 999 PE by the end of the year 2015 while in agglomerations above 100 000 PE the reduction level for nitrogen would be 85 % and for phosphorus 90 % (Gromiec 2010). This is omitted from our data, though, due to the lack of comprehensive and detailed original data on the Polish project.

Table 1 The size distribution of the selected sample and the whole population of WWTPs in the Baltic Sea littoral countries

Mean of load as PE	Sample/population						
	10 000–50 000	50 000–100 000	100 000–260 000	260 000–500 000	500 000–1 000 000	1 000 000–	Total
Denmark	15/79	3/19	2/9	1/2	1/1	0/0	22/110
Estonia	1/7	1/4	0/0	1/2	0/0	0/0	3/13
Finland	11/50	3/13	1/5	1/1	1/1	0/0	17/70
Germany	10/45	2/10	1/6	1/2	0/0	0/0	14/63
Latvia	3/6	1/1	1/1	0/0	1/1	0/0	6/9
Lithuania	0/0	0/0	1/7	2/2	1/1	0/0	4/10
Poland	58/240	14/64	9/44	3/13	2/7	0/2	86/370
Russia	3/15	1/3	1/1	0/0	0/0	2/2	7/21
Sweden	16/72	3/13	2/5	1/3	1/2	0/0	23/95
Total	117/514	28/127	18/78	10/25	7/13	2/4	182/761

Sample Generalization to Correspond the Population

The sample of 182 WWTPs was then reclassified into four size classes (groups 1–4) by PE: 10 000–80 000, 80 000–22 000, 220 000–500 000, and 500 000 or more. The first group includes the majority of the waste water treatment plants, 137 (75 % of the total amount) of our sample. In the second group there are 24 (13 %) plants and the third and the fourth group contains 12 (7 %) and 9 (5 %) plants, respectively. The sample is generalized to population level in two different ways: for Denmark, Finland, Germany, Sweden, and Russia the sample was considered to be representative. Thus, this data was straightforwardly multiplied group-wise to correspond with the population. The sample of Finland was also compared to the complete WWTP population data and found that the average abatement levels of nitrogen and phosphorus were only 2 and 0.2 % lower, respectively, in the sample than in the whole population.

The magnitude of the self-selection bias of the sample of Estonia, Latvia, Lithuania and Poland was impossible to detect. Relying on the experts' views and COWI (2007), we therefore assumed that in the population outside the sample the WWTPs' reduction percentage of nitrogen is either 30 or 50 (ESM B). In the two smallest size-groups the assumed reduc tion percentages are divided equally half-and-half among the plants, but for the two largest size-groups we assume that 2/5 of the plants abate at 30 % level while 3/5 of the plants abate at 50 % level. The corresponding percentages for phosphorus as well as an alternative case are reported in ESM B.

Current Nutrient Loads and Reduction Potentials

EU (EEC 1991) and HELCOM (HELCOM 2007, 2009a) have set their requirements of nutrient reduction to waste water treatment plants (ESM C). We use these requirements not only as a backbone of our reduction potential analysis but also introduce a few more demanding targets to be reached as well. In order to assess the reduction potential of WWTPs we have to find out the current loads and abatement levels of the treatment plants.

Reduction potential indicates how much we have to increase the abatement in order to reach some new level of abatement, i.e., how much is the gap between some required level of abatement and the abatement level at the moment. We examine the reduction potential measuring reduction in percentages instead of remaining concentration. There are several reasons for that. Firstly, the flow rates of the water, which are used in calculating the concentration, fluctuate considerably year by year and so do the concentration figures. The percentage measures are more stable as they are calculated from yearly measures of nutrients in inflow and effluent waters. Secondly, in water policy discussions percentages are the ones that are mainly used. Thirdly, choosing one measure only, keeps the illustration clearer.

Nutrient effluents and the abatement levels vary considerably in the Baltic Sea countries. Table 2 reports the loads and current abatement percentages in the WWTPs of each country. Municipalities' nutrient load into the Baltic Sea through WWTPs is around 10–20 % of the total nutrient load. Poland is responsible for 60 % of the total nitrogen loads and 75 % of the total phosphorus loads from WWTPs. When it comes to abatement, there are two countries which perform extremely well: Denmark and Germany. They abate both nitrogen and phosphorus at a very high rate. Finland and Sweden abate well phosphorus but fail to achieve even 70 % reduction rate in nitrogen abatement. The former Eastern bloc countries (Estonia, Latvia, Lithuania, Poland, and Russia) have quite much to do in reducing both nutrients.

We examine the costs of reducing nitrogen not only at 70 % level, as EU's Urban Waste Water Treatment Directive (UWWTD) and HELCOM recommendation suggest, but also increase abatement up to 80 and 90 %.

Table 2 Estimates of current nutrient loads and reduction rates of existing WWTPs in the Baltic Sea countries and the proportion of the population not connected to the sewage treatment system in the Baltic Sea littoral countries

Country	Nitrogen		Phosphorus		Non-connected population (%)[a]
	Load (t a^{-1})	Abatement (%)	Load (t a^{-1})	Abatement (%)	
Denmark	2800	92	330	94	11
Estonia	1700	61	230	69	30
Finland	9700	60	110	97	20
Germany	1800	86	56	97	6
Latvia	2700	34	270	63	30
Lithuania	3500	65	360	75	43
Poland	66 000	49	8500	59	41
Russia	10 000	61	1300	74	50
Sweden	11 000	67	170	97	8
Total	110 000	61	11 000	75	–

[a] *Source* COWI (2007). Individual values do not necessarily sum up to total due to rounding

The latter is close to the best available technology (BAT). For phosphorus we consider abatement levels 80 % (UWWTD), 90 % (HELCOM recommendation), and 95 % (close to BAT). The reduction potentials are calculated assuming that every plant reaches the targeted reduction as EU and HELCOM suggest. This means that overall target is met only when every plant is operating at the required reduction level or above that level. Note that this will not lead to a cost-effective solution (if not by coincidence).

If all the over 10 000 PE waste water treatment plants in the Baltic Sea catchment area removed nitrogen at least at 70 % level, there would be 44 000 tons of nitrogen less coming out of the sewers per year than currently (see Table 3). This is the reduction potential to meet the UWWTD. By increasing the target to 90 % level the reduction would be 83 000 tons more than currently. The corresponding levels for phosphorus are reported in Table 3. Table SD1 of alternative case is found in ESM D.

Looking at the reduction potentials country by country we can see that, e.g., Denmark abates nitrogen so well that their reduction potential is negligible before 90 % level (820 tons). Even that is only 1 % of the total reduction potential. Whereas phosphorus reduction potential in Denmark is only slightly larger relative to total potential.

The reduction potential in Polish WWTPs is clearly the largest among the littoral countries. Even to reach the 70 % abatement level of nitrogen yields 31 000 tons more reduction (70 % of the total reduction potential). As for phosphorus, to reach 80 % abatement level Poland would need to remove almost 4900 tons (86 %) more.

Nutrient Loads from Untreated Waste Waters

According to COWI (2007, p. 38) the three countries having the highest share of non-connected households are Russia, Poland, and Lithuania. Recent investments in Poland and Russia have supposedly increased the number of the connections to the waste water treatment system. Despite the fact, it is still justifiable to assume that the most considerable sources of untreated loads of waste water are in Russia and Poland due to the connection rates and the amount of the population living in the catchment area. By using various literary sources and experts' views we have estimated the Russian and Polish untreated nutrient loads reported in Table SE1 in ESM E.

Costs of Nutrient Abatement in WWTPs

Estimation of the abatement costs of phosphorus and nitrogen faces many challenges and complication. First, abatement of the nutrients, BOD_7 and other harmful substances is a joint production. Neither the managers of sewage plants nor the consultants of the field have so far had any need to assess separately costs associated with nutrients. This need is created by the environmental policy based on the cost-efficiency principle, which requires comparisons of the marginal abatement costs of nutrients between polluting units. Therefore, there are not accepted procedures to guide how to impute to overall costs to each substance. Second, the amounts and ratios of nutrients and other contents of incoming waste water vary between plants and impact greatly the technical feasibility of the abatement. Third, given the long life time of plants, each plant is unique, so that increasing abatement usually requires plant-specific actions. Fourth, the professional skill of the staff determines to a great extent how well the processes are optimized and thereby the outcomes of the abatement.

Despite these challenges, we conduct a serious effort to determine abatement costs of nitrogen and phosphorus. We

Table 3 Nutrient reduction potentials in existing WWTPs under selected abatement level targets

Abatement level	Nitrogen abatement potential (t a^{-1})			Phosphorus abatement potential (t a^{-1})		
	70 %	80 %	90 %	80 %	90 %	95 %
Denmark	0	41	820	0	51	160
Estonia	580	870	1300	100	150	190
Finland	3900	5400	7300	0	0	4
Germany	0	20	540	0	0	1
Latvia	1600	1900	2300	130	200	240
Lithuania	1400	2000	2500	180	240	290
Poland	31 000	41 500	53 000	4900	6600	7500
Russia	2500	5000	7600	400	800	1000
Sweden	3100	4700	7800	0	0	3
Total	44 000	61 000	83 000	5700	8000	9400

Individual values do not necessarily sum up to total due to rounding

draw on the previous description of the abatement technologies and the fact that the investment costs and prices of materials are practically the same in all littoral countries being aware that the personnel costs vary between the countries. We assume that the WWTPs are operated by high-skilled professionals and thus functioning at their technological limits. Furthermore, we assume that waste waters flowing into WWTPs are homogenous.

Our estimations are based on a thorough analysis of the true and complete investment and operative costs in selected WWTPs in the Baltic Sea area (ESM F). Our analysis consists of four different sized (representing size classes 10 000–80 000 PE, 80 000–220 000 PE, 220 000–500 000 PE, and over 500 000 PE) plants, which we name as WWTP 1…4 (from smallest to largest) to keep their anonymity.[5] Any plant is designed to automatically eliminate a high share of BOD_7 (95–98 %). This primary abatement level reduces also phosphorus and nitrogen both by 30 %. The next step is to reduce phosphorus applying mostly chemical abatement process, and then nitrogen with more challenging technology processes.

Nitrogen Abatement Costs in WWTPs

We derive the abatement costs for nitrogen assuming that phosphorus abatement is roughly at 95 % level. Nitrogen abatement costs consist of investments (pools), materials (methanol), and other operative costs and the real interest rate, which in our calculations is 4 % (discussion in ESM G). The novelty of our analysis is the imputation of costs on nutrients and BOD. Originally most of the costs are imputed to BOD, then to phosphorus and in an increasing fashion to nitrogen. We illustrate the total abatement cost and marginal abatement cost functions in four different size classes in Figs. 1 and 2 (average abatement cost functions are illustrated in Figure SH1 in ESM H). Costs in vertical *y*-axis are in euros and abatements in horizontal *x*-axis are in percentages. The functions are defined at abatement level $x \in [30, 90]$. Average annual costs are denoted by the annualized present value of the investment, which is assumed to have 30 years long life. The costs of nutrient abatement are thus annualized averages of the net present value. All plants are assumed to be built as new ones; this ensures that the level of abatement costs warrants sustained operation of WWTPs and investments in new plant capacity. The functions were formed by fitting them to a few marginal cost/abatement points observed from the data.[6] As we had access only to one representative plant of each size class, it is not reasonable to report any statistics.

From Fig. 1 we can see that the larger the plant, the more expensive to reach a certain abatement level in terms of total cost, as a given abatement level in a large unit entails large amounts abated. For example, to abate nitrogen at 90 % level in plant 4 (the largest one) costs almost 13 million euros per year, whereas in plant 1 (the smallest one) the cost is less than million euros. The amounts of nitrogen reduced at this level are more than 3 million kg and approximately 150 000 kg in plant 4 and plant 1, respectively.

In Fig. 2 we illustrate the respective marginal cost functions. Contrary to the total costs reported in Fig. 1, the larger the unit, the lower the marginal abatement cost at a given abatement rate. For example, at 70 % level the marginal cost in the largest plant (4) is around 5.5 euros kg^{-1}, while in the smallest unit (1) the marginal cost is 9.5 euros kg^{-1}.

[5] WWTPs 1, 2, and 4 are based on the corresponding data whilst WWTP 3 is an estimate based on the same data.

[6] Although reporting total abatement costs in EMS I, the most important form of functions to be used in further analyses is marginal abatement cost functions which were the fitted ones.

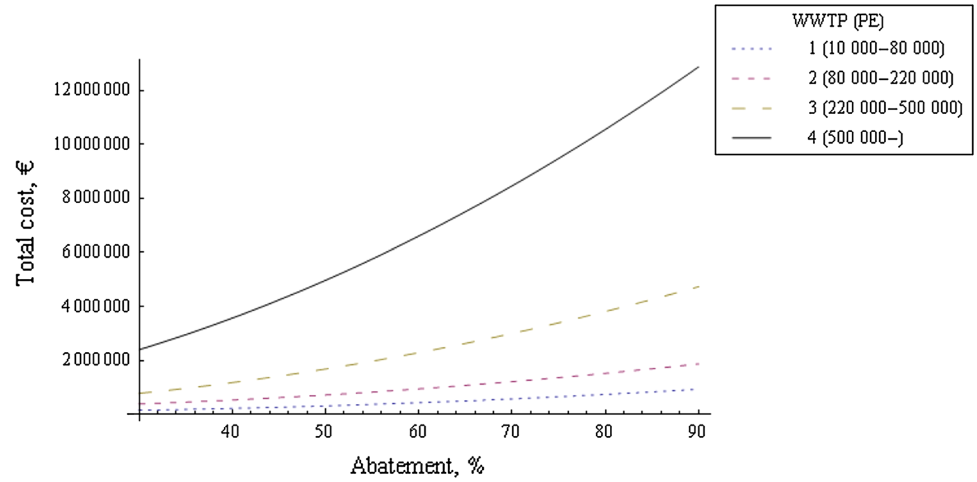

Fig. 1 Total abatement cost of nitrogen in WWTPs as a function of abatement for the chosen size classes

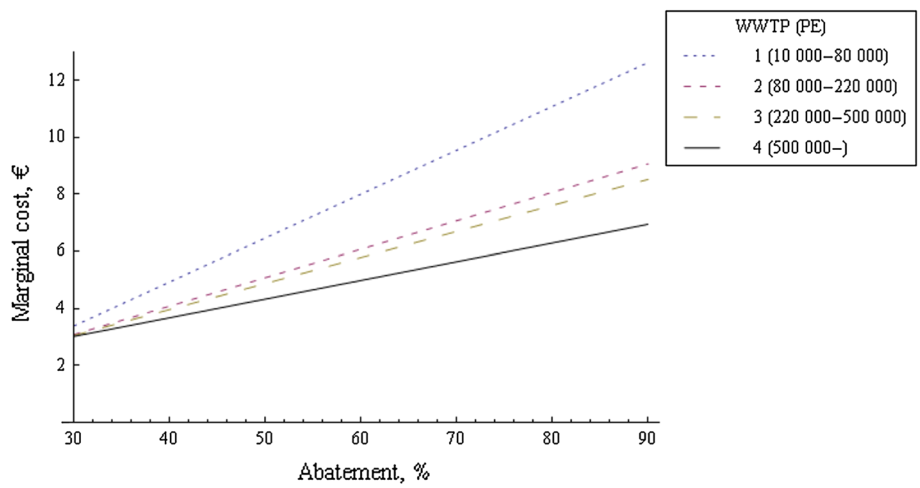

Fig. 2 Marginal abatement cost of nitrogen in WWTPs as a function of abatement for the chosen size classes

Our findings differ much from the results reported in previous studies. For example, in Gren (2008a) the marginal abatement costs of nitrogen vary from 12 to 79 euros kg^{-1}, which exceeds our estimations considerably. According to COWI (2007, p. 44),[7] on the other hand, the cheapest average abatement cost of nitrogen is found in WWTP of size 100 000 PE in "Eastern countries." The average cost is declining from 29 to 12 euros kg^{-1} when the abatement process is improved from "primary" to "tertiary." Comparing these figures with any of our size classes of WWTPs at any abatement level, reveals that the costs in COWI (2007) are much higher.

Phosphorus Abatement Costs in WWTPs

Phosphorus abatement costs consist mostly of chemicals and equipment required to dosing them. Thus, costs increase fairly linearly. Our cost estimates for phosphorus come from another set of WWTPs in which nitrogen abatement is kept at 30 % level but phosphorus abatement is gradually increased as high as 95 % level. The features of the following figures are equivalent to those of nitrogen abatement costs with one exception, that is, the functions are now defined at abatement level $x \in [30, 95]$.

The total abatement costs of phosphorus in the four size classes are illustrated in Fig. 3. For instance, to abate at 95 % level in WWTP 1, which is about 25 000 kg, costs around 450 000 euros. The same abatement level means approximately 550 000 kg in the WWTP 4 and costs more than 7.5 million euros.

Looking at the marginal abatement costs of phosphorus illustrated in Fig. 4 show that the slope of the function describing the costs in the smallest treatment plant diverges from the three largest plants by being somewhat steeper. This means that in plant 4 the marginal cost increases from 70 % abatement level to 95 % level with less than one euro while in WWTP 1 the marginal cost grows more than 1.5 euros in the same range.

The marginal abatement costs of phosphorus are lower than the marginal costs reported previously. For example, in Gren (2008a) the marginal abatement cost of phosphorus

[7] In 2004 euros. Discount rate is 3 %, lifetime for WWTP is 20 years and for sewage system 50 years.

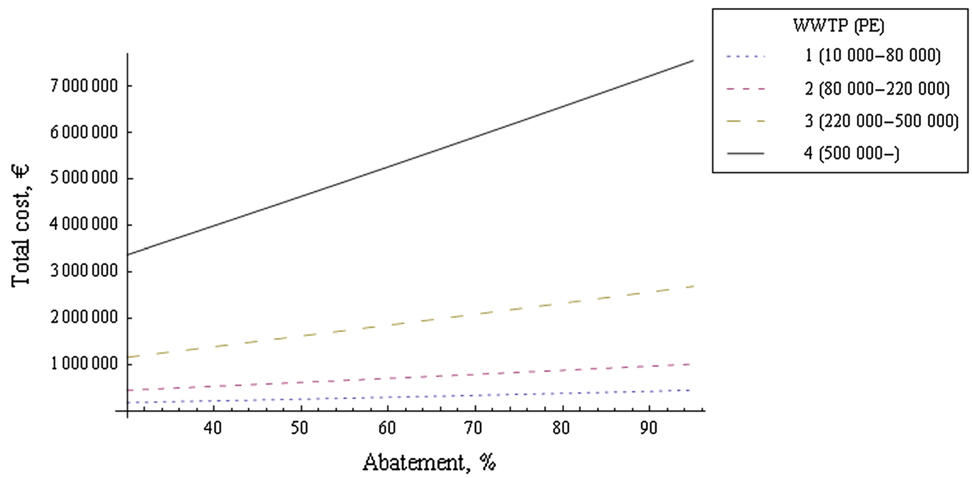

Fig. 3 Total abatement cost of phosphorus in WWTPs as a function of abatement for the chosen size classes

varies between 41 and 130 euros kg^{-1}, which is considerably higher than our analysis shows. Also the average abatement costs are much lower in our calculations (Figure SH2 in ESM H) than in COWI (2007, p. 44), which reports the cheapest average cost in WWTP of 100 000 PE declining from 157 to 41 euros kg^{-1} while improving the configuration.

RESULTS: TOTAL COSTS TO REACH THE REDUCTION POTENTIALS

We now examine how much it would cost to achieve the reduction potential studied above. We determine the costs as a sum of increased abatement costs in the existing plants and the cost of building new plants to join the currently untreated waste waters in Poland and Russia to sewage system (ESM E). We do not present the costs for a cost-efficient solution but follow our previous approach and determine the costs using cost functions representing each size class.

Table 4 presents the total costs of each country to meet the required reduction targets. The corresponding Table SJ1 without untreated waters is reported in ESM J. The total costs to meet the required 70 % abatement level of nitrogen in WWTPs in the Baltic Sea littoral countries are 310 million euros. Increasing the abatement level to 90 % level would more than double the cost to 670 million euros.

As for the country-wise burden, Poland bears the lion's share of it. For example at 70 % abatement level Poland carry 70 % of the total costs with 210 million euro. The next largest shares belong to Sweden, Russia, and Finland. Together they make 25 % (77 million euros) of the total costs at 70 % level. An alternative case is reported in Table SJ2 in ESM J.

To meet the 80 % target of phosphorus reduction set by EU directive would cost less than 100 million euros. Investing 55 million euros more would be enough to reach the 95 % level. Like before, Poland has the highest costs to meet: roughly 80 % (120 million euros) of the total costs to reach the 95 % abatement level. Adding Russia to that figure brings the proportion of these two countries to almost 95 % of the total burden.

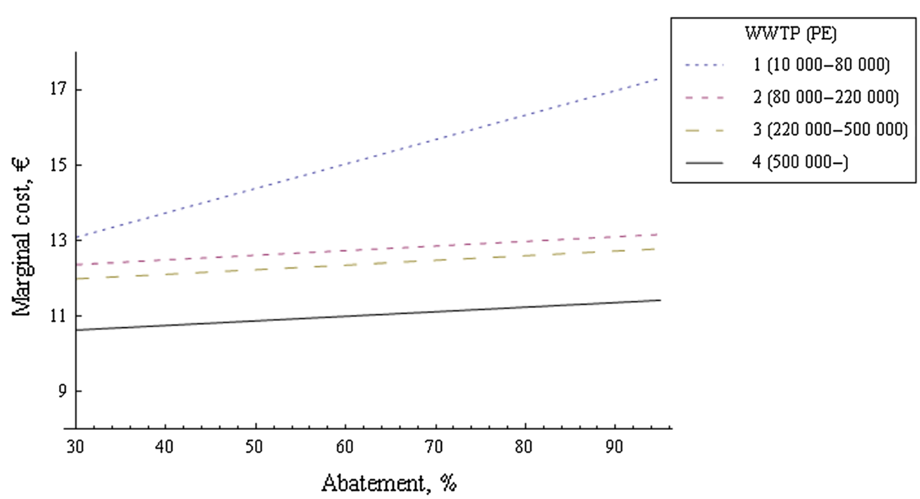

Fig. 4 Marginal abatement cost of phosphorus in WWTPs as a function of abatement for the chosen size classes

Table 4 Total costs of nitrogen and phosphorus reduction to reach the chosen levels of abatement (including 50 % of the untreated waste waters in Poland and Russia)

Country	Nitrogen abatement (million €)			Phosphorus abatement (million €)		
	70 %	80 %	90 %	80 %	90 %	95 %
Denmark	0	0.5	7.7	0	0	2.3
Estonia	3.7	6.1	9.9	1.4	2.1	2.6
Finland	29	43	63	0	0	0
Germany	0	0	3.4	0	0	0
Latvia	7.0	9.5	13	1.6	2.5	3.0
Lithuania	8.7	13	18	2.2	3.0	3.6
Poland	210	310	420	79	100	120
Russia	25	44	67	11	16	19
Sweden	23	39	68	0	0	0
Total	310	460	670	95	130	150

Individual values do not necessarily sum up to total value due to rounding

DISCUSSION

Our twin-aim was to assess the physical potential to reduce nutrient loads from WWTPs in the Baltic Sea region and determine the costs of abating nutrients based on the estimated potential. To these ends we estimated the current abatement levels and loads from WWTPs and developed the total, marginal, and average abatement cost functions for both nutrients. To our knowledge, our study is the first of its kind; there is no other study on this issue which would take advantage of detailed data of this extent.

We demonstrated that the reduction potential of nutrients is huge in WWTPs of the Baltic Sea littoral countries. In HELCOM's Baltic Sea Action Plan the agreed total reduction targets of nitrogen and phosphorus are 129 390 and 13 356 tons per year, respectively. Abating 90 % of nitrogen in sewage treatment plants, including half of the untreated waste waters in Poland and Russia, would count 70 % of the BSAP nitrogen target. As for phosphorus, the 95 % abatement level would mean achieving 80 % of the BSAP phosphorus target. This really is a good promise and as such supports the aggregate targets established in the BSAP: the low hanging fruits of nutrient reductions can be found by abating nutrients in WWTPs.

Another good finding is that the costs of reducing both nutrients are much lower than previously thought. The large reduction of nitrogen (83 000 tons) would cost 670 million euros per year and of phosphorus (9400 tons) 150 million euros per year. This is much lower than Gren (2008b) reports in her study. According to Gren (2008b), to reach the BSAP target cost-effectively would cost 3080[8] million euros per year in total. Our results are not fully comparable as Gren (2008b) includes other sectors than WWTPs as well. On the other hand our reduction does not reach the whole BSAP target nor is it cost-effective. Nevertheless, this gives a suggestion of the differences in costs between these studies.

It is evident that especially for phosphorus the abatement costs in agriculture would be much higher than in WWTPs. For example according to Ollikainen et al. (2012) to reduce the phosphorus loads in agriculture in Finland by 10 % which is around 200 tons would cost ca. 30 million euros a year. In Latvia the corresponding 200-ton reduction (90 % abatement level) would be reached in WWTPs with 2.5 million euros. Also the marginal costs of reducing phosphorus in agriculture are much higher than in WWTPs. At 10 % reduction level the marginal cost in agriculture is 45 euros kg^{-1}. Bearing in mind that the marginal cost in WWTPs at 95 % abatement level is not more than 18 euros kg^{-1} at the most, reveals the difference between the phosphorus reduction costs in agriculture and WWTPs.

Interestingly, nitrogen reduction costs in agriculture and WWTPs are fairly close to each other. With lower reduction rates the costs in agriculture seem to be even smaller than in WWTPs. For example to reduce 3600 tons (10 % reduction) in agriculture costs ca. 10 million euros per year while in WWTPs in Finland 3900-ton reduction (70 % abatement level) costs 29 million euros. The marginal costs of nitrogen reduction in agriculture increase almost linearly from 4 to 22 euros kg^{-1} when increasing the reduction rate from 10 to 40 %. Recall that the marginal abatement costs in WWTPs from 70 to 90 % abatement levels range from 5.5 to nearly 13 euros kg^{-1}.

While the costs in agriculture are only for Finland and the comparisons include WWTPs in different countries with different reduction potentials the results should be interpreted carefully. Nevertheless, this still gives valid estimates of the cost differences of nutrient reduction

[8] Converted from U.S. dollars to euros with the exchange rate (€1 = $1.3052) of Bank of Finland in April 12, 2013.

between agriculture and WWTPs around the whole Baltic Sea region. The above findings should encourage the decision makers to invest in WWTPs as there would be huge amount of nutrient reductions to be achieved in just a few years' time and cheaper than previously thought.

Note that we do not take into account the possible retention capacity of the inland waters. The reason for this is UWWTD's even abatement requirements which allow no exceptions for WWTPs in the catchment area of the Baltic Sea regardless of their location (EEC 1991). However, some exceptions are allowed after a judgment of EU Court of Justice. Namely, in Finland and Sweden some of the WWTPs may deviate from the directive as for nitrogen abatement (CJEU 2009).

CONCLUSION

An obvious drawback of our findings is that the reduction potentials and, therefore, the costs of abatement are divided unevenly between countries. As all cost calculations related to the Baltic Sea protection (e.g., Gren 2008a; Hautakangas and Ollikainen 2011) show, Poland will always bear the highest costs. Also, the Baltic countries and Russia have high costs. Thus, the question emerges: how to attract all the littoral countries to increase the abatement to amounts approaching the best available technology in WWTPs? It is our understanding that an approach based on cost-efficient reduction augmented with cost-sharing (or net-benefit-sharing) system could do the job. So far countries have been unwilling to take such a determined action.

Acknowledgments This paper is a part of the project "Cost-efficient instruments for the Baltic Sea Protection" funded by the Ministry of the Environment and Ministry of Agriculture and Forestry and the Bonus project "ProBalt: Improving societal conditions for the Baltic Sea protection" funded by the Academy of Finland. Ollikainen thanks Yrjö Jahnsson Foundation for a personal grant. The authors are very grateful for the high professional help by Ari Niemelä and research assistance by Inka Ruotsalainen. Constructive comments by two anonymous verifiers are gratefully acknowledged.

REFERENCES

CJEU. 2009. Judgment of the Court. 6 October 2009. In Case C-335/07. Retrieved 16 April, 2013, from http://curia.europa.eu/juris/document/document.jsf?doclang=EN&text=&pageIndex=0&part=1&mode=lst&docid=77864&occ=first&dir=&cid=2504783.

COWI. 2007. Economic Analysis of the BSAP with Focus on Eutrophication, Final Report, HELCOM and NEFCO, 112 pp.

EEC. 1991. Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. Retrieved 19 April, 2011, from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1991L0271:20081211:EN:PDF.

Gren, I.-M. 2008a. Costs and benefits from nutrient reductions to the Baltic Sea. Swedish Environmental Protection Agency, Report 5877, Stockholm, Sweden 68 pp.

Gren, I.-M. 2008b. Cost effectiveness and fairness of the HELCOM Baltic Sea Action Plan against eutrophication. *VATTEN* 64: 273–281.

Gromiec, M. 2010. Water policy and national programme of wastewater treatment in Poland. Baltic Sea Water Award Seminar, Warsaw, Poland.

Hautakangas, S., and M. Ollikainen. 2011. Making the Baltic Sea Action Plan Workable: a nutrient trading scheme. In *Governing the Blue-Green Baltic Sea. Societal challenges of marine eutrophication prevention*, ed. M. Pihlajamäki and N. Tynkkynen, 153 pp. Helsinki: The Finnish Institute of International Affairs.

HELCOM. 2006. Nutrient GIS. Retrieved 9 June, 2010, from http://maps.helcom.fi/website/NutrientGIS/viewer.htm.

HELCOM. 2007. HELCOM Baltic Sea Action Plan. HELCOM Ministerial Meeting, Krakow, Poland, 15 November 2007. Retrieved 19 April, 2011, from http://www.helcom.fi/stc/files/BSAP/BSAP_Final.pdf.

HELCOM. 2009a. HELCOM Baltic Sea Action Plan. Retrieved 27 April, 2011, from http://www.helcom.fi/BSAP/en_GB/intro/.

HELCOM. 2009b. Eutrophication in the Baltic Sea. An integrated thematic assessment of the effects of nutrient enrichment in the Baltic Sea region. Helsinki Commission, Baltic Sea Environmental Proceedings No. 115B, Helsinki, Finland, 150 pp.

Krüger International Consult A/S and V.F. Karpuhin. 2001. *Water and wastewater engineering handbook for Russia*. Ministry of Environment and Energy, Schultz Grafik.

Ollikainen, M., Hautakangas, S., Honkatukia, J., and J. Lankoski. 2012. New analyses and tools for the protection of the Baltic Sea. In *An economic perspective to the protection of the Baltic Sea*, ed. K. Hyytiäinen and M. Ollikainen, 134 pp. Helsinki, Finland: Finnish Ministry of the Environment, Ympäristöministeriön raportteja 22/2012 (In Finnish).

Schou, J.S., Neye, S. T., Lundhede, T., Martinsen, L., and B. Hasler (2006). Modelling cost-efficient reductions of nutrient loads to the Baltic Sea—concept, data and cost functions for the cost minimisation model. Danish Ministry of the Environment, NERI Technical Report No. 592, Copenhagen, Denmark, 71 pp.

Winther, L., Henze, M., Linde, J.J., and Jensen, H.T. 2004. *Sewage technology*, 3rd ed. Copenhagen: Polyteknisk forlag.

AUTHOR BIOGRAPHIES

Sami Hautakangas (✉) is a doctoral candidate of environmental economics at the University of Helsinki.
Address: Department of Economics and Management, University of Helsinki, P.O. Box 27, 00014 Helsinki, Finland.
e-mail: sami.hautakangas@helsinki.fi

Markku Ollikainen is a Professor of environmental economics at the University of Helsinki.
Address: Department of Economics and Management, University of Helsinki, P.O. Box 27, 00014 Helsinki, Finland.
e-mail: Markku.Ollikainen@helsinki.fi

Kari Aarnos is a project researcher of environmental economics at the University of Helsinki.
Address: Department of Economics and Management, University of Helsinki, P.O. Box 27, 00014 Helsinki, Finland.
e-mail: kari.aarnos@gmail.com

Pirjo Rantanen is a university teacher of water and waste water engineering at the Aalto University.
Address: Department of Civil and Environmental Engineering, Aalto University, PL 12100, 00076 Espoo, Finland.
e-mail: Pirjo.Rantanen@aalto.fi