Dynamic cost-and-effect model under changing climate and socio-economic drivers

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1. INTRODUCTION

Raised environmental awareness and accumulated knowledge on the causes and consequences of eutrophication have motivated research on the costs and effects of alternative nutrient abatement measures in the Baltic Sea region. Such information can be applied to compute cost-effective combinations of abatement measures across different polluting sectors, and in order to estimate the total costs of national and international efforts to reduce nutrient pollution.

The objective of this deliverable report is to review the existing literature about the costs and effectiveness of nutrient abatement in the Baltic Sea region in light of how well the existing research can serve long-term dynamic analysis. Also possibilities for further multi-model analysis are studied. When relevant, existing equations and parameters are translated at temporal and spatial scales applicable in further long-term analysis of nutrient abatement.

As a specific outcome, this report directly serves the further steps of the BONUS BALTICAPP project. The results provide the basis for assessment of the abatement effort needed to meet current environmental goal (HELCOM Baltic Sea Action Plan) under alternative baseline nutrient load projections reflecting alternative global climate change and socioeconomic developments.

This report is organized as follows. The second chapter reviews the literature on costs and effects of nutrient abatement in the Baltic Sea region. The third chapter itemizes the requirements for cost-and-effect-models in dynamic analysis. The 4th chapter divides the loads by sectors and source thus giving information on the relative importance of different nutrient sources. Chapters 5-8 itemize the relevant cost functions available for waste water treatment, on-the-site treatment, agricultural measures and atmospheric deposition, respectively. Chapter 9 represents existing cost equations aggregated over several sectors. The final 10th chapter summarizes the review and discusses possible caveats associated with further application of the cost models.

2. LITERATURE REVIEW

Research on the costs and effects of alternative nutrient measures in both point source and non-point nutrient pollution has been accumulating during the past 20 years. In their pioneering study, Gren et al. (1997) showed considerable gains from planning the nutrient reduction measures cost-effectively instead of applying uniform application rates. Ollikainen and Honkatukia (2001) approached the problem more generally and estimated the aggregate cost of the nutrient abatement. MARE research programme (1999-2006) contributed significantly to the development of cost-minimisation models for nutrient loading in the Baltic Sea region. The outcomes of the second phase of the programme were reported in Schou et al. (2006), and they included cost functions, load reductions functions and capacity constraints for six different measures and for each of the riparian countries. Another extensive review is the report by Gren et al. (2008) that summarizes several earlier studies and extends the marginal cost curves for a number of different sectors and nutrient sources.

The most recent and so far the most extensive effort to model the costs of nutrient abatement was taken by the BONUS RECOCA project that developed the spatially detailed BALTCOST cost-minimization model for both point and non-point source nutrient pollution of nitrogen and phosphorus (Hasler et al. 2012, 2014; Wulf 2014). They applied a bottom up approach to calculate cost functions for each watershed. The cost functions were based, where possible, on microeconomic analysis at the farm level (e.g. nonlinear yield functions link the usage of fertilizer with the value of agricultural production). The optimization process itself was conducted using aggregated data for 22 drainage basins and 6 measures. The model can be used for studying the cost of alternative programmes of measures and developing cost effective combinations of measures across the main polluting sectors.

Table 1. A sample of modelling approaches to estimate the costs of nutrient loading reductions to the Baltic Sea

Study	No. of measures	static/dyn	No. of target regions	No. of target levels	Cost function	leaching function, data
Gren et al. (1997)	5	static	14	8	nonlinear	linear, various sources
Ollikainen and Honkatukia (2001)	----	static	9	1	quadratic	----
Schou *et al.* (2006)	5	static	24	1	quadratic	linear, PLC-4 HELCOM data
COWI (2007)	9	static	24	1	linear	linear, based on distance
Gren (2008)	9	static	24	6	nonlinear	linear, PLC-4 HELCOM data
Hasler et al (2014), Wulff *et al.* (2014)	5	static	22	1	nonlinear	nonlinear, high resolution (117 watersheds) DAISY model
Ahlvik *et al.* (2014)	10	dynamic	23	1	nonlinear	nonlinear coupled with marine model
Czajkowski et al. (2017)	14 + 3	static	19,023	5 x 15	nonlinear	non-linear, very high resolution (19,023 grid cells), D AISY model with grid-level combined groundwater and surface water retention, data from various sources

The next approach (Czajkowski et al., 2017) used a similar modelling framework for identifying cost-effective policies for reaching nitrogen reduction targets. Their model is static. It is fully regionalized, in the sense that it uses the bottom-up approach – for any set of N reduction targets (specified at any level) it allows for identifying cost-effective levels of each measure to be implemented in each of the 19,023 10x10 km grid cells, in which the Baltic Sea drainage area is divided to. On the other hand, the model incorporates data for 2 agricultural measures only – fertilization reduction (14 crop types) and livestock reduction (3 livestock types). The model takes three components into account and evaluates them simultaneously: the efficiency of applying a particular measure in a grid cell (in terms of reduced leaching), the retention coefficient for each grid cell (i.e. the proportion of nutrients leached from each grid cell that does not reach the Baltic Sea) and the cost of applying the measures. Each of these components can be disaggregated into more detailed sub-components, each results in a non-linear relationship between the scale of application of the measure and its effect, and each uses grid-cell specific parameters. In addition, the model takes grid-cell levels interactions of the measures into account. Approaching the problem of nutrient reduction using such a disaggregated approach allows for identifying a cost effective solution for targets specified at any level (sea basins, countries, watersheds, and down to the grid-cell level). Both the nutrient loadings, leakage and retention as well as the cost of a proposed reduction are calculated for each grid cell individually and can later be aggregated, to calculate combined effects and costs for any region of the Baltic Sea drainage area.[1]

Another recent attempt to model the costs of nutrient abatement in the Baltic Sea region is Ahlvik et al. (2014). The cost model is largely built on the BALTCOST model and relevant earlier research and it is coupled with a simple box-model for the Baltic. The effect model is designed to include the delays and the dynamics between the implementation of the abatement measures, actual loading and impacts in the marine ecosystem and the interactions between different sectors. Hautakangas et al. (2014) used a sample of the investment and operational costs of the existing waste water treatments plants in the Baltic Sea region to develop total and marginal abatement cost functions for N and P in the sewage treatment.

The common feature in the earlier mentioned studies and models is that the costs and effects are described for one-time investments in technology or permanent changes in management. The costs are typically described in terms of annualized investment costs, and assume that abatement effort, once agreed, remains constant thereafter. Such cost estimates are not directly applicable in dynamic analysis that aims at studying gradual increase in the abatement infrastructure or time-dependent alterations in the abatement technology.

There are also a few studies that have developed cost functions allowing temporal changes in nutrient abatement effort. Lindkvist et al. 2013 applied an aggregated cost and effect model to study the cost trajectories of meeting the Baltic Sea Action Plan loading targets for a number of different baselines reflecting different global climate scenarios. Ahlvik and Hyytiäinen (2015) developed an aggregated nutrient abatement cost model for studying socially optimal nutrient abatement under uncertain but gradually accumulating knowledge about the magnitude and effects of climate change. Their cost equation was built by first ranking and determining cost-effective combination of measures for different effort levels, and then fitting an aggregated function to represent minimum cost at different effort levels as the material. One limitation of such an approach is that the relative costs of alternative measures must be assumed constant over time. The impacts of climate or socioeconomic factors on cost equation are also neglected.

3. REQUIREMENTS FOR COST-AND-EFFECT MODELS IN DYNAMIC ANALYSIS

In long-term dynamic analysis, it is of interest to investigate alternative paths of abatement effort and the potential impacts of global socioeconomic trends and developments on abatement technology and its costs. For this end, several modifications are typically needed to cost and effect models designed for one-time changes:

[1] The RECOCA project reports (http://www.bonusportal.org/about_bonus/bonus_and_era-net/bonus_2009-2011/bonus_projects/recoca) contain a more detailed description of the model.

1. Convert total cost curves to marginal cost curves, and update the marginal cost equation over time as new investment and technical advancement occurs
2. Add state variables for new infrastructure on waste water treatment and the remaining gap in the expansion capacity
3. Integrate the marginal cost curve to obtain periodic costs
4. If relevant and feasible, incorporate the temporal changes in technical progress and other socio-economic drivers and climate change on the effectiveness and marginal costs of different nutrient abatement measures

Nutrient abatement measures that do not involve investment cost are more easily applied in dynamic analysis. Many agricultural abatement measures that are applied annual and do not involve any irreversible changes in the infrastructure belong to this category. For example the cost equations (or parameters) for catch crops are directly applicable in dynamic analysis provided that the input prices (e.g. seed costs) remain unaffected by global developments. On the other hand nutrient abatement that involves new investment or periodic updates in technology in addition to annual maintenance costs require more detailed dynamic modelling with state variables. New investments in waste water treatment infrastructure belong to this category.

4. SOURCE APPORTIONMENT

Table 2 shows the division of initial nutrient loads between different sources and reflect the relative importance of different sectors from external nutrient loading to the Baltic Sea. Source apportionment is based on the fifth Baltic Sea pollution load compilation (HELCOM 2011). The transboundary load and unspecified loads are distribute across sources in the same proportions than the documented loads do. The direct loads ending up directly to the sea are divided between different point sources in the same proportions that they occur in the catchment area. Finally, the totals are adjusted to match the newest reported normalized loads from 2010-12 (HELCOM 2015).

Table 2. Initial nutrient loads by sector in thousand tons per year

Nutrient loads to the Baltic Sea 2010-12	N		P	
Atmosheric deposition to sea	193	23 %	2,1	7 %
Diffuse sources				
Agriculture	293	36 %	12,9	40 %
Background loading	169	21 %	6,1	19 %
Point sources				
Municipal waste water treatement	105	13 %	6,9	22 %
Rural areas outside sewege system	44	5 %	2,8	9 %
Industrial sources	19	2 %	1,0	3 %
Fish farms	1	0,2 %	0,2	0,5 %
Totals	825		31,9	

5. COST MODELS FOR IMPROVEMENTS IN WASTEWATER TREATMENT

BALTCOST model

Documentation: The model has been developed within the BONUS RECOCA project and reported in Hasler et al. (2012, 2014) and Wulff et al. (2014).

Data: population within tertiary, secondary, primary or outside municipal waste water treatment at 10 km x 10 km spatial resolution. Whole Baltic Sea drainage basin is included. The reference year is 2005.

The improvements in wastewater treatment are regarded as connection of additional person equivalent (PE) pollution load to tertiary waste water treatment. The models are applicable to the part of the population that is currently connected to the sewage system or which is technically connectable. The cost functions are developed separately for 23 combinations of drainage basins draining from a riparian country to the Baltic Sea sub-basins. The total costs are given by:

$$TC = a + b * Y + c * Y^d,$$

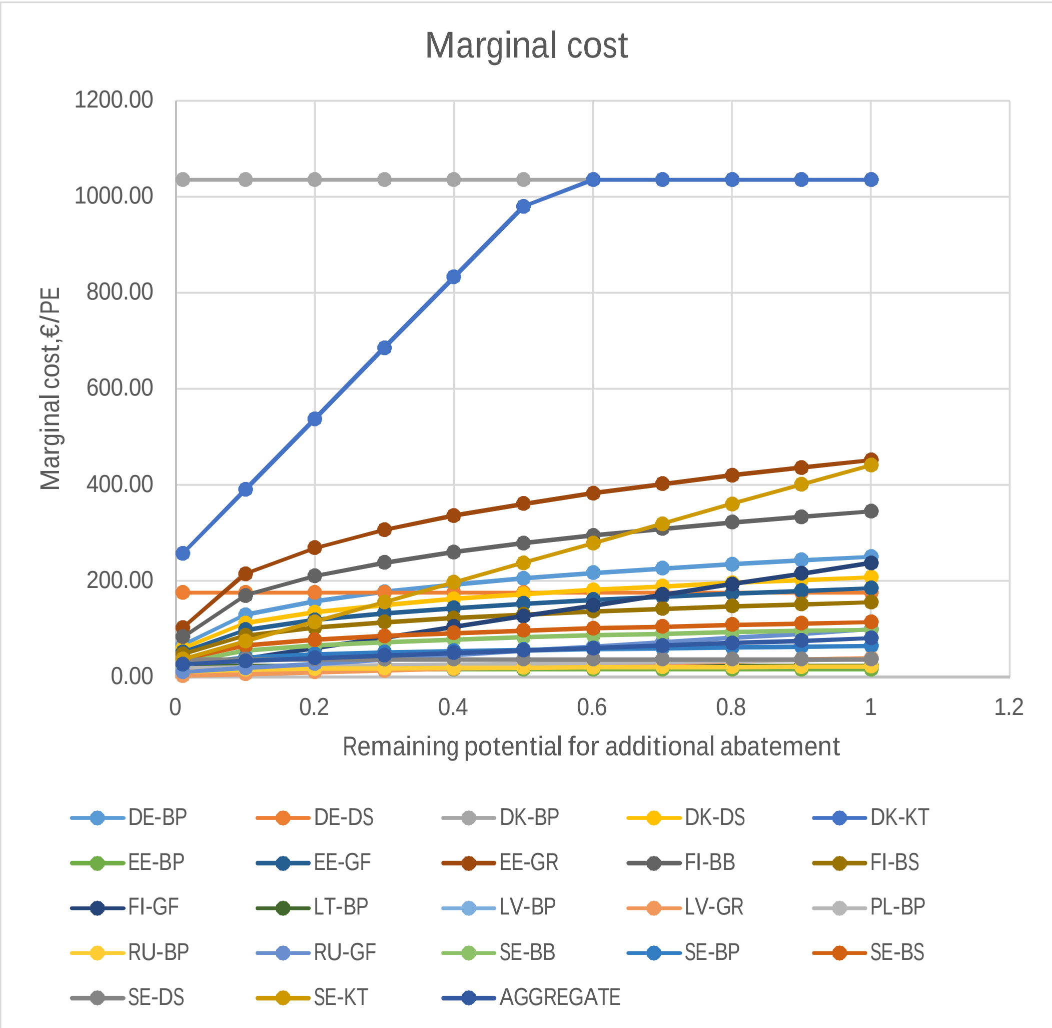
where Y represents the person equivalent pollution load.

Table 3. The parameters of the total cost models for additional waste water treatment (source: Hasler et al. 2014)

Drainage basin	Additional capacity available	a	b	c	d
DE-BP	104320	0	0	7.192	1.2856
DE-DS	51275	0	175.65	0	0
DK-BP	8348	0	18295.2	0	0
DK-DS	264024	0	0	5.71	1.269
DK-KT	291496	1.96E+06	242.7	2.53E-03	2
EE-BP	55097	0	15.84	0	0
EE-GF	74720	0	0	6.607	1.2754
EE-GR	86468	0	0	8.794	1.3219
FI-BB	88528	0	0	7.942	1.3075
FI-BS	129823	0	0	5.905	1.2586
FI-GF	94023	-1.97E+04	16.04	1.18E-03	2
LT-BP	2418962	-8.99E+04	23.64	0	0
LV-BP	275036	0	0	4.113	1.2047
LV-GR	1488380	1.60E+04	2.9	1.24E-05	2
PL-BP	15820718	1.29E+06	18.39	5.99E-07	2
RU-BP	692560	0	0	2.693	1.1462
RU-GF	4705256	1.39E+06	10.1	9.51E-06	2
SE-BB	36792	0	0	5.573	1.2521
SE-BP	575328	0	0	3.907	1.1987
SE-BS	135258	0	0	5.181	1.2438
SE-DS	38748	0	36.77	0	0
SE-KT	231621	-1.58E+05	33.45	8.81E-04	2

In Figure 1 the total cost curves are translated as marginal cost curves for each drainage basin. A ceiling of 1036 €/PE is applied to express areas where on-the-site treatment becomes cheaper than additional investment in municipal waste water treatment. Aggregated for the entire Baltic Sea and assuming uniform increases in abatement in all areas, the marginal costs increase from about 30 € to 80 €/additional PE connected to the tertiary waste water treatment.

Figure 1. Marginal cost of additional investment in waste water treatment in different drainage basins according to Hasler et al.



Hasler et al. 2014 also provides information on the relative contribution of input prices on the cost of waste water treatment:

- Elasticity of total cost with respect to output scale: 1.032
- Cost elasticity to labor price: 0.16

- Cost elasticity to electricity: 0.84

Elasticity of total cost to the input prices can be applied when considering the future costs of waste water treatment under alternative future socioeconomic trajectories for population growth, economic growth and technical development.

Nutrient abatement potential and abatement cost in waste water treatment according to Hautakangas et al. (2014)

Documentation: Hautakangas et al. (2014)

Data: sample from waste water treatment plans, data about the investment and running costs of individual plants

Hautakangas et al. (2014) develop total and marginal abatement costs separately for nitrogen and phosphorus abatement. The data is based on a sample of existing plants in several Baltic Sea countries. Relying on the fact that the investment costs and prices of materials are about the same in different countries, uniform equations are assumed for all countries.

The marginal costs vary in range of 3-12 € per additional abated kg of N and 11-17 € per additional abated kg of P at treatment levels increasing from 30 to 90% and across plants of different sizes. The marginal costs are given as function of treatment level x (expressed as ratio from the full abatement). Interpreted visually from the article, the marginal cost equations are given as:

Table 4. Marginal cost equations of nutrient abatement in waste water treatment

Plant size	*Nitrogen*	*Phosporus*
10000-80000 PE	MC=-0.75+14.2*x	MC=11+6.7*x
80000 - 220000 PE	MC=-0.4+8.7*x	MC=12.4+0.3*x
220000 - 500000 PE	MC=0.55+8.2*x	MC=11.9+0.5*x
> 500000 PE	MC= 1.4+5.3*x	MC=10.6+0.7*x

Note: the costs are expressed for treatment to the receiving water body, not the Baltic Sea

Marginal costs of nutrient load reductions by Gren (2008)

Documentation: Gren et al. 2008

Data: Panel data for Sweden and Poland, extension to other countries

Table 5. Marginal cost of nutrient load reductions (€/kg) to the Baltic Sea

	N reduction		P reduction	
	low end	high end	log end	high end
Denmark	15	35	61	135
Finland	15	45	61	180
Germay	15	48	61	330
Poland	12	48	41	140
Sweden	15	79	61	250
Estonia	12	35	41	138
Lithuania	12	41	41	126
Latvia	12	49	41	147
Russia	12	67	41	220

The costs are given as a range reflecting the location of the plant and the impact of retention. The lower end estimate is relevant for waste water treatment plants on the coastline while the upper end estimate is relevant for plants upstream.

Assuming that the marginal cost increases linearly with additional investment in waste water treatment, the following simplified marginal cost curves can be obtained:

Table 6. Equations for marginal costs of improvements in WWTP. x denotes the additional investment

	N reduction	P reduction
Denmark	MC = 15 + 20*x	MC = 61 + 74x
Finland	MC = 15 + 30*x	MC = 61 + 119*x
Germay	MC = 15 + 33*x	MC = 61 + 269*x
Poland	MC = 12 + 36*x	MC = 41 + 99*x
Sweden	MC = 15 + 64*x	MC = 61 + 189*x
Estonia	MC = 12 + 23*x	MC = 41 + 97*x
Lithuania	MC = 12 + 29*x	MC = 41 + 85*x
Latvia	MC = 12 + 37*x	MC = 41 + 106*x
Russia	MC = 12 + 55*x	MC = 41 + 179*x

Note: convexity of cost to the level of treatment is not considered here

Costs of improvements in waste water treatment according to Schou et al. 2008

Documentation: Schou et al. (2008)

Data: investment and maintenance cost for a sample of existing waste water treatment plans

Schou et al. (2008) give representative example of the investment and maintenance costs of waste water treatement plants of different sizes

Table 7. Investment and operation costs of representative wastewater treatment plants of different sizes

Plant size	Technology	Invesment cost, €	Operation and maintenance cost, €/year	Total costs, €/year	Annual cost, € per PE
2,000 PE	M	325,000	9,750	31,360	15.7
	M+K	475,000	22,500	54,083	27.0
	M+B+N	625,000	33,750	75,307	37.7
	M+B+N+K	875,000	37,500	95,680	47.8
	M+B+N+K+D	1,000,000	46,250	112,741	56.4
30,000 PE	M	2,437,000	82,500	244,539	8.2
	M+K	3,375,000	226,854	451,261	15.0
	M+B+N	3,937,000	243,750	505,525	16.9
	M+B+N+K	7,125,000	478,914	952,663	31.8
	M+B+N+K+D	7,500,000	450,000	948,683	31.6
100,000 PE	M	5,875,000	206,250	596,885	6.0
	M+K	8,125,000	625,000	1,165,240	11.7
	M+B+N	10,000,000	725,000	1,389,911	13.9
	M+B+N+K	15,000,000	1,125,000	2,122,366	21.2
	M+B+N+K+D	18,750,000	1,312,000	2,558,708	25.6

The investment costs are annualized using 3% rates of interest, a depreciation rate of 20 years and PE (person equivalent) wastewater of 72 m3 per person per year. Technology: M = Mechanic; B = Biological; N = Nitrification; D = Denitrification; K = Chemical.

Assuming that mechanical treatment accords with treatment level of 20% for both N and P and the most advanced technology (M+B+N+K+D) accords with the treatment levels of 91 and 96% of N and P, respectively, the marginal costs of improving the waste water treatment are 58, 34 and 28 €/m3 for plant sizes 2,000 PE; 30,000 PE and 100,000 PE, respectively. These translate to the marginal costs of

- 15 €/kg of removed N and 64 €/kg of removed P for 2,000 PE plant size
- 9 €/kg of removed N and 37 €/kg of removed P for 30,000 PE plant size
- 7 €/kg of removed N and 31 €/kg of removed P for 100,000 PE plant size

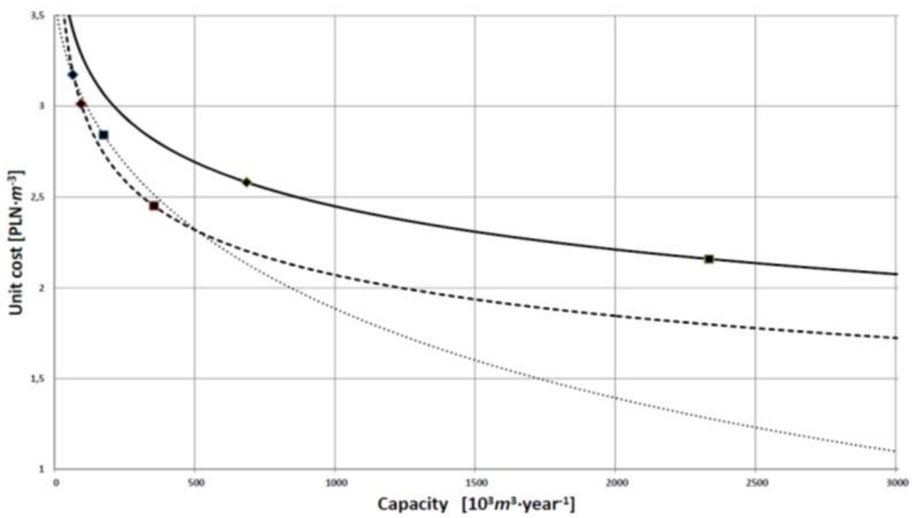
Costs of improvements in waste water treatment according to Barbeka et al 2012

Documentation: Berbeka et al. (2012)

Data: Empirical sample of 1,400 operators, who jointly collect and treat over 80% of wastewater in Poland

Berbeka et al. (2012) provide detailed cost estimates for the collection and treatment of municipal wastewater. The unit costs of collection and treatment, and the nitrogen and phosphorus treatment efficiency were investigated, and the effects of plant capacity on unit costs (scale effects) were explored. They found that wastewater treatment costs were increasing with technology efficiency (moving from the primary, through the secondary, to the tertiary treatment), and decreasing with higher wastewater treatment plant capacity. The results provide a comprehensive picture of municipal wastewater treatment in Poland but potentially, as the technology is fairly generic, they can also be used for applications in other countries, after accounting for capital and labor cost differences. The paper could thus provide an input into cost–benefit analyses of nutrient loading reduction achieved by extending or intensifying municipal wastewater treatment. Figure 2 illustrates the results. [2]

Figure 2. Modeled response of unit cost of treatment and collection with respect to WWTP capacity in Poland according to Barbeka et al. 2012



Unit cost of:

······ Primary treatment*

- - - Secondary treatment

—— Tertiary treatment

Mean and median capacity of each WWTP type:

◆ Median capacity in the sample

■ Mean capacity in the sample

[2] 1 PLN ≈ 0.25 EUR ≈ 0.33 USD

Other estimates

According to Bryhn (2009), the marginal abatement cost for phosphorus to the Baltic Sea vary between 20-138 €/kg of P in urban and rural waste water treatment plants.

One straight-forward way to make "reality check" is to compare the cost of additional waste water treatment with the costs of current waste water treatment infrastructure. The cost of waste water treatment are charged directly from the consumers in the form of waste water fees that typically make part of the water bill in many countries. In Finland, the waste water fee is in the class of 2-3 €/treated m3 of wastewater in municipalities under tertiary treatment. Assuming 60 m3 production of wastewater per capita, the annual cost of waste water treatment are in the class of 2-3 €/m3 x 60 m3 = 120-180 €/year per PE. Assuming 3.9 kg/person and 0.9 kg/person loading of N and P load and equal effort in removing these nutrient in tertiary treatment (80 and 95% treatment levels), the marginal of cost of N removal are in the class:

Marginal cost for nitrogen removal: 19-29 €/kg of N

Marginal cost for phosphorus removal: 70-105 €/kg of P

Marginal cost of treating the nutrient loading of one person: 120-180 €/PE/year

6. COST MODELS FOR IMPROVEMENTS IN ON-THE-SITE WASTE WATER TREATMENT

People living in rural areas that are too sparsely populated to build a new plant or households located too distant to be connected to existing sewage treatment plants have a number of alternative on-the-site treatment systems available.

According to Gren et al. (2008), the marginal cost of private sewers are in the range:

- 46 – 115 €/reduced kg of N
- 215 – 637 €/reduce kg of P

For comparison, consider the following straight forward computation of annualized cost of advanced (tertiary) on-the-site treatment facility:

Investment	10000	€
Life time	15	years
Running cost	150	€/year
Interest rate	4%	

Annualized cost	1036.548	€/year

The marginal cost for household varying between 1 and 5 person are in the class of:

- 41 – 166 €/reduced kg of N
- 166 – 640 €/reduce kg of P

for household draining directly to the sea. The cost of nutrient abatement to the Baltic Sea will increase the further the households are located upstream and higher the retention.

7. COST MODELS FOR MEASURES IN AGRICULTURE

The baseline scenarios extended to agricultural sector in the Baltic Sea region are built on projected developments in the diet preferences and food demand which translate to the regional developments in the number of production animals and changes in land use. Thus, the magnitude of agricultural production and the product mix is largely fixed in baseline scenarios representing different SSPs. In order not to violate the consistency of these assumption behind the baseline scenarios, we focus here on agricultural abatement that either improves the retention capacity of the soil or restrains the leached nutrient reaching the sea (such as wetlands) but does not affect crop yield. The studied abatement measures are

1. catch crops
2. restoration of wetlands
3. Structure liming

Analysis limited to these measures responds to a question how far can the externalities be mitigated without affecting the level of production. It also shows whether the environmental goal is feasible.

Note that there are a number of other potential measures to reduce agricultural loads not considered here:

- reductions of production animals (because the meat supply would be affected)
- large reductions of inorganic fertilization (because they would less to crop yield losses. Inorganic fertilization is strictly regulated already now, and additional reductions in the level of fertilization would lead to significant economic and yield losses
- additional buffer strips (as they reduce the crops in proportion to reduced productive agricultural land)

7.1. Restored wetlands

Baltcost-model (Hasler et al. 2014)

- Description: The abatment measures is limited to restoration of existing wetlands located on organic soils in agricultural land.
- Effect function: uniform 150 kg of N reduction and 0.7 kg of P reduction per 1 ha of wetland restored.
- Cost function: The cost is described as opportunity cost of arable land lost and vary between 186-904 €/ha/year
- Capacity constraint: 1.7% of the drainage basin (in total 29,579 km2) meaning 443,691 tons of N and 2,000 tons of P. The wetland restoration potential varies 0-15% of the total area of drainage basins.
- Computed for N reductions only, the marginal cost of restoring wetland is in the class of 1-6 €/kg of N annually

Schou et al. 2006

- Cost models for (new) wetlands constructed on agricultural land
- cost: opportunity cost of agricultural land, profits gone + administrative costs + machinery & labour cost
- Agricultural opportunity cost: $TC = 0.061x^2 + 215$ where x denotes the area of restored wetland in ha
- Investment cost: 92500 SEK (corresponding about 460 €/year at discounted at 5% rate of interest) following the a study by Söderqvist)
- Administration cost: 66 €/ha
- For a representative hectare the total cost is 215+460+66*0.05 = 670 €/ha/year

Gren et al. 2008

- Constructed wetlands

Table 8. Marginal cost of wetlands to the Baltic Sea (including the impact of retention – the range reflects the location and retention, lower end represents wetlands in the vicinity of the coast)

	N reduction		P reduction	
	lower end	upper end	lower end	upper end
Denmark	7	18	745	925
Finland	1	15	80	250
Germany	2	3	320	410
Poland	1	1	50	70
Sweden	8	290	2745	6790
Estonia	5	7	655	870
Lithuania	2	2	260	260
Latvia	7	10	450	545
Russia	10	15	960	1070

Observations from other studies

- According to Bryhn (2009) The marginal abatement costs for constructing wetlands range between 35 and 643 €/kg of P.
- BalticCompass project reported (Heeb 2012) N removal potential of 34 – 654 kg/ha and P removal potential of 4-12 kg/ha.

7.2. Catch crops

Description: Sowing of rye grass or other catch crops together with spring crops

Baltcost-model (Hasler et al. 2014):

- Cost: The only additional cost is the cost of seed purchase. In Denmark the seed cost is 57,90 €/ha
- Effectiveness: 35% reduction in N leaching
- Potential: Capacity constraint is the annually cultivated area of spring crops

- Assuming a 20 kg/ha nitrogen leaching from cultivated area, the marginal N abatement cost is around 8 €/kg of N.

Gren (2008)

- The minimum marginal costs of catch crops were 5-31 €/kg of N for fields in the vicinity of coast and 160-2030 for P.

Schou et al (2006).

- Catch crop has a positive effect on yields due to extra costs of seeds. The negative effects include the cost of seed and increased weed problem
- Following Danish estimates, catch crop reduce the hectarewise profits by 10%
- The costs vary between 4 €/ha/year (in Lithuania) and 43 €/ha/year (in Denmark and Germany) in Baltic Sea countries

7.3. Structure liming

Description: Structure liming have produced promising results about the potential to improve clay soil structure and to reduce P leaching. Lime is typically in the form of hydrated (slaked) lime ($Ca(OH)_2$). When mixed with a clay soil, several reactions take place at soil aggregate level and an immediate improvement in soil stability, porosity and aggregate strength. Structure liming has been experimented and applied in particular in Sweden (Ulén and Etana 2014).

Cost: According to Berglund and Blomquist 2015, the cost of hydrated lime spread in the field is around 500 kr/ton (representing about 50 €/ton) and cost of mixing with the soil is in the class of 1500 kr (representing about 150 €/ha). Thus application of 7 tons of lime per hectare costs approximately 500 €/ha. Repeated after every 3-5 year and assuming 0.5-1 kg/ha reduction in P leaching, the marginal cost of structure liming is in the class of 100-330 €/kg. Structure liming also tends to increase crop yield

Effectiveness: Structure liming has reduced leaching of phosphorus 36-50% in experiments conducted in Finland (Alakukku and Aura 2006) and up to 60% in experiments conducted in Sweden (Ulén and Etana 2014). In order to turn successful, structure liming must be performed under relatively dry conditions and with thorough and immediate mixing into the soil.

Potential: suitable for soils with high clay content. Structure liming is the most effective in soil with and high initial soil phosphorus concentration.

8. ATMOSPHERIC DEPOSITION

NOx emissions are mainly caused by traffic and combustion process in the countries that share the Baltic Sea catchment area, but also other countries in central Europe. Gren (2008) estimated that marginal costs of reducing NOx emission at source vary in the range of 23-80 €/kg of N finally ending to the Baltic Sea, which is higher than most other abatement measures. On the other hand only a small proportion of atmospheric N deposition finally ends at the sea. Moreover, the NOx emission have been in decline over the last decades, and they are expected to decline during the ongoing century (Rao et al. 2017).

Ammonia (NHx) emission originate mainly from local agricultural production. Ammonia emissions are largely dependent on the total numbers of production animals, storage and spreading technologies of manure.

9. COST MODELS AGGREGATED FOR SEVERAL SECTORS

Lindkvist et al (2003)

Lindkvist et al (2003) describes the total annual cost of nutrient abatement as the quadratic function of deviation between the current and baseline loads of N and P as follows:

$$TC_t = a(N^{bau} - N_t) + b(P^{bau} - P_t)$$

Table 8. The parameters of the cost model (from Lindkvist et al. 2013)

Region	*Nitrogen[1]:* *Kton*	*% of total*	*Phosphorus[2]:* *Kton*	*% of total*	*Coefficients in quadratic cost functions[3]* *N*	*P*
Denmark:		10.0		5		
Kattegat	36		0.8		14.15	4971
The Sound	30		0.9		4.71	2766
Finland:		6.8		9.5		
Bothnian Bay	16		1.5		8.79	4347
Bothnian Sea	18		1.2		8.21	2290
Gulf of Finland	11		0.5		7.78	2993
Germany:		10.7		1.5		
The Sound	23		0.3		8	61982
Baltic Proper	47		0.2		8.04	65525
Poland:		30.3		38.4		
Vistula	118		7.26		0.54	255
Oder	65		4.45		0.99	420
Polish coast	16		1.28		4.75	1483
Sweden:		14.2		11.0		
Bothnian Bay	9		0.95		64.93	10426
Bothnian Sea	18		1.14		24.99	2468
Baltic Proper	26		0.81		6.49	3230
The Sound	6		0.1		6.38	13118
Kattegat	34		0.72		2.95	6712
Estonia:		3.7		3.6		
Baltic Proper	1		0.02		18.77	20227
Gulf of Riga	10		0.25		10.03	9432
Gulf of Finland	13		0.93		1.33	2160
Latvia:		9.0		6.2		
Baltic Proper	8		0.25		22.27	5522
Gulf of Riga	51		1.84		4.93	1635
Lithuania	42	6.4	2.35	7.0	39.55	1268
Russia:		9.0		18.0		
Baltic Proper	10		1.19		43.62	5846
Gulf of Finland	49		4.90		4.68	734
	657	100	33.8	100		

1.Tables B1 and B3 in [20]; 2. Table B2 in [20]; 3 $TC=a(N^{Bau}-N)^2+ b(P^{Bau}-P)^2$ where TC is total cost, N^{Bau} and P^{Bau} in the reference case, and N and P are the optimal loads for achieving nutrient concentration targets [26].

Ahlvik and Hyytiäinen (2015)

Ahlvik and Hyytiäinen (2015) develop and apply cost functions for abatement effort that cumulatively increases over time. The cost at each period of time t is given as function of additional nitrogen abatement Δn_t and phosphorus abatement Δp_t (given as tons)

$$C(\Delta n_t, \Delta p_t) = \omega_1 + \omega_2 \Delta n_t + \omega_3 \Delta p_t + \omega_4 \Delta {n_t}^2 + \omega_5 \Delta n_t \Delta p_t + \omega_6 \Delta {p_t}^2 + \omega_7 e^{\omega_8 \Delta n_t} + \omega_9 e^{\omega_{10} \Delta p_t}$$

The parameters of the model are:

ω_1	0
ω_2	3.353842
ω_3	1.14635
ω_4	0.020453
ω_5	-0.71633
ω_6	22.65089
ω_7	4.27E-05
ω_8	0.074868
ω_9	1.22E-05
ω_{10}	1.320129

The cost function implicitly assumes cooperation and cost-efficient allocation of abatement measures among the littoral countries of the Baltic Sea, and the cost parameters of alternative measures as in Ahlvik et al. (2014)

Table 9. The average annual cost described as €/PE load for additional nutrient abatement effort as in Ahlvik & Hyytiäinen (2015)

	P reduction, 1000 tons/year					
N red, 1000 tons	*0*	*3*	*6*	*9*	*12*	*15*
0	3.3	62.2	123.3	184.7	252.6	597.7
20	14.7	28.3	68.8	118.5	177.2	450.7
40	16.3	21.2	48.3	86.7	135.3	360.3
60	17.9	18.9	38.1	68.3	108.9	299.3
80	19.5	18.2	32.3	56.7	91.0	255.6
100	21.1	18.4	28.9	48.9	78.2	222.8
120	22.7	19.0	26.8	43.4	68.8	197.5
140	24.3	19.8	25.7	39.6	61.7	177.5
160	26.0	21.0	25.2	36.9	56.3	161.4
180	28.1	22.6	25.5	35.3	52.4	148.4
200	31.7	25.7	27.4	35.6	50.7	138.9

10. DISCUSSION

Dynamic cost models reported in Lindkvist et al. (2013) and Ahlvik and Hyytiäinen (2015) are technically applicable for dynamic analysis. They can be associated with various baseline load projections characterized by combinations of regionally downscaled climate scenarios and regionally extended socioeconomic scenarios. These two models can be adjusted with the impacts of overall technological change if such changes can be expected to affect the costs, effects or the capacity constraint proportionally. On the other hand, it is more difficult to make adjustments to such aggregated cost curves if the rates of technological development vary between abatement measures. Thus, more detailed analysis would require that dynamic cost functions are developed for each sector separately. Such sectoral cost models allow temporal changes in the underlying determinants of the cost of abatement, and allow an analyst to better keep track on the abatement infrastructure in each sector.

According to our literature review, the number of cost estimates and independently developed approaches varies much between measures. The richest data is available for wastewater treatment. Interesting feature is that the cost estimates vary quite much from each other. The difference in the cost estimates may come from several sources: representativeness and the size of the investment and running costs, variation in the local conditions, different retention estimates etc. It may not be possible to judge which of the existing studies is more reliable than some other, without collecting a new sample of actual cost data. On the other hand, large number of independently developed functions allow multi-model simulations that can provide insights about the uncertainties associated with the data sources and modelling.

Large variation in the cost estimates for individual measures makes it more difficult to determine the cost-effective combination of nutrient abatement measures. The degree and consequences of uncertainties can be analyzed e.g. by repeating the optimization with alternative combinations of input parameters. Simulation techniques, assuming some exogenously given abatement responsibilities across sectors and space, offer a straight-forward approach for estimating the total costs of abatement programmes in case inadequate data, or if the spatially explicit abatement problem with interacting decision variables becomes technically too challenging to solve.

Two additional caveats are in order when further extending the cost and effect models for comparisons:

Firstly, all of the existing studies reviewed are based on the assumption that the abatement measures can be implemented without any transaction costs associated to the choice and implementation of the policy instrument. Also distributional effects are not typically considered in cost-effectiveness studies.

Second, the existing studies on the cost of the nutrient abatement are based engineering approach or firm-level optimization or partial equilibrium models. Engineering method has been popular in particular for studying the costs of waste water treatment. Firm-level optimization has been applied to estimate the profits foregone from environmental restrictions or altered management in agricultural production (such as reduction of fertilization or production animals). The disadvantage of engineering and farm-level optimization is that they do not account the spill-over impacts to other sectors. The spill over impacts can be positive if environmental policies create additional opportunities for industries and retail sector in the development and production of cleaning technologies. Some of the spillover impacts are negative: for example, reduced agricultural intensity reduces the demand for inputs (fertilizers, fodder etc.). Computable general equilibrium models (CGM) for the entire economy would be the tools to account for dispersion of impacts of abatement on the other sectors of the economy. However, such models have not been used as the main polluting sectors (agriculture, water) still represent only small shares of the economy.

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