Electronic Supplementary Material

Nutrient abatement potential and abatement costs of waste water treatment plants in the Baltic Sea region

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Electronic Supplementary Material A

Data Collection and Definition of WWTP Treatment Technologies

Two main databases from which data was collected at first:

- European Environmental Agency (EEA, 2010a, 2010b) provides a database on Urban Waste Water Treatment Directive (UWWTD) containing data on every reported wastewater treatment plant in the European Union.

- Helsinki Commission (HELCOM, 2006, 2010) collects data on inputs of land-based sources of the Baltic Sea drainage basin, including wastewater treatment plants and their nitrogen and phosphorus emissions.

The additional data sources include the following:

- The Central Data Repository of ReportNet (CDR; EIONET, 2010) provides data for assessing the state of environment in Europe. CDR is used as a reporting system to EEA. Database for Denmark, Estonia, Germany, Latvia and Poland.

- The National Water Management Authority in Poland has implemented The National Programme for Municipal Waste Water Treatment (KZGW, 2010) that offers data on the progress and scenarios of the programme. This data includes technology used in general terms.

- The Agency for Spatial and Environmental Planning in Denmark has published a report as a part of the national monitoring programme also containing detailed information on WWTPs (By- og Landskabsstyrelsen, 2009).

- Unpublished data was provided by Finnish Environment Institute's (2010) VAHTI database, Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg – Vorpommern (2010), and Ministry of Agriculture, Environment and Rural Areas the State of Schleswig-Holstein (2010). The Finnish data was also partially checked using OIVA database (Valtion ympäristöhallinnon virastot, 2010).

- The data on Russian WWTPs is from Vodokanal (2006), Swedish Environmental Protection Agency 2009, 2010) and Ovaskainen (2010).

- Various Internet sources were also used to supplement data of Sweden and Lithuania. For Lithuanian data also scientific articles (Pietilä 2005; Aukštaitijos Vandenys 2009; Klaipedos Vanduo 2010; Šiaulių Vandenys 2010a, 2010b) were used.

- An excursion to Poland was also made to collect data.

- The reference years of the data differs from 2003 to 2009.

- More details on data collection see Ruotsalainen (2011).

The following information was collected from each WWTP: 1) name of the WWTP and the city with coordinates, 2) reference year of data, 3) annual means of the PE loads and the influent flow rates, 4) annual means of the influent and effluent loads of BOD_5[1] or BOD_7[2], COD_{Cr}[3], total nitrogen and total phosphorus, and 5) the process configuration of the WWTP.

Table A1. The estimation of the treatment processes utilizing effluent concentrations and required technological procedures to reach certain abatement levels

N reduction	**P reduction**	**Estimated treatment**	
< 30 %	< 30 %	Mechanical (M)	
30 % - 50 %	30 % - 70 %	Mechanic-biological (MB)	
50 % - 85 %	70 % - 98 %	Mechanical, biological and chemical (MBC)	
> 85 %	> 98 %	Mechanical, biological, chemical and advanced (MBCA)	
N reduction target	**50 %**	**70 %**	**85- 95 %**
Required procedure	40 % more volume in biological process	Methanol addition	Methanol addition and tertiary biological filter
P reduction target	**70 %**	**80- 90 %**	**98- %**
Required procedure	Precipitation chemical addition	Precipitation chemical addition and tertiary sand filter	Precipitation chemical addition, tertiary sand filtration enhanced with final microfiltration

[1] Biological Oxygen Demand; quantity of oxygen consumed over 5 days.
[2] Biological Oxygen Demand; quantity of oxygen consumed over 7 days.
[3] Chemical Oxygen Demand with dichromate method.

Electronic Supplementary Material B

Estimated Abatement outside the Sample

Table B1. Estimated nutrient abatement levels in WWTPs in the population outside the sample in Estonia, Latvia, Lithuania and Poland

Proportion of the WWTPs	**WWTPs 10 000 – 220 000 PE**		**WWTPs over 220 000 PE**	
	½	**½**	**⅖**	**⅗**
Baseline case	**Abatement level**	**Abatement level**	**Abatement level**	**Abatement level**
Nitrogen	30 %	50 %	30 %	50 %
Phosphorus	40 %	60 %	40 %	60 %
Alternative case	**Abatement level**	**Abatement level**	**Abatement level**	**Abatement level**
Nitrogen	40 %	65 %	40 %	65 %
Phosphorus	50 %	70 %	50 %	70 %

Electronic Supplementary Material C

EU's Urban Waste Water Treatment Directive and HELCOM Recommendations

Table C1. EU Requirements and Helsinki Commission recommendations for discharges from WWTPs to sensitive areas. The values for concentration or for the percentage of reduction shall apply

Nutrient	Maximum concentration	Minimum percentage of reduction [4]
EU's Urban Waste Water Treatment Directive		
Total phosphorus	2 mg l^{-1} (WWTP size: 10 000 – 100 000 PE) 1 mg l^{-1} (more than 100 000 PE)	80
Total nitrogen[5]	15 mg l^{-1} (10 000 – 100 000 PE) 10 mg l^{-1} (more than 100 000 PE)[6]	70-80
Recommendations by Helsinki Commission's Baltic Sea Action Plan		
Total phosphorus[7]	0.5 mg l^{-1} (more than 10 000 PE)	90
Total nitrogen[8]	15 mg l^{-1} (10 001 – 100 000 PE) 10 mg l^{-1} (more than 100 000 PE)	70-80

Sources: EEC (1991) and HELCOM (2007).

[4] Reduction in relation to the load of the influent.

[5] Total nitrogen means the sum of total Kjeldahl nitrogen (organic and ammoniacal nitrogen) nitrate-nitrogen and nitrite-nitrogen.

[6] These values for concentration are annual means. However, the requirements for nitrogen may be checked using daily averages when it is proved that the same level of protection is obtained. In this case, the daily average must not exceed 20 mg/l of total nitrogen for all the samples when the temperature from the effluent in the biological reactor is superior or equal to 12 °C. The conditions concerning temperature could be replaced by a limitation on the time of operation to take account of regional climatic conditions.

[7] Discharging directly or indirectly to the marine areas.

[8] Discharging directly or indirectly to the marine areas sensitive to nitrogen.

Electronic Supplementary Material D

Nutrient Reduction Potentials; an Alternative Case

Table D1. Nutrient reduction potentials in each country under different abatement level targets; an alternative case

Country	Nitrogen abatement potential, t a^{-1}			Phosphorus abatement potential, t a^{-1}		
Abatement level	**70 %**	**80 %**	**90 %**	**80 %**	**90 %**	**95 %**
Denmark	0	41	820	0	51	160
Estonia	340	630	1100	69	120	160
Finland	3900	5400	7300	0	0	4
Germany	0	20	540	0	0	1
Latvia	1500	1900	2300	120	190	230
Lithuania	810	1400	1900	120	180	230
Poland	17 500	28 000	40 000	3200	4900	5800
Russia	2500	5000	7600	410	800	1000
Sweden	3100	4700	7800	0	0	3
TOTAL	**30 000**	**47 000**	**69 000**	**3900**	**6200**	**7700**

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

Electronic Supplementary Material E

Untreated Waste Waters in Poland and Russia and Costs of New Sewers

Table E1. Untreated nitrogen and phosphorus loads and combined nutrient reduction potentials of untreated waste waters and in currently treated waste waters at different percentage levels in Poland and Russia

Untreated loads	**POL**			**RUS**		
Nitrogen, t a^{-1}	4380			3395		
Phosphorus, t a^{-1}	821			453		
BOD_7, kg d^{-1}	84 000			31 000		
Reduction potential	**Nitrogen**			**Phosphorus**		
t a^{-1}	**70 %**	**80 %**	**90 %**	**80 %**	**90 %**	**95 %**
POL, untreated	3066	3504	3942	657	739	780
treated+untreated	33 709	45 001	57 074	5 520	7 314	8 274
RUS, untreated	2376	2716	3055	362	407	430
treated+untreated	4852	7721	10 687	770	1202	1470

Sources: EIONET 2010 and HELCOM 2010b.

The costs of new sewers are based on COWI (2007), but inflated to 2010 prices by the cost index of water supply and sewerage in Finland (Statistics Finland 2011). This is the closest index available we had access to. Drawing on these costs, we estimate that the annual costs are roughly 27 million euros in Poland and around 9 million euros in Russia to construct a pipe system to connect non-connected households to the new waste water treatment plants.

Table E2. Annual costs of new sewers connecting households to WWTP in three chosen WWTP size

WWTP size, PE	**Total cost, €**	**Cost PE^{-1}, €**
2 000	160 000	80
30 000	1 500 000	49
100 000	3 700 000	37

Sources: COWI (2007) and Statistics Finland (2011).

Assuming somewhat arbitrarily that Poland and Russia will treat 50 % of their currently untreated waters the PEs are approximately 600 000 and 220 000, respectively. We assume that the waste waters will be handled by constructing several small-sized (approximately 50 000 PE) plants. Thus they need to build 12 new plants in Poland and 4 new plants in Russia. The sewage costs are divided equally among nitrogen, phosphorus and BOD.

Supplementary Material F

Cost Structure of Nutrient Abatement Process in WWTPs

Table F1. Total cost (million euros) calculations of nitrogen abatement in WWTPs 1, 2 and 4 under selected abatement levels

Size class	1 (PE 10 000 – 80 000)			2 (PE 80 000 – 220 000)			4 (PE 500 000 -)		
Abatement	30 %	70 %	90 %	30 %	70 %	90 %	30 %	70 %	90 %
Investment costs (NPV*)	28	43	53	73	81	100	600	710	830
Operating costs (NPV)	11	17	18	31	35	37	93	120	140
Total cost (NPV) a^{-1}	13	2.0	2.3	3.5	3.9	4.7	23	28	32
Share of costs for N	10 %	25 %	40 %	10 %	25 %	40 %	10 %	25 %	40 %
Total cost of N abatement	**0.1**	**0.5**	**0.9**	**0.3**	**1.0**	**1.9**	**2.3**	**6.9**	**13**

*NPV = Net Present Value

Table F2. Total cost (million euros) calculations of phosphorus abatement in WWTP 1, 2 and 4 under selected abatement levels

Size class	1 (PE 10 000 – 80 000)			2 (PE 80 000 – 220 000)			4 (PE 500 000 -)		
Abatement	30 %	70 %	95 %	30 %	70 %	95 %	30 %	70 %	95 %
Investment costs (NPV*)	24	28	29	64	70	71	600	630	630
Operating costs (NPV)	12	12	13	26	26	27	76	78	87
Total cost (NPV) a^{-1}	1.2	1.3	1.4	3.0	3.2	3.3	22	23	24
Share of costs for P	15 %	25 %	30 %	15 %	25 %	30 %	15 %	25 %	30 %
Total cost of P abatement	**0.2**	**0.3**	**0.4**	**0.4**	**0.8**	**1.0**	**3.4**	**5.9**	**7.2**

*NPV = Net Present Value

Investment costs include 4 % expected returns with 30 years life span. Operating costs are discounted by 4 % rate. The costs are allocated to nitrogen, phosphorus and BOD.

Electronic Supplementary Material G

On Interest Rate

We use 4 % real interest rate. The effect of this rate through discounting is moderate, but through the expected returns of investments is remarkable. Increasing the real interest rate to 6 %, the total influence of these two will more than double the average abatement costs of phosphorus, while decreasing the rate to 2 % will cut the average costs by less than a half. The exact results depend on the size of the WWTP as well as on the abatement level, but the above estimations are approximate. In the case of nitrogen the effects are not so great. With 6 % real interest rate the average abatement costs are roughly ⅓ larger, while 2 % rate yields 10 to 20 % smaller costs compared to 4 % rate.

Economics does not provide an unambiguous answer to which real interest rate to choose. Here there are two points of view to be considered. First, the individual interest rate of the WWTPs owners i.e. how they value the future and what are their expected returns of the investments. Second, society's social interest rate i.e. how the society as a whole values the future; bearing in mind that waste water treatment is not naturally lucrative business. Therefore WWTPs are usually owned by society or made possible to be run by private company with various incentives. Nevertheless, waste water treatment plants are financed invariably by the society, in the last resort. Thus, we can fairly use the concept of social discounting.

As the investment period in the WWTPs here is 30 years, we are operating within one generation, saving us from the discussion of intergenerational discounting (see e.g. Portney et al. 1999). The 30 year span is also a long enough period to achieve considerable changes in the status of the Baltic Sea. Society considers this status along with other factors related to investments in waste water treatment to decide upon discount rate. If stressing the environmental part, as would be safe to assume when investing in WWTPs, society should not value present too much over future. Dasgupta et al. (2000) even show that in a special case an optimal social discount rate would be zero. All in all, the real interest rate we use for discounting and for the expected returns is reasonable and rather conservative in economics.

Electronic Supplementary Material H

Average Abatement Costs in WWTPs

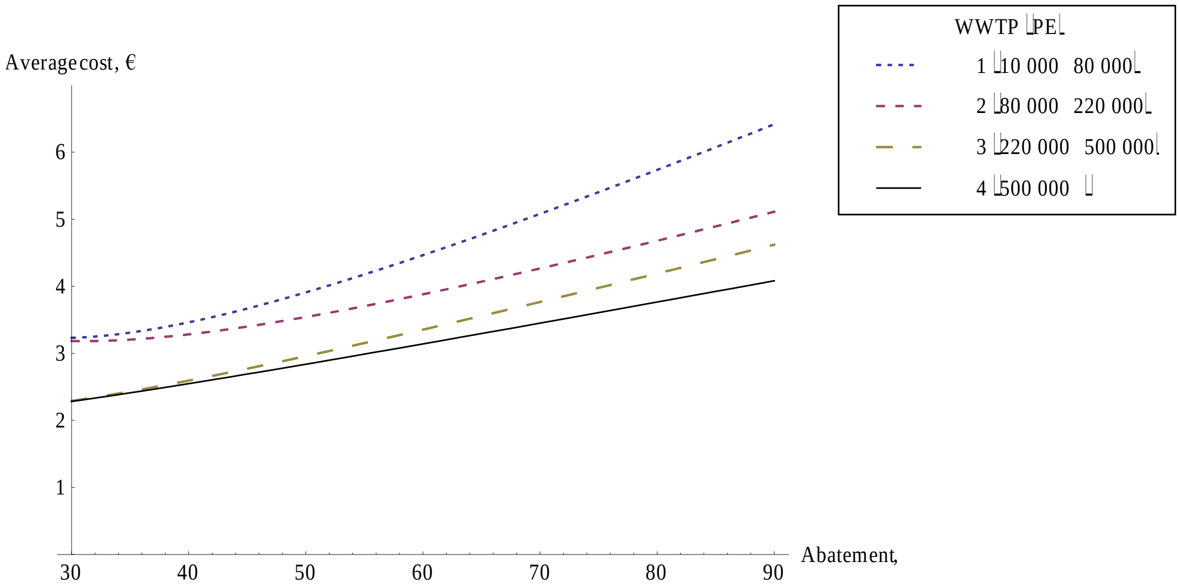

Figure H1. Average abatement cost of nitrogen in WWTPs as a function of abatement for the chosen size classes

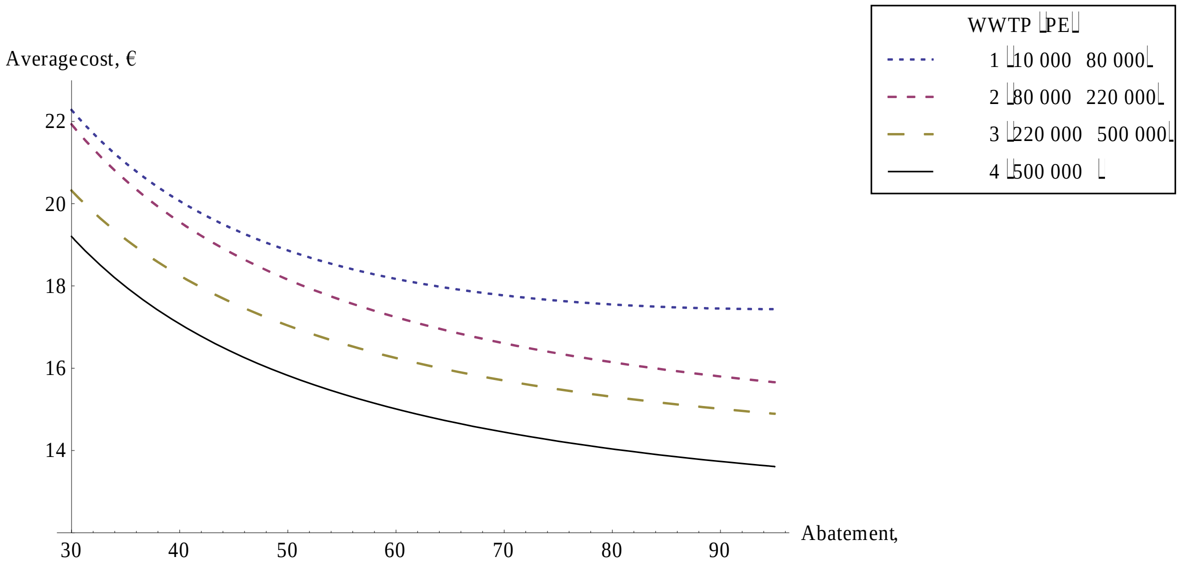

Figure H2. Average abatement cost of phosphorus in WWTPs as a function of abatement for the chosen size classes

Electronic Supplementary Material I

Total Abatement Cost Functions in WWTPs

Total cost functions for nitrogen abatement [9]

$$f(x_{N1}) = 104982 - 2009.73x_{N1} + 124.883{x_{N1}}^2 \quad (N1)$$

$$f(x_{N2}) = 195480 + 354.589x_{N2} + 203.259{x_{N2}}^2 \quad (N2)$$

$$f(x_{N3}) = 209999 + 3496.8x_{N3} + 519.862{x_{N3}}^2 \quad (N3)$$

$$f(x_{N4}) = 263235 + 36778x_{N4} + 1147.99{x_{N4}}^2 \quad (N4)$$

Total cost functions for phosphorus abatement [10]

$$f(x_{P1}) = 82371 + 3008.7x_{P1} + 8.774{x_{P1}}^2 \quad (P1)$$

$$f(x_{P2}) = 198500 + 8146.4x_{P2} + 4.1665{x_{P2}}^2 \quad (P2)$$

$$f(x_{P3}) = 484460 + 22073x_{P3} + 11.528{x_{P3}}^2 \quad (P3)$$

$$f(x_{P4}) = 1533000 + 59981x_{P4} + 35.467{x_{P4}}^2 \quad (P4)$$

Functions describe the total costs of abating nutrients in euros; x_i is the abatement percentage of each nutrient (*N* = nitrogen, *P* = phosphorus) in corresponding WWTP size class($i = N1, .., N4, P1, \dots, P4$).

Size classes:

1. (10 000-80 000 PE)

2. (80 000-220 000 PE)

3. (220 000-500 000 PE)

4. (500 000- PE)

[9] Figure 1
[10] Figure 4

Electronic Supplementary Material J

Cost of Abatement without Untreated Waste Waters

Table J1. Total costs of nitrogen and phosphorus abatement to reach the chosen levels of abatement without untreated waste waters

	Nitrogen abatement, million €			Phosphorus abatement, million €		
Country	**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	12.5	1.6	2.5	3.0
Lithuania	8.7	13	18	2.2	3.0	3.6
Poland	190	280	390	65	89	100
Russia	16	34	54	5	10	13
Sweden	23	39	68	0	0	0
TOTAL	**280**	**430**	**630**	**75**	**110**	**130**

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

Table J2. 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); an alternative case

	Nitrogen abatement, million €			Phosphorus abatement, million €		
Country	**70 %**	**80 %**	**90 %**	**80 %**	**90 %**	**95 %**
Denmark	0	0.5	7.7	0	0	2.3
Estonia	2.4	4.7	8.5	1.0	1.7	2.2
Finland	29	43	63	0	0	0
Germany	0	0	3.4	0	0	0
Latvia	6.7	9.2	12	1.5	2.4	2.9
Lithuania	5.4	9.6	15	1.4	2.2	2.9
Poland	140	240	350	57	82	95
Russia	25	44	67	11	16	19
Sweden	23	39	68	0	0	0
TOTAL	**230**	**380**	**590**	**72**	**100**	**130**

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

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