Technical Report No. 5

External nutrient loads to the Baltic Sea, 1970-2006

April 2012

Oleg P. Savchuk, Bo G. Gustafsson, Miguel Rodríguez Medina, Alexander V. Sokolov & Fredrik V. Wulff

Baltic Nest Institute

The Baltic Nest Institute

The Baltic Nest Institute host the Nest model, a decision support system aimed at facilitating adaptive management of environmental concern in the Baltic Sea.

Nest can be used to calculate required actions needed to attain politically agreed targets for the Baltic Sea ecosystem. By modeling the entire drainage area, Nest is a novel tool for implementing the ecosystem approach in a large marine ecosystem. The main focus of the model is on eutrophication and the flows of nutrients from land to sea.

Reducing the nutrient input to the sea and thus decreasing the negative environmental impacts is a politically prioritized area of international cooperation. Baltic Nest Institute can contribute to this process by formulating policies that are fair, transparent and cost-efficient. The main target group for the Nest Decision Support System is HELCOM and regional water directors in the riparian countries.

Technical Report No. 5
External nutrient loads to the Baltic Sea, 1970-2006 (April 2012)
Authors: Oleg P. Savchuk, Bo G. Gustafsson, Miguel Rodriguez Medina, Alexander V. Sokolov and Fredrik V. Wulff
ISBN: 978-91-86655-04-4
Layout: Marmar Nekoro

Baltic Nest Institute
Stockholm Resilience Centre, Stockholm University
Address: Baltic Nest Institute, Stockholm University, SE-106 91 Stockholm, Sweden
www.balticnest.org

External nutrient loads to the Baltic Sea, 1970-2006

(April, 2012)

Oleg P. Savchuk, Bo G. Gustafsson,
Miguel Rodríguez Medina,
Alexander V. Sokolov & Fredrik V. Wulff

External nutrient loads to the Baltic Sea, 1970-2006

Oleg P. Savchuk,
Bo G. Gustafsson,
Miguel Rodríguez Medina,
Alexander V. Sokolov
and Fredrik V. Wulff

BNI Technical report No 5, 2012

Contents

1. Introduction

Any research related to nutrient biogeochemistry of the Baltic Sea, especially studies of eutrophication requires knowledge of the long-term dynamics of external nutrient inputs. Information accumulated in the HELCOM's pollution load compilations is too aggregated and, until recently, covered only specific years. On the other hand, national datasets with higher resolutions are often difficult to access. Therefore, over the years considerable efforts have been put into a compilation of consistent estimates of nutrient input to the entire Baltic Sea.

Excluding exchange with the Skagerrak from this report, the external nutrient input is considered here as consisting of three component parts: waterborne land loads, direct point sources at the coasts, and atmospheric depositions. The present reconstruction of time series of these three components is based on three major sources. The compilation of the land loads database has started within the project "Large-scale Environmental Effects and Ecological Processes in the Baltic Sea, 1990-1995" (Wulff et al., 2001c), continued during the MARE ("Marine Research on Eutrophication, 1999-2006") project (Wulff et al., 2001a, Eriksson Hägg et al., 2010), and was most recently updated and expanded in connection with the latest HELCOM's activities on the pollution load compilation (HELCOM, 2011) and the revision of the Baltic Sea Action Plan (BSAP, Wulff et al., 2009).

However, there is an important difference between information contained in the HELCOM publications and the data presented here. By its very international nature HELCOM has to deal with whatever data are officially provided by the contracting parties, ending up with certain gaps and inconsistencies in the data sets (*e.g.* see discussion in HELCOM, 2011). On the other hand, considering eutrophication as an imbalance in the large-scale nutrient cycles, whereby more nutrients come into the system than leave it (e.g. Savchuk and Wulff, 2009 and references therein), we need to know the total amounts of external input as close to the reality as possible. Therefore, in our reconstructions we have been trying to both fill such gaps in and correct possible sources of inconsistencies.

The reconstructed data sets have extensively been used by ourselves for various nutrient budget estimates (*e.g.* Wulff et al., 2001b, Savchuk, 2005) and as the boundary conditions for biogeochemical models (*e.g.* Savchuk and Wulff, 2007, 2009) including development of the eutrophication segment of BSAP (Wulff, 2007), as well as by many researchers around the Baltic Sea, for instance, within several projects of the BONUS+ research programme (*e.g.* Eilola et al., 2011; Eriksson Hägg et al., 2011; Meier et al., 2011). The implemented nutrient inputs have naturally been described in these publications, but briefly. In order to facilitate a further distribution of reconstructed inputs and their usage, here we describe the process of reconstruction in more detail and make available the full data sets in digital form.

The data used for the reconstruction have kindly been provided by several institutions and agencies around the Baltic Sea (see below) as well as directly by HELCOM during preparation of PLC-4 and PLC-5 (see HELCOM, 2004, 2011). Since not all data providers had given the permission to distribute the original raw measurements, we have here aggregated all the inputs according to the spatial segmentation of the Baltic Sea (Fig.1) currently implemented in the biogeochemical model BALTSEM (BAltic sea Long-Term large Scale Eutrophication Model). Note also that some part of riverine inputs is available in a decision support system Baltic Nest with a much higher spatial resolution, as is further explained below.

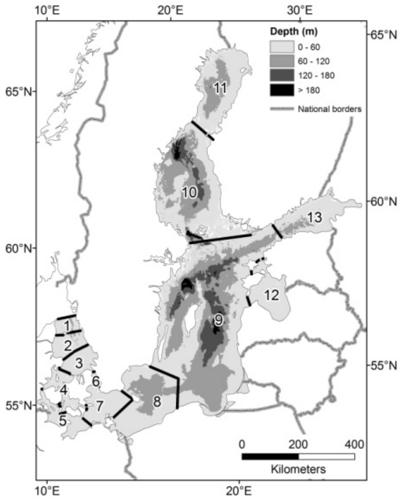

Fig. 1. The Baltic Sea partitioning into thirteen BALTSEM basins.
1 – Northern Kattegat (NK), 2 – Central Kattegat (CK), 3 – Southern Kattegat (SK), 4 - Samsø Belt (SB), 5- Fehmarn Belt (FB), 6 – Öresund (OS), 7 – Arkona basin (AR), 8 – Bornholm basin (BN), 9 – Gotland Sea (GS), 10 – Bothnian Sea (BS), 11 – Bothnian Bay (BB), 12 – Gulf of Riga (GR), 13 – Gulf of Finland (GF); hereafter Kattegat (KT) comprises NK, CK, and SK, Danish Straits – SB, FB, and OS, Baltic Proper – AR, BN, and GS.

2. River loads

The purpose of this reconstruction was to estimate the entire waterborne nutrient input to the marine basins, originated both from monitored and non-monitored watersheds, as well as from diffusive sources in coastal areas. The reconstruction included filling in some "dry" and/or "empty, nutrient free" months in rivers and coastal areas as well as correction of evidently erroneous data. Therefore, the BALTSEM riverine inputs are expected to be generally higher than estimates that can be done from the original data reported to HELCOM.

The Baltic Nest 1970-2000 reconstruction

The data set originally available in the Baltic Environmental Database (BED) was compiled by Per Stålnacke (Stålnacke,1996; Stålnacke et al. 1999) for the period of 1970-1993. These data had been updated and extended with additional information kindly provided by the Estonian Environment Information Centre; Finnish Environment Institute; BALTEX community (http://www.baltex-research.eu); Institutionen för miljöanalys, SLU, Sweden; Joint Research Centre, Vilnius, Lithuania; North-Western Administration of Roshydromet, Russia; Sea Fisheries Institute, Gdynia and Instytut Meteorologii i Gospodarki Wodnej, Warszawa, Poland, and the project SIBER (Silicate and Baltic Sea Ecosystem Response, see Humborg et al., 2008). After careful revision and correction, the resulting reconstructed database was made publicly and conveniently accessible via the decision support system Baltic Nest (http://nest.su.se/nest). Presently, it contains information on monthly water discharge and nutrient loads for 85 main rivers and 95 coastal and non-monitored watersheds almost covering the entire Baltic Sea drainage basin for the period 1970-2000. The available variables are: freshwater runoff (10^6 m^3) and loads (tonnes) of ammonium (NH4), nitrite + nitrate (NO23) and total (TOTN) nitrogen, phosphate (PO4) and total (TOTP) phosphorus, and silicate (SI). The data are openly accessible with annual resolution, while access to monthly resolved data requires a specifically obtained permission.

The actual measurements were not always available for all watersheds for the entire time interval with the same resolution. For example, the data from Estonia and Lithuania for the initial periods were not complete, and then from 1990 onwards the data were available only with annual resolution, and were missing for Estonia in 1991-1994. The data for Denmark and Germany were delivered as a total estimate, i.e. inputs from monitored rivers, non-monitored rivers and coastal areas lumped together both for the freshwater runoff and loads. The data were available with an annual resolution for the Denmark and monthly resolution in the case of Germany. Monthly values were constructed for Denmark by dividing the yearly transport by 12.

The next step in reconstruction of this dataset available in the Baltic Nest was an attempt on filling in all the gaps for the entire time series from 1970 to 2000. For this purpose, the major approach was to establish and use relationships between nutrient concentrations or loads and water discharges.

For reconstruction of missing values in the monitored rivers, first the particular river runoff was reconstructed from total freshwater runoff to the different basins provided by BALTEX. The time series for each river and nutrient variable were reconstructed for each year and each month separately. The data for each river were first sorted by month and then year (all Januaries, all Februaries, etc.). The percentage that each available measured value in the database makes from BALTEX's total freshwater runoff each year for a specific month (% approach) was calculated, and then their average of all years for that particular month was used to fill all missing runoff values for this month. For the 1970s no total runoff data from BALTEX were available as reference for the reconstructions. Therefore, the averages of available runoff data in BED from all years for each river and month were used separately, in a similar way as mentioned above.

Afterwards, the loads presented in tonnes were converted to concentrations in $\mu g\ L^{-1}$ for every nutrient variable. We then used the average monthly concentration of all years for the river in question or from the nearest river with complete series as well as regressions against a complete series (*e.g.* PO4P vs. TOTP) to fill in missing values.

Reconstruction of missing values in coastal (non-monitored) areas was also started with reconstruction of runoff from the available non-monitored data in the database and the total runoff from BALTEX as reference. Once the runoff was reconstructed, the percentage that each available coastal load value makes of the total riverine nutrient load in tonnes was calculated. Then the average of all years for each month was used to fill missing values in.

Finally, the obtained time series were checked for negative values of the difference between total and inorganic fractions: TOTN-(NH4+NO23) and TOTP-PO4. Considering chemical analysis of inorganic fractions more reliable than the analysis of total nutrients, the revealed inconsistent values of TOTN or TOTP were up-scaled from the available values of inorganic nutrient load with the factors TOTN/(NH4+NO23) or TOTP/PO4, estimated from remaining members of time series with positive values of the difference or from the neighbouring areas.

An example of these reconstructed riverine loads, which are currently available in the Baltic Nest, is shown in Fig. 2.

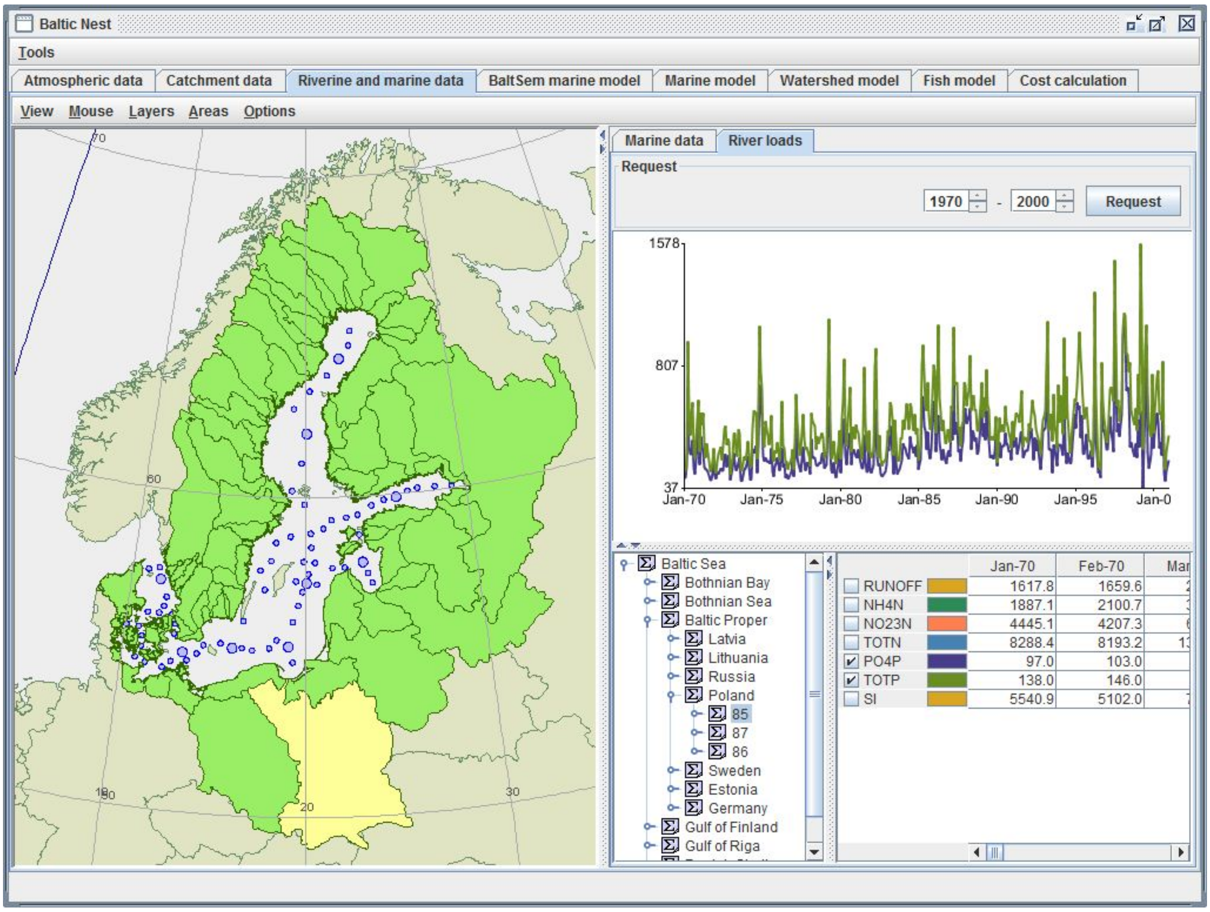

Fig. 2. The riverine database in the Baltic Nest exemplified with the time series of monthly runoff (10^6 m^3 $month^{-1}$) and nutrient input (tonnes $month^{-1}$) from the River Vistula.
The graph shows phosphate (violet) and total phosphorus (olive green) monthly dynamics

Further updating and extension over 2001-2006

The updating and extension of the river load time-series up to 2006 is based on officially submitted national information on annual values for 1994-2006 obtained by BNI from HELCOM during the preparation of PLC-5 (HELCOM, 2011).

Here again, first an attempt was made to fill in gaps in water discharges as averages from the same river for missing years, as well as from regressions between monitored rivers and non-monitored areas or from neighboring rivers. Nutrient loads were then reconstructed from regressions with the filled in time-series on water discharges. The resulting time series have also been checked and appropriately corrected for negative values in the differences between total and inorganic fractions of nitrogen and phosphorus.

Additionally, the time-series for 1971-2005 for BALTSEM basins in the Kattegat and Danish Straits have been somewhat adjusted and refined with the Danish, German and Swedish data compiled and processed in the Danish BNI at the National Environmental Research Institute (NERI), Aarhus University by Cordula Göke and Jingjie Zhang.

In addition to those "routine" corrections for gaps and inconsistencies made as explained above, there are three regions that demanded more elaborate reconstruction: the gulfs of Riga and Finland as well as the Kaliningrad area watersheds.

The Gulf of Riga case

The striking feature of the phosphorus riverine input to the Gulf of Riga is an outstanding level of the ratio between phosphate and total phosphorus loads, appeared already in the data from Stålnacke (Stålnacke, 1996) and then persisted in the updated database (Fig. 3).

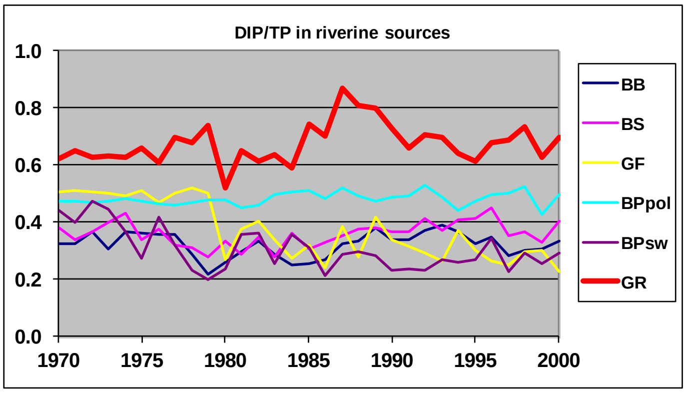

Fig. 3. The proportion (dimensionless) of phosphate in total phosphorus load to the Baltic Sea basins in "Riverine and marine data" module of the Baltic Nest

For abbreviated basin's names see Fig. 1, BP_{pol} and BP_{sw} stand for loads to the Baltic Proper from the entire Polish and Swedish watersheds.

In result, the DIP/TP input ratio to the Gulf of Riga of 0.68 ± 0.07 is surprisingly higher than the ratios of 0.32 ± 0.04, 0.36 ± 0.04, 0.37 ± 0.10, and 0.49 ± 0.02 in the inputs to the Bothnian Bay, Bothnian Sea, Gulf of Finland, and the entire Baltic Proper, respectively. The same high ratios of 0.6-0.8 have also been found in all the major Latvian rivers (Stålnacke et al., 2003), while at the River Daugava mouth it was only 0.4, estimated from unfiltered samples (Yurkovskis and Poikāne, 2008). Furthermore, in the HELCOM PLC-5 time series of annual inputs for 1994-2006, the average DIP/TP ratios in the Kasari, Pärnu, and coastal watersheds draining into the Gulf of Riga from Estonia has the same value of 0.42 in both

1994-2000 and 2001-2006, while in the Daugava, Lielupe, Gauja, Salaca and coastal watersheds draining into the Gulf of Riga from Latvia, the ratio abruptly decreased by a third, from 0.64 in 1994-2000 to 0.42 in 2001-2005, especially noticeably in the last two-three years.

The most likely reason for this peculiarity is that the historical loads of total phosphorus from Latvian rivers draining into the Gulf of Riga were based on filtered samples (Savchuk and Wulff, 2007), as was demanded by manuals for the hydrochemical monitoring in the times of the USSR (cf. *e.g.* Anonymous, 2012). If this was the case, the reported total phosphorus load to the Gulf of Riga was underestimated by the amount of phosphorus occurred in a particulate form. Although the unknown suspended fraction of total phosphorus concentration can be rather variable both seasonally and interannually, we decided to upscale the TP-DIP difference for BALTSEM forcing with a constant factor of 4.5 during 1970-2000, and reconstructed TP time series for 2001-2006 from the regression between water discharge and reconstructed TP time series for 1994-2000. In result, BALTSEM TP loads to the Gulf of Riga almost doubled comparing to PLC-5 (3893±951 t yr^{-1} vs. 2219±586 t yr^{-1} in 1994-2006), while the DIP/TP ratio was reduced down to 0.32±0.06.

The Gulf of Finland case

According to data in the Baltic Nest, the Russian watershed contributed about two thirds to three quarters of the total phosphorus riverine load to the Gulf of Finland. Similarly to the Gulf of Riga case, this input had most likely also been underestimated by the neglected particulate phosphorus fraction. The correction for this missing amount with an intention to bring the DIP/TP ratio closer to the recent values of about 0.2 was made in a step-wise way: the TP-DIP difference was up-scaled with a factor 3 for 1970-1979, and with a factor 2 for 1980-1989, while the 1990s were left as reconstructed for the Baltic Nest.

Even more severe inconsistencies have been noticed in the information on nutrient inputs from the Russian part of the Gulf of Finland drainage area that was officially supplied to HELCOM for preparation of PLC-5. Some of these inconsistencies have recently been confirmed within the BaltHazAR project (Anonymous, 2012). Therefore, the following reconstruction was made in an attempt to overcome these deficiencies.

River Neva water runoff implemented here for the reconstruction of nutrient loads was estimated from time-series of water discharges registered at Novosaratovka monitoring site upstream of the Neva River delta, i.e. before the river branching. As appeared, these water flows are about 10% larger than those contained in PLC-5 data during all the 1994-2006 years except 2001 and 2002, most likely because one of five tributaries to the recipient Neva Bay was omitted in the PLC-5 data.

For some incomprehensible reasons, the minimum detection limit of total phosphorus concentration was set at 40 µg L^{-1} in the Russian data reported to HELCOM. Moreover, the same value of 40 µg L^{-1} was assumed for the samples with concentration below the detection limit, instead of usual 50% value of 20 µg L^{-1} (see also Anonymous, 2012). Most likely, both conditions should result in the overestimation of calculated phosphorus load. Furthermore, the values of total nitrogen load that have been reported only since 2000 and that can be considered as a product of the measured concentration and the water runoff, were actually negatively correlated to the runoff. Therefore, the consistent reconstruction of time series of TN and TP nutrient loads was made in the following three steps.

Firstly, realistic annual inputs were estimated from joint measurements made by the Regional Environment Centre of South-eastern Finland and St. Petersburg Water Research and Control Centre at the mouths of all five Neva River's branches in 2000 (11 samplings), 2001 (14 samplings), 2002 (17 samplings), 2005 (6 samplings), and 2006 (4 samplings - April, July, November twice). Annual average concentrations at each of the five mouths were multiplied by a fixed fraction of annual water runoff discharged via this particular mouth, and then the five inputs were summed up. Next, linear regressions were established between annual water discharges and TN, and TP inputs for 2000-2002 and 2005. Data for 2006 have been excluded from the regression due to both unrepresentative seasonal coverage (compared to other years) and because the South-Western WWTP was launched in the end of 2005 that now collects a fraction of untreated wastewaters previously emitted into the Neva River and discharges treated waters directly into the Neva Bay. Finally, TN and TP annual loads were computed from these regressions for 1994-1999, 2003, 2004, and 2006.

Nutrient inputs from “Russian coastal areas” were available only for 2000, while data for sixteen small rivers were available only for 2003. Therefore, these inputs were treated as invariable between years and summed up with the inputs from direct point sources. In result, our estimates for the annual land loads averaged over 2000-2006 of 72,298 t TN yr^{-1} and 5,399 t TP yr^{-1} occurred to be almost identical to 70,820 t TN yr^{-1} and 5,233 t TP yr^{-1} estimated for 2007-2008 within rather different approach (Kondratyev, 2011).

The Kaliningrad area case

For this area, besides estimates of point sources, national data supplied for PLC-5 contained information only from the River Pregolia, for freshwater discharges only for 2000-2006 and even fewer values of TN inputs, i.e. only for 2004-2006. Thus, TP inputs are entirely missing, while TN data are incomplete. At the same time, data in BED contain all the necessary information for 1994-2000 both for Pregolia River and for diffuse sources. The reconstruction was therefore made in the following way:

1) TN input from River Pregolia was averaged for 2004-2006 and assumed invariable for 2000-2006;
2) TP inputs from Pregolia River in 2000-2006 were reconstructed from a linear regression between annual water discharges and TP loads using data for the same river available for 1994-2000;
3) Nutrient “diffuse” inputs from Kaliningrad area into the Baltic Proper were reconstructed from Pregolia inputs using the ratios between these inputs as established for 1994-2000;

4) Finally, these invariable non-normalised inputs from the watershed were summed up together with the direct point sources.

The final touch

Since in the BED data are available for 1970-2000 as monthly inputs, while the improved HELCOM data with filled in gaps and corrected inconsistencies cover 1994-2006 as annual integrals, the merging of these datasets was made in the following way. The time series from BED for 118 watersheds had been aggregated (pooled together) according to the boundaries of thirteen marine BALTSEM basins (cf. Fig. 1). Aggregated time-series for 1994-2000 (tonnes month^{-1}) have been used to reconstruct basin-wise seasonal patterns in a form of twelve monthly fractions of annual integrals (dimensionless). Finally, these patterns were used as multiplication factors to decompose annual reconstructed integrals aggregated for BALTSEM basins over 2001-2006 into monthly time-series. For silicate, the reconstruction over the 2000s was made from the regressions with the freshwater discharge, estimated from 1970-2000 monthly time series. Examples of reconstructed river loads are presented in Figs. 4-6.

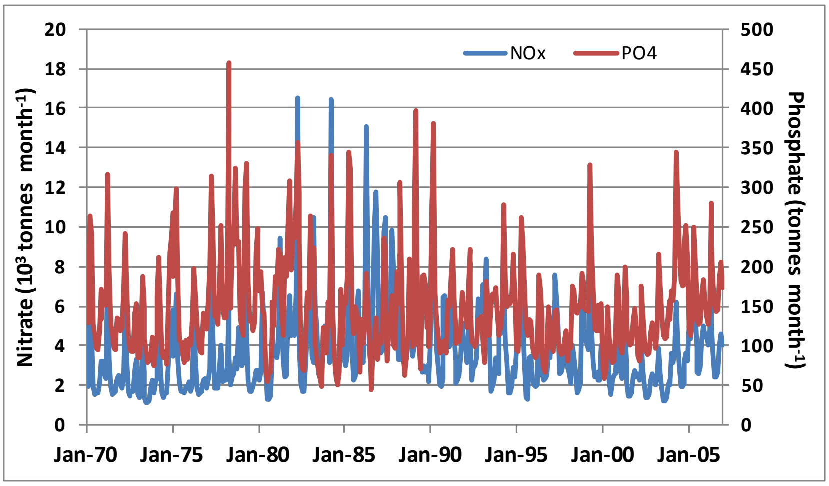

Fig. 4. Reconstructed dynamics of inorganic nutrient loads to the Gulf of Finland

NOx – oxidized (nitrite + nitrate) nitrogen, PO4 – phosphate

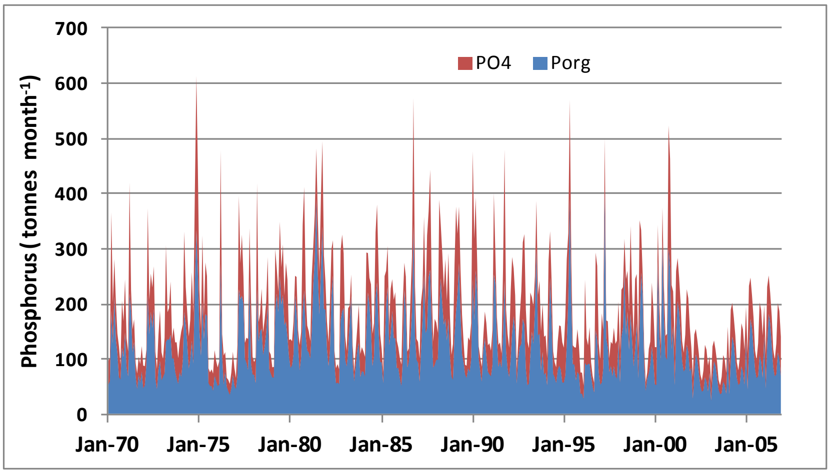

Fig. 5. Reconstructed dynamics of phosphorus load to the Bothnian Sea.

PO4 – phosphate, Porg – difference TP-PO4

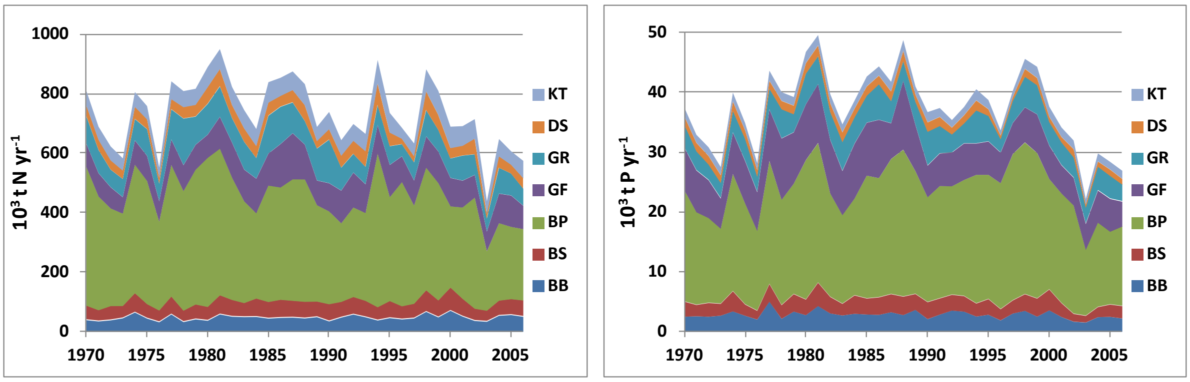

Fig.6. Reconstructed total nitrogen (left) and phosphorus (right) riverine loads into the Baltic Sea basins

For abbreviated basin's names see Fig. 1

The reconstructed time-series of monthly riverine loads of inorganic and total nutrients aggregated for the thirteen BALTSEM basins (tonnes month^{-1} basinXX^{-1}) are contained as Comma Separated Values in the files riverXX.csv, where XX is a number of the basin according to Fig. 1.

3. Direct point sources

The direct nutrient inputs from point sources, situated at the coast, have been reconstructed from annual TN and TP integrals with country-per-basin spatial resolution published by HELCOM (1987, 1993, 1998, 2004) for each fifth year starting from 1985 and, lately annually for 1994-2006 reconstructed on the data obtained from HELCOM within development of the BSAP and preparation of PLC-5 (HELCOM, 2011). For the earlier periods, some old papers, technical reports, and working documents similar to those used, for instance, by Larsson et al. (1985) have been used. The intervals between reference years were filled in by linear interpolation. Reconstruction according to BALTSEM resolution and extrapolation backwards were made with geographical coordinates of over 325 individual point sources reported in 2000 and by the appropriate apportionment based on the data for 1994 (Wulff et al., 2009). As indicated above, Russian direct point sources to the Gulf of Finland were supplemented by the reported annual inputs from coastal area in 2000 and small monitored rivers in 2003, assumed invariable. The reconstructed annual inputs of TN and TP are presented in Fig. 7.

The reconstructed time-series of annual loads of total nitrogen and total phosphorus aggregated for the thirteen BALTSEM basins (tonnes year^{-1} basinXX^{-1}) are contained as Comma Separated Values in the files pointXX.csv, where XX is a number of the basin according to Fig. 1.

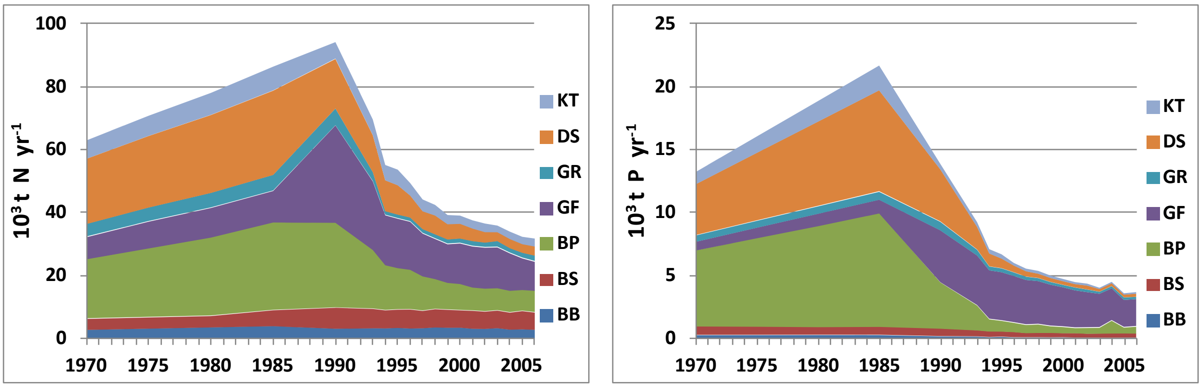

Fig. 7. Reconstructed total nitrogen (left) and total phosphorus (right) loads from the direct point sources into the Baltic Sea basins

For abbreviated basin's names see Fig. 1

4. Atmospheric depositions

Atmospheric deposition of inorganic nitrogen was reconstructed at the Baltic Nest Institute from estimates obtained by Granat (2001) and from simulations made by the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmissions of Air Pollutants in Europe (EMEP, see *e.g.* Bartnicki et al., 2008). The data from Granat are available in BED as monthly mean depositions of four components (wet and dry deposition of reduced and oxidized nitrogen) for 1970-1991 with a spatial resolution of 1° × 1° squares for the entire Baltic Region. The EMEP annual depositions of the same four components for 1980, 1985, 1990, 1995-2006 with a resolution of 50 × 50 km are available through the "Atmospheric data" module of the Baltic Nest. For reconstruction of continuous 1970 – 2006 monthly time series, both BED and EMEP data were first appropriately interpolated and integrated over thirteen BALTSEM basins (see Fig. 1). Next, integrated monthly time-series for 1986-1990 from BED were used to reconstruct basin specific seasonal patterns in a form of twelve monthly dimensionless fractions of annual integrals. Finally, these patterns were used as multiplication factors to decompose annual EMEP integrals into monthly time-series; the 1991 – 1994 gaps were filled with data from (HELCOM, 1997). Dynamics of atmospheric deposition of inorganic nitrogen over the Baltic Sea reconstructed as described above are presented in Fig.8.

Already historical estimates of phosphorus atmospheric deposition of 5,000 – 9,000 tonnes yr^{-1} (Davidavichiene and Sopauckiene 1989; HELCOM, 1987, 1989; Larsson et al., 1985; Nehring and Wilde, 1982) were comparable to phosphorus input from the land of about 40,000 tonnes P yr^{-1} (HELCOM, 1987, 1993). However, for no apparent reason this contribution has been deemed insignificant and atmospheric source of phosphorus was excluded from HELCOM's pollution load compilations (see, for instance, HELCOM, 2011). Generally, the published phosphorus deposition data are rather scarce and fragmentary, and for the Northern Europe are found in the range of 5–40 kg P km^{-2} yr^{-1} (Anttila et al. 1995; Ellermann et al., 2003; Mahowald et al., 2008; Pollman et al. 2002; Rolff et al. 2008;

Savchuk, 2005 and references therein). Dealing with the eutrophication problem determined at large by a balance between nutrient sources and sinks, we cannot afford a luxury of ignorance of the phosphorus atmospheric deposition and, for the sake of simplicity, in our reconstruction assumed 15 kg P km^{-2} yr^{-1} invariably and evenly deposited over the entire Baltic Sea, which with the total marine area of 410,366 km^2 would correspond to annual integral deposition of 6,155 tonnes of phosphate.

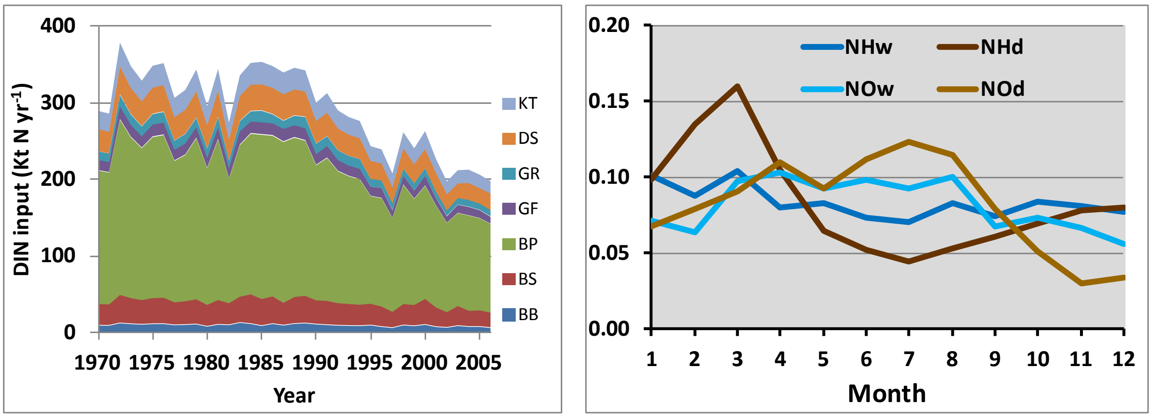

Fig. 8. Nitrogen atmospheric deposition onto the Baltic Sea basins

Left – annual integrals over 7 major basins. Right – dimensionless monthly contributions of wet (w) and dry (d) fractions of reduced (NH) and oxidized (NO) nitrogen compounds. For abbreviated basin's names see Fig. 1

The reconstructed time-series of monthly atmospheric depositions of four components of the inorganic nitrogen inputs together with phosphate inputs aggregated for the thirteen BALTSEM basins (tonnes month^{-1} basinXX^{-1}) are contained as Comma Separated Values in the files atmloadXX.csv, where XX is a number of the basin according to Fig. 1.

5. Total nutrient inputs

Annually integrated reconstructed inputs of total nitrogen and total phosphorus from external atmospheric and terrestrial sources are presented in Fig. 9.

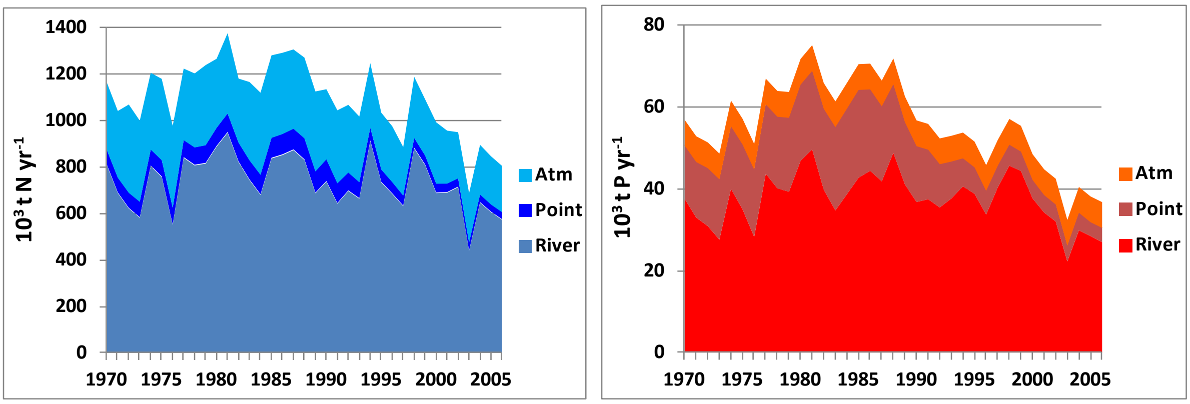

Fig. 9. External inputs of nitrogen (left) and phosphorus (right) to the entire Baltic Sea

For abbreviated basin's names see Fig. 1

6. Comparison of different compilations

As was indicated in the Introduction, these recently reconstructed external nutrient inputs have already been and will further be used for various estimates and simulations, including modelling activity within the revision of the Baltic Sea Action Plan. Therefore it is interesting to compare them both to the official compilation (HELCOM, 2011) and to the earlier estimates made by ourselves (see Marine model module in the Baltic Nest).

As seen in Table 1, there is a close similarity between our current reconstruction finished by July 2009 and HELCOM compilation (Appendix 2 in HELCOM, 2011), but only in "non-problematic" basins, where the reconstructed loads are also slightly higher. The significant differences exemplified also in Figs. 10 and 11 are found in those specific cases with deliberate corrections that were explained above. However, at the basin-wise scale the differences are not large and, probably, are much smaller than the inherent uncertainty of the load's estimates.

Table 1. Comparison of BALTSEM and PLC-5 nutrient riverine loads

Parameter		BB	BS	BP	GF	GR	DS	KT	Total
BALTSEM / PLC5	**TN**	**1.04**	**1.07**	**1.10**	**0.91**	**0.87**	**0.98**	**1.01**	**1.02**
	TP	**1.04**	**1.08**	**1.16**	**0.97**	**1.86**	**0.97**	**1.00**	**1.04**
Correlation coefficient	**TN**	**0.99**	**0.96**	**0.93**	**-0.25**	**0.69**	**1.00**	**1.00**	**0.87**
	TP	**0.99**	**0.98**	**0.96**	**0.39**	**0.59**	**0.99**	**0.96**	**0.88**

BALTSEM/PLC5– ratio between mean loads averaged over 1994-2006; Correlation coefficient – coefficient of linear correlation at the same interval; for abbreviated basin's names see Fig. 1

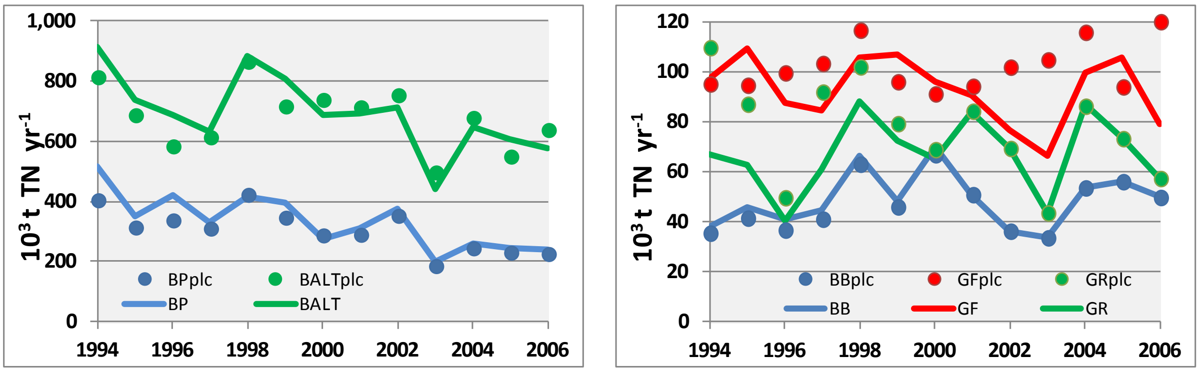

Fig. 10. Nitrogen riverine loads to the Baltic Sea and its basins reconstructed for BALTSEM (lines) and compiled in PLC-5 (dots)
BALT shows loads for the entire Baltic Sea, for abbreviated basin's names see Fig. 1

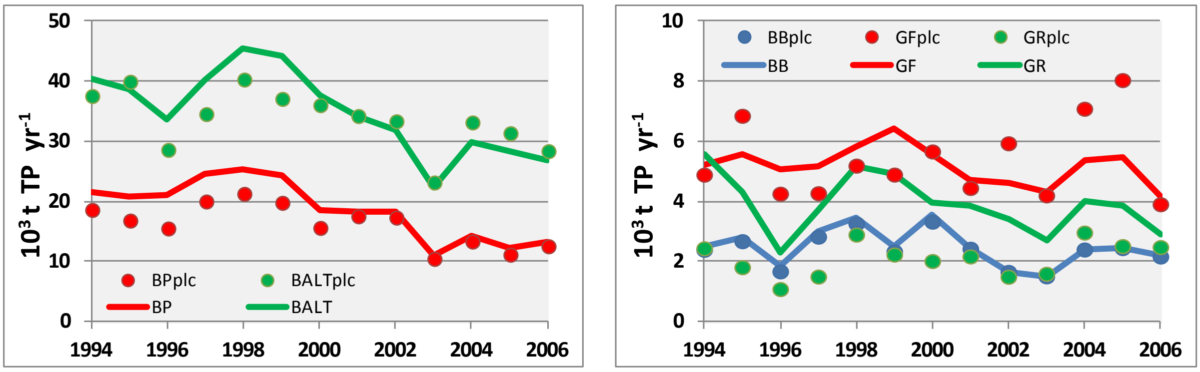

Fig. 10. Phosphorus riverine loads to the Baltic Sea (BALT) and its basins reconstructed for BALTSEM (lines) and compiled in PLC-5 (dots)
BALT shows loads for the entire Baltic Sea, for abbreviated basin's names see Fig. 1

Another specific interest is to compare those average nutrient inputs for 1997-2003 that were used for the country allocation in the BSAP in 2007 (i.e. the same as are given for the SANBALTS model in the Baltic Nest) and the present data set (BALTSEM) with the latest compilation by HELCOM (Table 2). Unfortunately, the main text of published PLC-5 (HELCOM, 2011) contains no digital data for this time interval either on the direct point sources, or on the real, non flow-normalized riverine inputs. Instead, we used our reconstruction of the direct points sources and country-to-basin time-series of riverine TN and TP loads from Appendix 2 to (HELCOM, 2011).

Table 2. Different estimates of TN and TP inputs from the land, average for 1997-2003

Compilation	**BB**	**BS**	**BP**	**GF**	**GR**	**DS**	**KT**	**Total**
Total nitrogen input from riverine and direct point sources (10^3 t yr^{-1})								
SANBALTS	51	57	327	113	78	46	64	737
PLC-5	51	57	321	114	78	45	66	739
BALTSEM	53	60	336	102	71	44	67	733
Total phosphorus input from riverine and direct point sources (10^3 t yr^{-1})								
SANBALTS	2.6	2.5	18.9	6.9	2.2	1.4	1.6	35.9
PLC-5	2.6	2.5	17.9	8.1	2.2	1.4	1.6	38.8
BALTSEM	2.7	2.6	20.6	8.3	4.2	1.3	1.6	41.3

Except of the clear differences produced by our corrections made to the loads into Baltic Proper, Gulf of Riga, and Gulf of Finland, the comparison further confirms a general consistency of estimates, especially for nitrogen. Note, however, that in the current model simulations these loads are augmented by about 277 10^3 tonnes of nitrogen and 6.2 10^3 tonnes of phosphorus being annually deposited onto the Baltic Sea from the sky above it.

7. Concluding remarks

1. Judging by the everlasting discussion in the periodic process of pollution load compilation and from our data mining experience we can hardly expect some additional, non-recovered historical information that could significantly modify the reconstruction presented here. Therefore, further improvements of its reliability can only be made by a careful reconstruction of the dynamics of variety of nutrient sources at the entire Baltic Sea watershed that have then to be coupled to sophisticated mechanistic models of the drainage areas.

2. Here, the presented digital data are aggregated in a correspondence to the spatial resolution of the presently implemented biogeochemical model BALTSEM. Loads with more detailed resolution for 1970-2000 are found in the Baltic Nest, while disaggregation of data for 2001-2006 can be made by variety of methods, for instance, by estimating the required downscaling proportions from the data for 1970-2000.

3. Potential users of the land data should be reminded that in our modelling efforts we consider the differences TOTN-DIN and TOT-DIP, i.e. “organic nutrients” as consisting of two fractions: labile and refractory. For example, in the present version of BALTSEM, only 30% of organic nitrogen in the land loads has been assumed bioavailable (e.g. Ptacnik et al., 2010; Seitzinger et al., 2002, Stepanauskas et al., 2002, Wiegner et al., 2006).

4. Also, in the BALTSEM simulations the deposition of organic nitrogen is assumed to be 20% of DIN wet deposition, or about 12-13% of the total bioavailable nitrogen (*e.g.* Cornell et al., 1995, 2003; Rolff et al. 2008; Savchuk, 2005 and references therein).

8. Bibliography

Anonymous, 2012. DRAFT REPORT on Identification of obstacles in producing reliable data and collecting the existing data. HELCOM BaltHazAR II project, Component 2.2: Building capacity within environmental monitoring to produce pollution load data from different sources for *e.g.* HELCOM pollution load compilations

Anttila, P., Paatero, P., Tapper, U., Jarvinen, O., 1995. Source identification of bulk wet deposition in Finland by positive matrix factorization. Atmos. Environ. 29, 1705 - 1718.

Bartnicki, J., Gusev, A., Aas, W., Fagerli, H., Valiyaveetil, S., 2008. Atmospheric supply of nitrogen, lead, cadmium, mercury and dioxines/furanes to the Baltic Sea in 2006. EMEP Centres Joint Report for HELCOM. EMEP/MSC-W Techn. Rep. 3/2008: 119 pp.

BED – Baltic Environmental Database. http://nest.su.se/bed Accessed 1 April 2012

Cornell, S., Rendell, A., Jickells, T., 1995. Atmospheric inputs of dissolved organic nitrogen to the oceans. Nature 376: 243–246.

Cornell, S., Jickells, T. D., Cape, J. N., Rowland, A. P., Duce, R. A., 2003. Organic nitrogen deposition on land and coastal environments: a review of methods and data. Atmos. Environ. 37: 2173–2191.

Davidavichiene, L.G., Sopauckiene, D.A., 1989. Inputs of nitrogen and phosphorus compounds from atmosphere. In: Davidan, I.N., Savchuk, O.P. (Eds.), Baltica Project. Problems of research and modelling of the Baltic Sea ecosystem. Issue 4. Main Tendencies of the Ecosystem's Evolution. Hydrometeoizdat, Leningrad, pp. 112–118 (in Russian).

Eilola, K., Gustafsson, B.G., Kuznetsov, I., Meier, H.E.M., Neumann, T., Savchuk, O.P., 2011. Evaluation of biogeochemical cycles in an ensemble of three state-of-the-art numerical models of the Baltic Sea. J. Mar. Syst., 88: 267-284.

Ellermann, T., Hertel, O., Skjøth, C.A., Kemp, K., Monies, C., 2003. Atmosfærisk deposition 2002. NOVA 2003. Danmarks Miljøundersøgelser. 90s. – Faglig rapport fra DMU, nr. 466 (In Danish).

Eriksson Hägg, H., Humborg, C, Swaney, D.P., Mörth C.-M., 2011. Riverine nitrogen export in Swedish catchments dominated by atmospheric inputs. Biogeochemistry, DOI:10.1007/s10533-011-9634-7.

Eriksson Hägg, H., Humborg, C., Mörth, C.-M., Rodriguez Medina, M., Wulff, F., 2010. Scenario Analysis on Protein Consumption and Climate Change Effects on Riverine N Export to the Baltic Sea. Environ. Sci. Technol. 44: 2379-2385

Granat, L., 2001. Deposition of nitrate and ammonium from the atmosphere to the Baltic Sea. In Wulff, F., L. Rahm & P. Larsson (eds), A Systems Analysis of the Baltic Sea. Springer, New York: 133–148.

Gustafsson, B.G., Savchuk O.P., Meier, H.E.M., 2011. Load scenarios for Ecosupport. BNI Techn. Rep. No. 4, 18 pp.

Gustafsson, B.G., Schenk, F., Blenckner, T., Eilola, K., Meier, H.E.M., Müller-Karulis, B., Neumann, T., Ruoho-Airola, T., Savchuk, O.P., Zorita, E., 2012. Reconstructing the development of Baltic Sea eutrophication. Ambio. (in print)

HELCOM, 1987. First Baltic Sea pollution load compilation. Baltic Sea Environ. Proc. 20: 56 pp.

HELCOM, 1989. Deposition of airborne pollutants to the Baltic Sea area, 1983-1985 and 1986. Baltic Sea Environ. Proc. 32: 58 pp.

HELCOM, 1993. Second Baltic Sea pollution load compilation. Baltic Sea Environ. Proc. 45: 157 pp.

HELCOM, 1997. Airborne pollution load to the Baltic Sea, 1991-1995. Baltic Sea Environ. Proc. 69: 139 pp.

HELCOM, 1998. Third Baltic Sea pollution load compilation (PLC-3). Baltic Sea Environ. Proc. 70: 133 pp.

HELCOM, 2004. Fourth Baltic Sea pollution load compilation (PLC-4). Baltic Sea Environ. Proc. 93: 188 pp.

HELCOM, 2011. Fifth Baltic Sea Pollution Load Compilation (PLC-5). Balt. Sea Environ. Proc. No. 128, 217 pp.

Humborg, C., Smedberg, E., Rodriguez Medina, M., Mörth C.-M., 2008. Changes in dissolved silicate loads to the Baltic Sea – the effects of lakes and reservoirs. J. Mar. Syst. 73: 223-235.

Kondratyev, S. A., 2011. Estimation of the Nutrient Load on the Gulf of Finland from the Russian Part of Its Catchment. Water Resources 38: 63–71.

Larsson, U., Elmgren, R., Wulff, F., 1985. Eutrophication and the Baltic Sea: causes and consequences. Ambio 14: 9 –14.

Meier, H.E.M., Andersson, H.C., Eilola, K., Gustafsson, B.G., Kuznetsov, I., Müller-Karulis, B., Neumann, T., Savchuk, O.P., 2011. Hypoxia in future climates: A model ensemble study for the Baltic Sea. Geophys. Res. Lett., 38, L24608, 6pp.

Nehring, D., Wilde, A., 1982. Untersuchungen uber den atmospherischen Nahrstofflihtrag in die Ostsee. Acta Hydrochim. Hydrobiol. 10: 89– 100.

Nest – an information environment for decision support system at the Baltic Nest Institute, Stockholm University. http://nest.su.se/nest Accessed 1 April 2012.

Pollman, C.D., Landing, W.M., Perry, J.J. Jr., Fitzpatrik, T., 2002. Wet deposition of phosphorus in Florida. Atmos. Environ. 36: 2309‑2318.

Ptacnik, P., Andersen, T., Tamminen, T., 2010. Performance of the Redfield ratio and a family of nutrient limitation indicators as thresholds for phytoplankton N vs. P limitation. Ecosystems 13: 1201–1214.

Rolff, C., Elmgren, R., Voss, M., 2008. Deposition of nitrogen and phosphorus on the Baltic Sea: seasonal patterns and nitrogen isotope composition. Biogeosciences 5: 1657–1667.

Savchuk, O.P., 2005. Resolving the Baltic Sea into seven subbasins: N and P budgets for 1991-1999. J. Mar. Syst. 56: 1-15.

Savchuk, O.P. and F. Wulff., 2007. Modeling the Baltic Sea eutrophication in a decision support system. Ambio 36: 141-148.

Savchuk, O.P. and F. Wulff., 2009. Long-term modeling of large-scale nutrient cycles in the entire Baltic Sea. Hydrobiologia 629: 209-224.

Seitzinger, S. P., Sanders, R.W. and R. Styles., 2002. Bioavailability of DON from natural and anthropogenic sources to estuarine plankton. Limnol. Oceanogr. 47: 353-366.

Stepanauskas, R., Jorgensen, N.O.G., Eigaard, O.R., Zvikas, A., Tranvik, L.J. and Leonardson, L., 2002. Summer inputs of riverine nutrients to the Baltic Sea: bioavailability and eutrophication relevance. Ecol. Monogr. 72: 579-597.

Stålnacke, P., 1996. Nutrient loads to the Baltic Sea. Ph.D. Thesis. Linköping Studies in Arts and Science 146: 78 pp.

Stålnacke, P., Grimwall, A., Sundblad, K., Tonderski, A., 1999. Estimation of riverine loads of nitrogen and phosphorus to the Baltic Sea 1970-1993. Environ. Monit. Assess 58: 173-200.

Stålnacke, P., Grimvall, A., Libiseller, C., Laznik, M. and Kokorite, I., 2003. Trends in nutrient concentrations in Latvian rivers and the response to the dramatic change in agriculture. Journal of Hydrology 283: 184–205

Wiegner, T.N., Seitzinger, S.P., Glibert, P.M., Bronk, D.A., 2006. Bioavailability of dissolved organic nitrogen and carbon from nine rivers in the eastern United States. Aquat. Microb. Ecol. 43: 277-287.

Wulff, F., 2007. An approach to set country-wise nutrient reduction allocations to reach good ecological status of the Baltic Sea. Adopted at the HELCOM Heads of Delegation 22nd Meeting, Helsinki, Finland, 17-19 September 2007. BSAP, background documents, 34 pp. Accessed 1 April 2012 from http://www.helcom.fi/BSAP/en_GB/intro

Wulff, F., Bonsdorf, E., Gren, I.-M., Johansson, S., Stigebrandt, A., 2001a. Giving advice on cost effective measures for a cleaner Baltic Sea: a challenge for science. Ambio, 30: 254–259.

Wulff, F., Humborg, C., Rodriguez-Medina, M., Mörth, M., Savchuk, O.P., Sokolov, A., 2009. Revision of the country allocation of nutrient reductions in the Baltic Sea Action Plan. Section A: Hydrological adjusted riverine loads and atmospheric loads from different countries averaged for 2000 – 2006. Compilation June 5, 2009. BNI Techn. Rep. No 1: 49 pp.

Wulff, F., Rahm, L., Hallin, A.-K., Sandberg, J., 2001b. A nutrient budget model of the Baltic Sea. In: Wulff, F., Rahm, L., Larsson, P. (Eds.). *A Systems Analysis of the Baltic Sea.* Springer, N.-Y., Berlin, pp. 353–372.

Wulff, F., Rahm, L., Larsson, P. (Eds.), 2001c. A Systems Analysis of the Baltic Sea. Springer, N.-Y., Berlin, 455 p.

Yurkovskis, A., Poikāne, R., 2008. Biogeochemical, physical and anthropogenic transformations in the Daugava River estuary and plume, and the open Gulf of Riga (Baltic Sea) indicated by major and trace elements. J Mar. Syst. 70: 77-96.