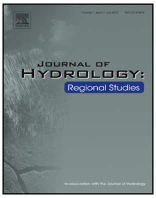
Journal of Hydrology: Regional Studies 1 (2014) 44–56

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh



Societal, land cover and climatic controls on river nutrient flows into the Baltic Sea

Rémon Saaltink[a,*], Ype van der Velde[b], Stefan C. Dekker[a], Steve W. Lyon[c,d], Helen E. Dahlke[e]

[a] Department of Environmental Sciences, Copernicus Institute of Sustainable Development, Utrecht University, Utrecht 3508TC, The Netherlands
[b] Soil Geography and Landscape, Wageningen University, Wageningen 6700AA, The Netherlands
[c] Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden
[d] Baltic Nest Institute, Baltic Sea Centre, Stockholm University, Stockholm, Sweden
[e] Department of Land, Air & Water Resources, One Shields Avenue, Davis, CA 95616-8627, United States

ARTICLE INFO

Article history:
Received 10 March 2014
Received in revised form 6 June 2014
Accepted 7 June 2014
Available online 15 July 2014

Keywords:
Baltic Sea Drainage Basin
Correlation analysis
Eutrophication
Factor analysis
N:P ratio
Trend analysis

ABSTRACT

Study region: River basins draining into the Baltic Sea, known as the Baltic Sea Drainage Basin (BSDB).
Study focus: Dramatic shifts in water quality have been observed in the Baltic Sea in past decades. This study investigated the spatial distribution of trends in nitrogen (N) and phosphorus (P) in relation to societal, land cover and climatic changes. A 31-year record of observed catchment scale nutrient concentration and discharge data for the period 1970–2000 was combined with climate and land cover data. A Mann–Kendall test was applied to reveal trends in N and P, the N:P ratio, discharge, temperature and precipitation. Classical factor analysis and Kendall's rank correlation identified the most important relationships between nutrients, land cover and climate.
New hydrological insights for the region: A large spatial variability in N and P trends was observed with a notable difference between the east and west of the BSDB. The existence of regional trend variations are important for nutrient load reduction management strategies. Specifically, it is recommended that strategies targeting seawater eutrophication should focus more on P rather than N reduction because increasing P in the eastern catchments is responsible for the overall declining trend in the N:P ratio, an important trigger for algal blooms.

---

* Corresponding author. Tel.: +31 30 253 2404.
E-mail address: r.m.saaltink@uu.nl (R. Saaltink).

http://dx.doi.org/10.1016/j.ejrh.2014.06.001

1. Introduction

In past decades, dramatic shifts in water quality have been observed in the Baltic Sea. Problems occurring with such shifts include stagnation events that have resulted in anoxic bottom waters, the spreading of dead bottom zones and increased frequency and intensity of algal blooms (Boesch et al., 2006, 2008; Österblom et al., 2007; Vahtera et al., 2007; Voss et al., 2011). Of particular concern are blooms of toxic dinoflagellates and raphidophytes, which cause fish mortalities in both the wild and aquaculture (Boesch et al., 2006). More of these events are likely to occur in the future as the majority of projections point to increased nitrogen (N) and phosphorus (P) loads coming into the Baltic Sea in the 21st century (Graham and Bergström, 2001; Hägg et al., 2013; Reckermann et al., 2011). In addition to loads, it may be insightful to consider other indicators such as the N:P ratio which can also change under conditions where one nutrient is declining/increasing faster than the other. This in turn can cause algal blooms as different optimal N:P ratios exist for the growth of various algae (Anderson et al., 2002; Hodgekiss and Ho, 1997). As such, monitoring the water quality of the rivers that drain into the Baltic Sea is important as they directly influence the Sea's water quality state (Jansson and Stålvant, 2001). This is because the Baltic Sea has little water exchange with the North Sea, and as a result is more susceptible to anthropogenic impacts compared to other, more open, seas (Pastuszak and Igras, 2012; Pawlak et al., 2009). Therefore, it is important to understand and identify mechanisms that control the water quality in the catchments surrounding the Baltic Sea, known as the Baltic Sea Drainage Basin (BSDB).

Investigating possible mechanisms influencing the water quality of the rivers draining the catchments in the BSDB, however, is not straightforward as differences exist among the catchments in terms of societal, land cover and climatic characteristics (Graham and Bergström, 2001; Thorborg, 2012). Changes in society, land cover and climate can all lead to changes in the water quality of the catchments. Hägg et al. (2013) showed that regional anthropogenic effects are potentially more important for projecting nutrient load than climate change impacts. Anthropogenic effects are evident in a large part of the BSDB manifested through "the fall of the iron curtain" in 1989, which was an important societal change creating a clear transition period. During the transition period following the 1989 events, several fundamental shifts associated with livelihoods within the BSDB occurred including: (1) a drop in artificial fertilizer and manure application, (2) a decrease in livestock keeping, (3) closure of several factories, (4) improvements in farm management practices and (5) modernization of wastewater treatment plants all impacted the nutrient dynamics (Iital et al., 2005; Pastuszak et al., 2012). In addition, land cover change affected the hydrological cycle by altering infiltration, groundwater recharge, base flow and run-off in catchments (Lin et al., 2007; Todd et al., 2007). In the BSDB, conversion of wetlands into forests or agriculture have had significant impact on the terrestrial water balance as wetlands can maintain high discharges in dry periods of the year, which in turn alters flow regimes (Lyon et al., 2012; Van der Velde et al., 2013).

Climate change potentially influences water quality through several mechanisms. Temperature and precipitation change can cause changes in river flow regimes, which in turn affect hydrology and water quality. According to Wilson et al. (2010), a trend in temperature may cause long-term changes in the seasonal distribution of flow and in the magnitude and frequency of floods and droughts in Scandinavia. The same conclusion from model results was reported by Moore et al. (2008). Wright (1998) reported that an increase in temperature resulted in an increase in decomposition of organic matter leading to enhanced amounts of N in a river area in Norway. Similar observations were reported for P (Bowes et al., 2009).

Several regional studies have shown that changes in society, land cover and climate impacted the water quality of individual rivers in the BSDB in various ways (Hussian et al., 2005; Iital et al., 2005; Pastuszak et al., 2012). Recent modelling studies projecting future changes of nutrient loads into the Baltic Sea focused on the basin scale (Arheimer et al., 2014; Donnelly et al., 2014; Meier et al., 2012, 2014) whereas the Helsinki Commission (HELCOM) provided data on riverine nitrogen and phosphorus inputs on the basin to the sub-basin scale (e.g. HELCOM, 2011, 2013). The aforementioned modelling studies are often considered by policy makers when they formulate and implement management strategies. However, an overall spatial analysis on the catchment scale in the BSDB has not been presented yet. Such an analysis might reveal additional information which can lead to more focused and effective management strategies. In this study we aim to investigate the spatial distribution of trends in N and P at the catchment scale and relate these to changes in society, land cover and climate. Such a spatially explicit regional analysis is essential to establish understanding of factors influencing observed trends in total N and total P in order to develop workable management strategies that can improve water quality of the Baltic Sea.

2. Material and methods

2.1. Data sampling

The Baltic Nest Institute (BNI) compiled a uniform dataset based on measurements of monthly discharge and nutrient concentrations of total N (TN) and total P (TP) for 117 catchments flowing into the Baltic Sea (Mörth et al., 2007; Smedberg et al., 2006). Time series of 84 catchments span the period 1970–2000, while 33 catchments have data available for the period 1980–2000. Data after the year 2000 are not available. To complement these data, monthly averages of temperature and precipitation of each catchment were obtained from the E-OBS gridded dataset (Haylock et al., 2008, http://eca.knmi.nl). This is a high resolution grid (10 km × 10 km) based on roughly 250 weather stations in Europe (Haylock et al., 2008). Also, fractions of land cover for the year 2000 in the BSDB were retrieved from the Corine Land-use dataset for European catchments. For catchments in Russia, the Global Land Cover dataset was used. These two datasets were merged by the BNI (Mörth et al., 2007). The types of land cover extracted are artificial (urban) area, cultivated area, deciduous forest, coniferous forest, mixed forest, shrubs and herbs, wetlands and water bodies (rivers and lakes).

2.2. Dataset preparation

For some years in six catchments located in Estonia, Latvia and Russia (one catchment in the period 1970–1976 and five catchments in the period 1994–2000) only yearly average values for discharge, TN and TP were reported. To restore the monthly seasonality in the data for these catchments and periods, the average monthly deviations from the yearly mean derived from the years with monthly measurements were used to correct the reported yearly average value. Six other catchments were rejected completely for analysis because both monthly and yearly variability was lacking for the period 1980–1990. The rejected catchments were located in the Danish Straits and the Kattegat.

In this study, it was worthwhile to distinguish between nutrient concentrations and loads (hereafter referred to as TN_C, TP_C for concentrations and TN_L, TP_L for loads). In addition, we considered specific loads of nutrients ($\mathrm{kg\,km^{-2}\,yr^{-1}}$) obtained by multiplying concentrations with the discharge and dividing by catchment size. Total loads ($\mathrm{kg\,yr^{-1}}$) were also considered in this study. With the total load, the net changes in TN and TP exported to the Baltic Sea were calculated. From the total loads, the N:P (mass) ratio was derived which formed another important variable in this study.

To analyze potential differences in processes impacting nutrient loads and concentrations by societal change, the BSDB was split up in east and west. All catchments that were located at the eastern side of the historical iron curtain were labelled as ‘east’, the remaining catchments as ‘west’ (Figs. 2 and 3 show this division). This way, three groups were created for analysis: “east”, “west” and “east + west”. Although the east covers $1004 \times 10^3\,\mathrm{km}^2$ and the west $711 \times 10^3\,\mathrm{km}^2$, the number of catchments in the east is less than in the west (28 and 83 respectively). This is because smaller catchments are located in the west than in the east (catchment size in the dataset differ from $302\,\mathrm{km}^2$ to $280 \times 10^3\,\mathrm{km}^2$). It is this difference that motivates the primary use of specific loads in the study with total loads as complimentary data.

2.3. Data analysis

For each group (east, west and east + west), aggregated yearly time series were constructed for temperature, precipitation, discharge, TN_C, TN_L, TP_C, TP_L and the N:P ratio to characterize the interannual variability. The aggregated yearly averages for the time series (Fig. 1) and the aggregated averages of all

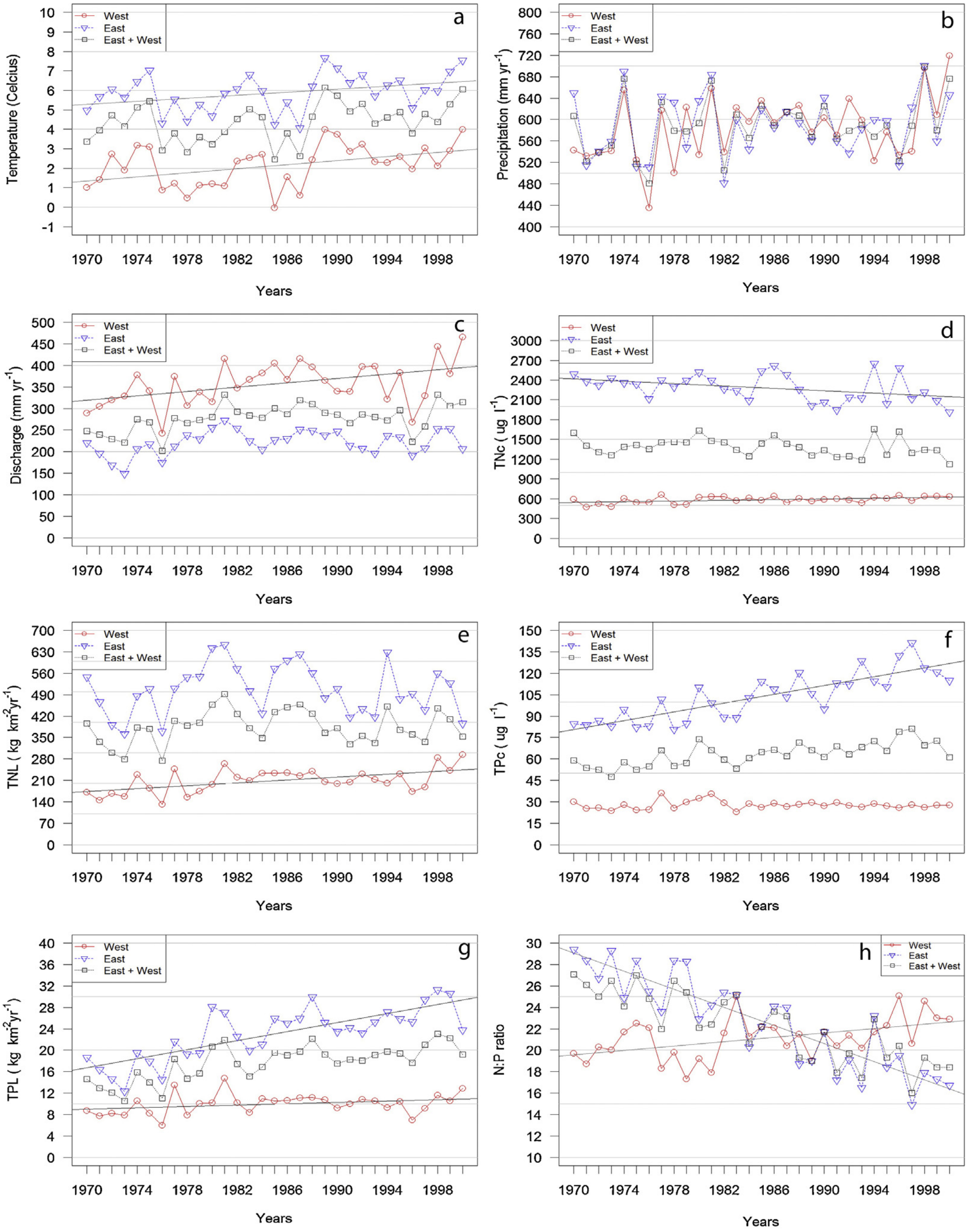


Fig. 1. Aggregated yearly time series for the period 1970–2000 for temperature (a), precipitation (b), discharge (c), TN_C (d), TN_L (e), TP_C (f), TP_L (g) and the N:P ratio (h). A distinction was made between east (blue), west (red) and east + west (black). Trend lines (black) shown only if the Mann–Kendall trend test confirmed a significant trend.

Table 1
Average values for the period 1970–2000 for catchment size, temperature, precipitation, discharge, TN_C, TN_L, TP_C and TP_L divided by east, west and east + west.

Variable	Unit	East	West	East + west
Catchment size	km^2 (×10^3)	1004	711	1715
Temperature*	°C yr^{-1}	5.9	2.1	4.4
Precipitation	mm yr^{-1}	590	584	588
Discharge*	mm yr^{-1}	221	357	277
TN_C*	$\mu g\,l^{-1}$	2284	583	1387
TN_L*	kg km^{-2} yr^{-1}	506	209	384
TP_C*	$\mu g\,l^{-1}$	103.7	27.8	63.3
TP_L*	kg km^{-2} yr^{-1}	23.0	9.9	17.6
N:P ratio		22.6	21.1	22.2

* Indicates that the average values between east and west are significantly different ($p < 0.05$).

years (Table 1) for the three groups were calculated by accounting for the catchment size. Furthermore, a paired *t*-test was applied to test whether variables are significantly different for east and west.

To detect significant trends in the monthly time series of temperature, precipitation, discharge, TN_C, TN_L, TP_C, TP_L and the N:P ratio, a seasonal Mann–Kendall trend test was carried out for each catchment in the BSDB (the significance level was set to 0.05). The seasonal Mann–Kendall trend test is a non-parametric test for the existence of a monotonic trend and has the advantage that the power and significance of the test are not affected by the actual distribution of the data (Hamed, 2009; Hipel and McLeod, 2005). For all significant trends, the slope was determined using an ordinary least square regression to estimate the true slope of the linear trend present in the time series. The slopes were categorized using the Jenks natural optimization method. This statistical mapping method is a common way to determine optimal size classes by minimizing the squared deviations of the class means. The Mann–Kendall trend test was also carried out to investigate the existence of trends in the aggregated annual temperature, precipitation, discharge, TN_C, TN_L, TP_C, TP_L and the N:P ratio time series.

In addition to these straightforward trend investigations, the Kendall rank correlation coefficient τ was estimated to determine the statistical dependence between two time series of variables based on the slope of significant trends. Tau-values near zero indicate statistical independence of the compared quantities, while τ-values near 1 (or −1) indicate that the two variables tend to strongly move in the same (opposite) direction. TN_L and TP_L were excluded from this analysis because loads are composites of discharge and TN_C or TP_C and thus lead to spurious correlations.

To analyze potential differences in processes impacting nutrient loads and concentrations by land cover and climate change, a classical factor analysis was carried out. Because land cover variables were only available for the year 2000, all remaining variables used in the factor analysis were averaged over the period 1996–2000 to represent a reliable (stable) average that can be correlated to the land cover of the year 2000. We assume that no significant changes in land cover occurred during this 5-year period. The catchment size was also included in the analysis to see if size is influencing nutrient loads and concentrations. Furthermore, TN_C, TN_L, TP_C and TP_L were excluded in the analysis to isolate climate- and land cover related factors. In the factor analysis, no distinction was made between east and west due to the fact that the east contains too few catchments (28) for a reliable estimate of the factor loadings and scores. Therefore, east and west were grouped together. First, all land cover variables, discharge and the catchment size were log-transformed (temperature and precipitation were already normally distributed) where after the factor loadings and factor scores of the first three factors were extracted from the analysis (a varimax rotation was used for the factor loadings). In the factorial analyses, the first three factors reflecting the most important relationships among the variables were used in this study. The factor loadings were used to interpret the factors whereas the factor scores were used for Kendall's rank correlation. Here, the scores and the original variables of TN_C, TN_L, TP_C and TP_L were put into the analysis to see if the factors were significantly correlated with the corresponding nutrients.

Table 2
Results of the seasonal Mann–Kendall trend test. Trends are divided in east and west. %pos and/or %neg show the percentage of area that contains a positive/negative significant trend in east or west. Δpos and/or Δneg show the average change per year of the positive/negative trends. Δ of temperature is in $^\circ C\,yr^{-1}$, Δ of precipitation and discharge is in $mm\,yr^{-2}$, Δ of TN_C and TP_C is in $\mu g\,l^{-1}\,yr^{-1}$ and Δ of TN_L and TP_L is in $kg\,km^{-2}\,yr^{-2}$. Trends in N:P ratio are per year.

Variable	Unit	East				West				East + west			
		%pos	Δpos	%neg	Δneg	%pos	Δpos	%neg	Δneg	%pos	Δpos	%neg	Δneg
Temperature	$^\circ C\,yr^{-1}$	97	0.04	–	–	89	0.04	–	–	94	0.04	–	–
Precipitation	$mm\,yr^{-2}$	18	3.0	–	–	39	3.2	–	–	27	3.2	–	–
Discharge	$mm\,yr^{-2}$	46	1.8	43	−0.9	69	3.6	2	–	56	2.8	26	−0.9
TN_C	$\mu g\,l^{-1}\,yr^{-1}$	36	8.9	42	−32.2	45	4.7	22	−8.7	40	6.9	34	−25.8
TN_L	$kg\,km^{-2}\,yr^{-2}$	36	2.2	41	−7.4	65	2.5	11	−1.6	48	2.4	28	−6.4
TP_C	$\mu g\,l^{-1}\,yr^{-1}$	76	2.5	7	−0.3	18	0.5	60	−0.4	52	2.2	29	−0.4
TP_L	$kg\,km^{-2}\,yr^{-2}$	78	0.39	3	−0.16	31	0.12	26	−0.12	59	0.33	13	−0.13
N:P ratio		–	–	71	−1.3	37	0.4	15	−0.6	16	0.4	48	−0.9

3. Results

3.1. Trend analysis

The seasonal Mann–Kendall trend test revealed a positive trend in temperature across almost the entire BSDB with an average increase of 0.04 °C yr^{-1} over the 31-year record (Table 2). Temperature increase was higher in catchments located at the coast of the Baltic Sea compared to catchments located further away from the Baltic Sea, as shown in Fig. 2a where for each catchment the yearly trend is plotted for the whole BSDB. A positive trend in precipitation was visible in 18% of total eastern area (A_E) and in 39% of total western area (A_W) with an average increase of 3.2 mm yr^{-2} across the entire BSDB (Table 2). The spatial map of precipitation trends for the BSDB shown in Fig. 2b does not have a clear spatial pattern although most of the trends are located in the more northern catchments. Fig. 2c shows that in general, discharge decreased in the more southern catchments and increased in the more northern catchments with the average rate of increase being 2.8 mm yr^{-2} and the average rate of decrease being 0.9 mm yr^{-2}. The Mann–Kendall trend test performed on annual time series confirmed significant trends for temperature (east and west) and discharge (west) (Fig. 1a and c).

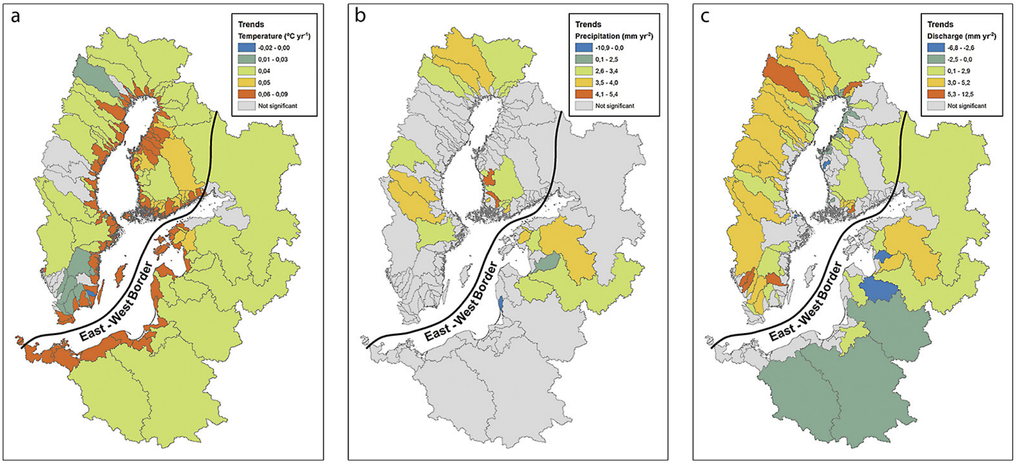


Fig. 2. Significant trends of temperature in °C yr^{-1} (a), precipitation in mm yr^{-2} (b) and discharge in mm yr^{-2} (c) over time for the period 1970–2000 according to the seasonal Mann–Kendall trend test with a significance level of $p < 0.05$. Intervals defined with Jenks natural breaks optimization method.

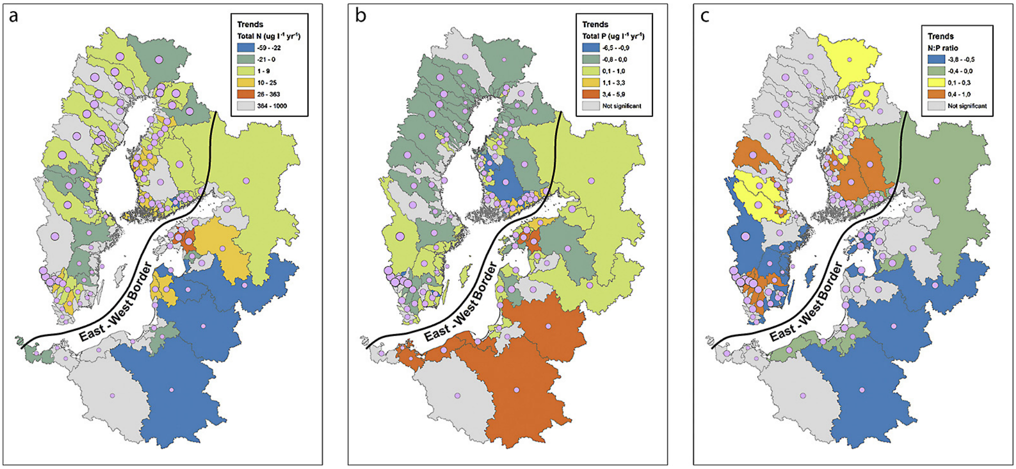


Fig. 3. Significant trends of TN $\mu g\, l^{-1}\, yr^{-1}$ (a) TP in $\mu g\, l^{-1}\, yr^{-1}$ (b) and N:P ratio (c) over time for the period 1970–2000 according to the seasonal Mann–Kendall trend test with a significance level of $p < 0.05$. Intervals defined with Jenks natural breaks optimization method. In each catchment, purple circles represent factor scores for factor 1 (a), factor 2 (b) and factor (3). The size of the circle is proportional to the importance of the factor.

Note that Fig. 1 shows all catchments while in Table 2 only catchments with significant trends are included.

There were clear, significant, differences between east and west (Fig. 3a and b) in terms of the concentrations (TN_C and TP_C). It should be noted that, while the loads are not shown here, their distributions look similar to those exhibited by the concentrations. The average negative trends for TN_C and TN_L are stronger in the east (32.2 $\mu g\, l^{-1}\, yr^{-1}$, 7.4 $kg\, km^{-2}\, yr^{-2}$) than in the west (8.7 $\mu g\, l^{-1}\, yr^{-1}$, 1.6 $kg\, km^{-2}\, yr^{-2}$) while positive trends are low in both the east and west (Table 2). On the contrary, positive trends for TP_C and TP_L in the eastern catchments are stronger (2.5 $\mu g\, l^{-1}\, yr^{-1}$, 0.39 $kg\, km^{-2}\, yr^{-2}$) than in the west (0.5 $\mu g\, l^{-1}\, yr^{-1}$, 0.12 $kg\, km^{-2}\, yr^{-2}$) while negative trends are low in both the east and west. For the aggregated yearly time series, the Mann–Kendall trend test confirmed significant trends for TN_C (both east and west), TN_L (west), TP_C (east) and TP_L (east and west) (Fig. 1d, e, f and g).

Clear differences were found between east and west (Fig. 3c) in terms of significant changes in the N:P ratio. 71% of the eastern catchment area showed a negative trend in the N:P ratio with an average decrease of 1.3 yr^{-1}. 15% of the western catchment area exhibited a negative trend in the N:P ratio with an average decrease of 0.6 yr^{-1} while 37% of the western area has a positive trend of 0.4 yr^{-1}. In the eastern catchments the N:P ratio declined over time from a ratio of almost 30 in 1970 to a ratio of almost 16 in 2000 (Fig. 1h). In the western catchments the N:P ratio appeared stable at around 20. However, for the aggregated yearly time series, the Mann–Kendall trend test confirmed significant trends for both the east and west.

3.2. Correlation and factor analysis

In order to gather more insight in whether the strength of the trend in one variable influences the strength of the trend in another variable, Kendall's rank correlation analysis was carried out based on the slopes of all significant trends in east and west (Table 3). In the east and west, as expected, a positive correlation ($p < 0.05$) was found between the increase in precipitation and the increase in discharge ($\tau = 0.4$ for east and $\tau = 0.2$ for west) as more precipitation will in general lead to more discharge (Bae et al., 2008). However, a positive correlation ($p < 0.05$) was also found between TN_C and discharge in the east ($\tau = 0.4$), which was not expected as more discharge will in general dilute the concentration. In the west, a positive correlation ($p < 0.05$) was found between TN_C and TP_C ($\tau = 0.2$), meaning that if the strength of the trend of one nutrient increases, the strength of the trend in the other nutrient will also increase (or vice versa). In the west, the strength of the trend in temperature

Table 3
Kendall's rank correlations (τ) between the average trends of all western (above marked cells) and eastern (under marked cells) catchments. Correlations only shown if significant ($p < 0.05$).

	TN_C	TP_C	Discharge	Precipitation	Temperature
TN_C	-	0.2			0.2
TP_C		-			0.2
Discharge	0.4		-	0.2	-0.3
Precipitation			0.4	-	
Temperature					-

Table 4
Factor matrix and output of Kendall's rank correlation on factor scores. Values in the factor columns represent the loadings of the corresponding variables. Loadings between −0.3 and 0.3 are not shown. Positive loadings are correlated with each other and comprise the positive component. The same is true for the negative loadings. The positive and negative components have an inverse relationship. Values in the Kendall's rank correlation represent significant coefficients (τ). *NS* means not significant.

	Factor 1	Factor 2	Factor 3
Variance	21%	18%	8%
Precipitation	0.42		
Discharge		0.38	
Temperature	0.77	−0.45	
Catchment size			
Artificial area	0.56	−0.49	−0.33
Cultivated area	0.51	−0.74	−0.33
Deciduous forest			0.72
Mixed forest	−0.48		
Coniferous forest		0.71	−0.30
Shrubs and herbs	−0.69		
Wetlands	−0.63		
Water bodies		0.55	
	Kendall's rank correlation		
	Factor 1	Factor 2	Factor 3
TN_C	0.33	*NS*	*NS*
TN_L	0.17	*NS*	0.18
TP_C	0.17	*NS*	−0.14
TP_L	*NS*	*NS*	*NS*

has a positive correlation ($p < 0.05$) between TN_C and TP_C (both $\tau = 0.2$). Hence, in western catchments where temperature increase is high, trends in TN_C and TP_C are also high. However, as expected, a negative correlation ($p < 0.05$) was found between temperature and discharge ($\tau = -0.3$) as higher temperatures generally evaporate more water leading to decreased discharge. Please note that both temperature and discharge in most western catchments are increasing (Fig. 2a and c). Therefore, this negative correlation means that in catchments where temperature is increasing at a relatively faster pace, the discharge is increasing at a relatively slower pace (and vice versa). This correlation was not found in eastern catchments.

From the factor analysis, it is concluded that the first three factors explained 47% of the variance in the dataset (Table 4). In the first factor, positive loadings consist of temperature, precipitation, artificial area and cultivated area. The negative loadings consist of shrubs and herbs, wetlands and mixed forest. These positive and negative components have an inverse relationship such that the first factor explains 21% of the variance. TN_C, TN_L and TP_C are positively correlated with the factor scores of this factor. This means that the more positive the factor scores in a catchment (explained by the positive loadings), the higher TN_C, TN_L and TP_C will be in that catchment. The opposite is also true. The factor scores of the first factor are presented in Fig. 2a. This figure shows that the first factor is more important in the more northern catchments. The positive loadings of the second factor consist of coniferous forest, water bodies and discharge and the negative loadings consist of cultivated area, artificial area and temperature. This relationship explains 18% of the variance. TN_C, TN_L, TP_C and TP_L are not influenced by this factor. The factor scores of the second and third factor do not show a clear pattern (Fig. 2b and c). The third factor explains 8% of the variance and consists of deciduous forest (positive) and artificial area, cultivated area and coniferous forest (negative). TP_C is negatively correlated with this factor which means that the more positive the factor scores in a catchment (more deciduous forest), the lower TP_C will be in that catchment. The more negative the factor scores in a catchment (more artificial area, cultivated area and coniferous forest), the higher TP_C will be in that catchment. The opposite is true for TN_L. The size of the catchment is not influencing any factor.

4. Discussion

The seasonal Mann–Kendall trend test revealed a sharp difference in trends for TN and TP between the east and the west of the BSDB both in loads and concentrations. In the east, trends for TN_C and TN_L are generally negative whereas trends for TP_C and TP_L are generally positive. In western catchments, more positive trends are found for the loads while more negative trends are found for the concentrations, likely because of increased discharge in the west. Since the eastern BSDB has experienced a more drastic change in the socio-economic structure and development in the period 1970–2000 (resulting in the aforementioned transition period), the difference in nutrient trends in the east suggests that the societal changes have led to significant changes in the diffuse and point sources influencing the concentrations and loads of TN and TP. Furthermore, significant differences observed in the direction and strength of the trends between TN and TP suggests that different controls exist for the two nutrients across the BSDB. This finding is in line with previous research done on trends in N and P in Estonian rivers (Iital et al., 2005). Iital et al. (2005) found a downward trend in the amount of N in 91% of the studied sites while a downward trend in the amount of P was observed in only 9% of the studied sites while also some upward trends were observed (9% of the studied sites).

Table 2 and Fig. 3 show that there is a lot of variability between the catchments in both east and west. The regional variation in trends can prove interesting for management strategies that aim to reduce nutrient loads into the Baltic Sea. The focus should be more on catchments experiencing an increasing trend or no trend at all. Previous modelling studies projecting future changes of nutrient loads into the Baltic Sea focused on the entire basin-scale (Arheimer et al., 2014; Donnelly et al., 2014; Meier et al., 2012, 2014). These modelling studies and their findings are often considered by policy makers to implement management strategies. Since our study demonstrates that large variation exists among the catchments, it can be suggested to look more at catchment-scale interactions when developing management strategies. This might reveal additional information which can lead to more focused and effective approaches to reach targeted reductions. The results in Table 2 show the potential for nutrient reductions in the BSDB. Upscaling the $0.13\,\mathrm{kg\,km^{-2}\,yr^{-2}}$ reduction in TP observed in 13% of the total BSDB area (east + west) results in a potential reduction of 223 tonnes per year. Considering a similar upscaling for TN, there is a potential reduction of 10,980 tonnes per year. Target reductions set by the Baltic Sea Action Plan (BSAP) correspond to a reduction of 135,000 tonnes TN and 15,250 tonnes TP by 2021 (HELCOM, 2007). If we assume these potential reduction rates for TN and TP, then the target reduction of TP would be reached in 68 years while the target reduction of TN would be reached in 12 years. Although it is unlikely that change rates calculated for the year 1970–2000 will be the same for 2000–2021, these estimates suggest it is possible to reduce TP in the BSDB but that it will be difficult to reach the target reductions by 2021 without significant shifts in land management.

Table 2 and Fig. 3 also show that the focus for management strategies should be more on P reduction rather than on N reduction as more catchments show an increasing trend rather than a negative trend for TP.

This suggestion is further reinforced when the N:P ratio is taken into account. The N:P ratio steadily declined in eastern catchments from 30 to 16, which will ultimately affect the N:P ratio for the whole Baltic Sea. The results presented in this study suggest that a declining trend in N:P ratio is largely caused by an increase of TP from eastern catchments. Pliński and Jóźwiak (1999) confirmed that the main cause of green algal blooms is the lowering of the N:P ratio due to an increased input of phosphorus (N:P ratio below 8). Hodgekiss and Ho (1997) found that the growth of most red tide algal blooms is optimized at ratios between 6 and 15. Hence, N:P ratios can act as an early warning signal for algal bloom types and frequencies. Based on the N:P ratio trend observed in this study, the N:P ratio should be monitored throughout the BSDB and P input should be reduced in eastern catchments in order to stop the decreasing trend in the N:P ratio found in this study.

From our study we can conclude that the socio-economic changes were most likely responsible for the change in nutrient dynamics in the BSDB. This is because of the steady decrease in TN due to changes in the diffuse sources from agricultural activities mainly in the east (HELCOM, 2011). The transition period brought about improvements in farm management practices, which resulted in reduced nitrogen loads. In contrast to the changes in diffuse nitrogen sources, changes in point sources are likely the main driver for the observed trends in TP_C presented in this study (consistent with modelling work from Mörth et al., 2007). Negative trends for TP_C in the western catchments can be explained by the increasing percentage of wastewater being treated and by the implementation of advanced treatment techniques in municipal and industrial facilities (HELCOM, 2011). Moreover, lifestyle changes such as closure of heavily polluting factories and an increased use of phosphorus-free detergents also helped in reducing phosphorus concentrations in the catchments. However, a substantial increase in TP was found in the eastern catchments. Reduction of P from point-source discharges started only after the transition period for the eastern countries. Although P loads to the Baltic Sea reduced from 1989 onwards, the major reductions happened after 2005 when Latvia, Lithuania, Estonia and Poland joined the EU (HELCOM, 2011).

The large socio-economic transition in the east was accompanied by a change in land cover that also affected nutrient dynamics. Because no data were available on land cover change, land cover for the year 2000 was used. The first factor shows that cultivated and urban areas both have a positive effect on TN_C, TN_L and TP_C, which is logical as these types of land cover are associated with high input of nitrogen and phosphorus due to anthropogenic activities. Furthermore, wetlands, mixed forest and shrubs and herbs have an adverse effect on TN_C, TN_L and TP_C. This inverse relationship to wetlands confirms that wetlands are important for N-retention (Richardson et al., 1997). It is especially important in the more northern catchments (Fig. 2). Jansson et al. (1998) estimated that wetlands in the BSDB retain approximately 5–13% of the annual total amount of nitrogen entering the BSDB. It was found that during the transition period large scale land cover changes occurred affecting the hydrological cycle by altering infiltration, groundwater recharge, base flow and discharge in catchments (Lin et al., 2007; Todd et al., 2007). Moreover, conversion of wetlands into forests or agriculture has had a big impact on the terrestrial water balance as wetlands can maintain high discharges in dry periods of the year (Lyon et al., 2012; Van der Velde et al., 2013).

Lastly, our study showed that there appears to be an impact of climatic changes on the nutrient dynamics. Although some future projections for the BSDB with regards to climate change do not show dramatic trends in nutrient loads, seasonal variations in discharge will change more rapidly which might lead to changes in nutrient loads due to shifts in ecosystem functioning (Arheimer et al., 2014). More insight in these potential drivers is necessary to see if additional reductions are needed (Meier et al., 2014). In our study, a temperature increase was observed in a large part of the BSDB ranging from 0.01 °C to 0.09 °C per year for linear change rates. The International Panel of Climate Change (IPCC) reported that the global average air temperature increased by 0.013 °C per year in the period 1956–2005 (Trenberth et al., 2007) so the trends for temperature found in this study fit well with the global changes by the IPCC. The higher increase observed near the coast can have two explanations. First, warming of Baltic Sea water could influence air temperatures in coastal areas. From literature, it was found that Baltic Sea water indeed warmed in the past 100 years by 1–2 °C (Boesch et al., 2006) and will continue to increase in the future (Meier et al., 2012). Second, due to warming of sea water, the time per year that northern parts of the Baltic Sea are covered with ice decreased which results in air temperature increase in coastal regions due to a lengthening of the exposure to sea water. This warming of Baltic Sea potentially can increase denitrification rates removing N from the nutrient pool in sediments of the Baltic Sea (Deutsch et al., 2010). Algal blooms are also influenced by an increase in temperature. In general, higher temperatures result in more intense algal blooms (Pliński and Jóźwiak, 1999). Our study shows a positive correlation between the increase in temperature and the increase in TN_C and TP_C, likely due to increased decomposition rates (Bowes et al., 2009; Wright, 1998). This positive correlation also suggests that increased rates of denitrification, as a result of temperature increase, did not result in a substantial decrease in TN in the catchments of the BSDB. Trends in discharge have a positive effect on TN ($\tau = 0.4$), but only in eastern catchments. This positive correlation between discharge and TN_C signals the large surplus in N stored in the eastern catchments due to past agricultural activities, compared to the N surplus in the western catchments (Basu et al., 2010).

5. Conclusion

The results presented in this study indicate that the reasons behind the trends for TN and TP are not the same. Therefore, improving water quality in the catchments requires different approaches. Since changes in TN depend on changes in diffuse sources, improving agricultural techniques that reduce nitrogen discharge should be the way forward in reducing nitrogen loads. Subsequently, conserving wetlands should be prioritized as they are essential for N- and P-retention. Improving wastewater treatment plants and closing antiquated and/or heavy-polluting factories could reduce phosphorus loads to the Baltic Sea even more, especially in the eastern countries where many increasing trends are observed. Overall, the focus for management strategies should be more on P reduction rather than on N reduction as the increasing trends in TP are responsible for a declining trend in the N:P ratio in eastern catchments. Because people in the BSDB rely on many ecosystem services that are vulnerable to eutrophication, it is important to further improve the water quality in the catchments. This is necessary to secure and sustain these services in the future.

Acknowledgements

This study was supported with funding from the Swedish Research Council through the Baltic Nest Institute and Stockholm University's Strategic Marine Environmental Research Funds in the BEAM Program and affiliated projects (VR grant 2011-4390).

References

Anderson, D.M., Glibert, P.M., Burkholder, J.M., 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries 25, 704–726.

Arheimer, B., Dahné, J., Donnelly, C., 2014. Climate change impact on riverine nutrient load and land-bases remedial measures of the Baltic Sea Action Plan. Ambio 41, 600–612.

Bae, D.H., Jung, I.W., Chang, H., 2008. Long-term trend of precipitation and runoff in Korean river basins. Hydrol. Processes 22, 2644–2656.

Basu, N.B., Destouni, G., Jawitz, J.W., Thompson, S.E., Loukinova, N.V., Darracq, A., Zanardo, S., Yaeger, M., Sivapalan, M., Rinaldo, A., Rao, P.S.C., 2010. Nutrient loads exported from managed catchments reveal emergent biogeochemical stationarity. Geophys. Res. Lett. 37, 1–5.

Boesch, D., Hecky, R., O'Melia, C., Schindler, D., Seitzinger, S., 2006. Eutrophication of Swedish Seas. Swedish Environmental Protection Agency, Stockholm, Sweden.

Boesch, D., Carstensen, J., Paerl, H.W., Skjodal, H.R., Voss, M., 2008. Eutrophication of Seas Along Sweden's West Coast. Swedish Environmental Protection Agency, Stockholm, Sweden.

Bowes, M.J., Smith, J.T., Neal, C., Leach, D.V., Scarlett, P.M., Wickham, H.D., Harman, S.A., Armstrong, L.K., Davy-Bowker, J., Davies, C.E., 2009. Changes in water quality of the river Frome (UK) from 1965 to 2009: is phosphorus mitigation finally working? Sci. Total Environ. 409, 3418–3430.

Deutsch, B., Forster, S., Wilhelm, M., Dippner, J.W., Voss, M., 2010. Denitrification in sediments as a major nitrogen sink in the Baltic Sea: an extrapolation using sediment characteristics. Biogeosciences 7, 3259–3271.

Donnelly, C., Yang, W., Dahné, J., 2014. River discharge to the Baltic Sea in a future climate. Climate Change 122, 157–170.

Graham, L.P., Bergström, S., 2001. Water balance modelling in the Baltic Sea Drainage Basin—analysis of meteorological and hydrological approaches. Meteorol. Atmos. Phys. 77, 45–60.

Hägg, H.E., Lyon, S.W., Wällstedt, T., Mörth, C.M., Claremar, B., Humborg, C., 2013. Future nutrient load scenarios for the Baltic Sea due to climate and lifestyle changes. Ambio 43, 337–351.

Hamed, K.H., 2009. Exact distribution of the Mann–Kendall trend test statistic for persistent data. J. Hydrol. 365, 86–94.

Haylock, M.R., Hofstra, N., Klein-Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J. Geophys. Res. 113, 1–12, http://dx.doi.org/10.1029/2008JD010201.

HELCOM, 2007. Baltic Sea Action Plan, Helsinki, Finland.

HELCOM, 2011. Fifth Baltic Sea pollution load compilation (PLC-5). In: Baltic Sea Environment Proceedings 128, Helsinki, Finland.

HELCOM, 2013. Review of the fifth Baltic Sea pollution load compilation for the 2013 HELCOM ministerial meeting (PLC-5.5). In: Baltic Sea Environment Proceedings 141, Helsinki, Finland.

Hipel, K.W., McLeod, A.I., 2005. Nonparametric tests for trend detection. In: Hipel, K.W., McLeod, A.I. (Eds.), Time Series Modelling of Water Resources and Environmental Systems. Elsevier, Amsterdam, pp. 853–938.

Hodgekiss, I.J., Ho, K.C., 1997. Are changes in N:P ratios in coastal waters the key to increased red tide blooms? Hydrobiologia 352, 141–147.

Hussian, M., Grimvall, A., Petersen, W., 2005. Estimation of the human impact on nutrient loads carried by the Elbe river. Environ. Monit. Assess. 96, 15–33.

Iital, A., Stålnacke, P., Deelstra, J., Loigu, E., Pihlak, M., 2005. Effects of large-scale changes in emissions on nutrient concentrations in Estonian rivers in the lake Peipsi drainage basin. J. Hydrol. 304, 261–273.

Jansson, Å., Folke, C., Langaas, S., 1998. Quantifying the nitrogen retention capacity of natural wetlands in the large-scale drainage basin of the Baltic Sea. Landsc. Ecol. 13, 249–262.

Jansson, B.O., Stålvant, C.E., 2001. The Baltic Basin Case Study—towards a sustainable Baltic Europe. Continental Shelf Res. 21, 1999–2019.

Lin, Y.P., Hong, N.M., Wu, P.J., Lin, C.J., 2007. Modelling and assessing land-use and hydrological processes to future land-use and climate change in watershed land-use planning. Environ. Geol. 53, 623–634.

Lyon, S.W., Nathanson, M., Spans, A., Grabs, T.J., Laudon, H., Temnerud, J., Bishop, K.H., Seibert, J., 2012. Specific discharge variability in a boreal landscape. Water Resour. Res. 48, 1–13, http://dx.doi.org/10.1029/2011WR011073.

Meier, H.E.M., Andersson, H.C., Arheimer, B., Blenckner, T., Chubarenko, B., Donnelly, C., Eilola, K., Gustafsson, B.G., Hansson, A., Havenhand, J., Höglund, A., Kuznetsov, I., MacKenzie, B.R., Müller-Karulis, B., Neumann, T., Niiranen, S., Piwowarczyk, J., Raudsepp, U., Reckermann, M., Ruoha-Airola, T., Savchuk, O.P., Schenk, F., Schimanke, S., Väli, G., Weslawski, J.M., Zorita, E., 2012. Comparing reconstructed past variations and future projections of the Baltic Sea ecosystem—first results from multimodel ensemble simulations. Environ. Res. Lett. 7, 1–8.

Meier, H.E.M., Andersson, H.C., Arheimer, B., Donnelly, C., Eilola, K., Gustafsson, B.G., Kotwicki, L., Neset, T.S., Niiranen, S., Piwowarczyk, J., Savchuk, O.P., Schenk, F., Weslawski, J.M., Zorita, E., 2014. Ensemble modeling of the Baltic Sea ecosystem to provide scenarios for management. Ambio 43, 37–48.

Moore, K., Pierson, D., Pettersson, K., Schneiderman, E., Samuelsson, P., 2008. Effects of warmer world scenarios on hydrologic inputs to lake Malaren, Sweden and implications for nutrient loads. Hydrobiologia 599, 191–199.

Mörth, C.M., Humborg, C., Eriksson, H., Danielsson, A., Rodriguez-Medina, M., Löfgren, S., Swaney, D.P., Rahm, L., 2007. Modeling riverine nutrient transport to the Baltic Sea—a large-scale approach. Ambio 36, 124–136.

Österblom, H., Hansson, S., Larsson, U., Hjerne, O., Wulff, F., Elmgren, R., Folke, C., 2007. Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. Ecosystems 10, 877–889.

Pastuszak, M., Igras, J., 2012. Temporal and Spatial Differences in Emission of Nitrogen and Phosphorus from Polish Territory to the Baltic Sea. National Marine Fisheries Research Institute, Gdynia, Puławy, Poland.

Pastuszak, M., Stålnacke, P., Pawlikowski, K., Witek, Z., 2012. Response of polish rivers (Vistula, Oder) to reduced pressure from point sources and agriculture during the transition period (1988–2008). J. Mar. Syst. 94, 157–173.

Pawlak, J.F., Laamanen, M.M., Andersen, J.H., 2009. Eutrophication in the Baltic Sea: An Integrated Thematic Assessment of the Effects of Nutrient Enrichment in the Baltic Sea Region, Executive Summary. Helsinki Commission, Helsinki, Finland.

Pliński, M., Jóźwiak, T., 1999. Temperature and N:P ratio as factors causing blooms of blue-green algae in the Gulf of Gdańsk. Oceanologia 41, 73–80.

Reckermann, M., Langner, J., Omstedt, A., von Storch, H., Keevallik, S., Schneider, B., Arheimer, B., Markus-Meier, H.E., Hünicke, B., 2011. BALTEX—an interdisciplinary research network for the Baltic Sea region. Environ. Res. Lett. 6, 1–11.

Richardson, C.J., Qian, S., Craft, S.B., Qualls, R.G., 1997. Predictive models for phosphorus retention in wetlands. Wetlands Ecol. Manage. 4, 159–175.

Smedberg, E., Mörth, C.M., Swaney, D.P., Humborg, C., 2006. Modeling hydrology and silicon–carbon interactions in taiga and tundra biomes from a landscape perspective: implications for global warming feedbacks. Global Biogeochem. Cycles 20, 1–15, http://dx.doi.org/10.1029/2005GB002567.

Thorborg, M., 2012. Demographic development in the Baltic Sea region. In: Karlsson, I., Rydén, L. (Eds.), Rural Development and Land Use. The Baltic University Programme, Uppsala University, pp. 103–116.

Todd, D.C.E., Goss, A.M., Tripathy, D., Harbor, J.M., 2007. The effects of landscape transformation in a changing climate on local water resources. Phys. Geogr. 28, 21–36.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein-Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B., Zhai, P., 2007. Observations: surface and atmospheric climate change. In: Solomon, S., Gin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Vahtera, E., Conley, D.J., Gustafsson, B.G., Kuosa, H., Pitkänen, H., Savchuk, O.P., Tamminen, T., Viitasalo, M., Voss, M., Wasmund, N., Wulff, F., 2007. Internal ecosystem feedbacks enhance nitrogen-fixing cyanobacteria blooms and complicate management in the Baltic Sea. Ambio 36, 186–194.

Van der Velde, Y., Lyon, S.W., Destouni, G., 2013. Data-driven regionalization of river discharges and emergent land cover-evapotranspiration relationships across Sweden. J. Geophys. Res. 118, 2576–2587.
Voss, M., Dippner, J.W., Humborg, C., Hürdler, J., Korth, F., Neumann, T., Schernewski, G., Venohr, M., 2011. History and scenarios of future development of Baltic Sea eutrophication. Estuar. Coast. Shelf Sci. 92, 307–322.
Wilson, D., Hisdal, H., Lawrence, D., 2010. Has streamflow changed in the Nordic countries?—recent trends and comparisons to hydrological projections. J. Hydrol. 394, 334–346.
Wright, R.F., 1998. Effect of increased carbon dioxide and temperature on runoff chemistry at a forested catchment in southern Norway (CLIMEX project). Ecosystems 1, 216–225.