REPORT

Saving the Baltic Sea, the Inland Waters of Its Drainage Basin, or Both? Spatial Perspectives on Reducing P-Loads in Eastern Sweden

Ingela Andersson, Jerker Jarsjö, Mona Petersson

Received: 14 December 2013 / Revised: 19 March 2014 / Accepted: 28 March 2014 / Published online: 6 May 2014

Abstract Nutrient loads from inland sources to the Baltic Sea and adjacent inland waters need to be reduced in order to prevent eutrophication and meet requirements of the European Water Framework Directive (WFD) and the Baltic Sea Action Plan (BSAP). We here investigate the spatial implications of using different possible criteria for reducing water-borne phosphorous (P) loads in the Northern Baltic Sea River Basin District (NBS-RBD) in Sweden. Results show that most catchments that have a high degree of internal eutrophication do not express high export of P from their outlets. Furthermore, due to lake retention, lake catchments with high P-loads per agricultural area (which is potentially of concern for the WFD) did not considerably contribute to the P-loading of the Baltic Sea. Spatially uniform water quality goals may, therefore, not be effective in NBS-RBD, emphasizing more generally the need for regional adaptation of WFD and BSAP-related goals.

Keywords WFD · HELCOM · Catchment · Marine · Eutrophication · Nutrient load

INTRODUCTION

The Baltic Sea is the largest brackish water body in the world with an area of approximately 377 000 km². It has a fourfold larger drainage basin populated by 85 million people. The problem of marine eutrophication is today the most serious threat to the Baltic Sea ecosystem, and is one of the most severe environmental problems in the EU (Aarnio et al. 2007). Eutrophic risk areas in EU include

coastal waters in enclosed and semi-enclosed basins (Baltic Sea, North Sea, Black Sea, and Adriatic Sea) enriched by anthropogenic nutrient input (Ferreira et al. 2011). All basins and coastal waters of the Baltic Sea are currently affected by eutrophication, except for the Bothnian Bay and the northeastern parts of the Kattegat. The eutrophication causes cyanobacterial blooms, resulting in high oxygen demand during their degradation. The associated oxygen depletion contributes to the formation of dead zones across the Baltic Sea (e.g., Diaz and Rosenberg 2008). Net inflow events through the Danish Straits contributing to oxygen-rich deeper waters are governed by relatively rare atmospheric conditions.

Inland pollution sources are a primary cause of eutrophication of the Baltic Sea (see, e.g., Gren and Destouni 2012). In the drainage basin, the loads to surface waters originate from diffuse sources (mainly agriculture) of nitrogen (N) and phosphorus (P), and from point sources (municipal waste water treatment plants) of primarily P. The nutrients reach the Baltic Sea mainly via streams within the basin and direct discharge from e.g., wastewater treatment plants. Nutrient sources are to relatively large degree diffuse, accounting for about 60 % of N and 50 % of P inputs to the Baltic Sea. Furthermore, approximately 80 % of the diffuse P inputs originate from the agriculture sector. Between 1990 and 2006, the total input of P and N has been reduced by 45 and 30 %, respectively (Andersen et al. 2010); however, existing nutrient rich sediments may contribute to the current loading. Adverse impacts of nutrient loads are, however, not restricted to the Baltic Sea, but have been seen in large parts of its inland drainage basin, where many surface water bodies suffer from eutrophication. This study focuses on loadings of P, which is the main limiting factor of growth in lakes and water-courses, while both N and P are important for coastal

Electronic supplementary material The online version of this article (doi:10.1007/s13280-014-0523-x) contains supplementary material, which is available to authorized users.

waters, estuaries, and for the Baltic Sea (Pitkänen and Tamminen 1995; Conley et al. 2009). In the latter waters, the relative importance of N and P varies between basins and seasons.

The riparian EU countries together with Russia act within the Helsinki Commission (HELCOM), which is the governing body of the Helsinki Convention from 1974 that aims at protecting the marine environment of the Baltic Sea area. In 2007 HELCOM, now also including the European Commission, adopted the Baltic Sea Action Plan (BSAP) with the goal of achieving good ecological status in the Baltic Sea by 2021. The BSAP specifically considers eutrophication, hazardous substances, biodiversity, and good environmental performance of shipping. Five objectives need to be fulfilled in order to achieve good ecological status with regard to eutrophication, namely, concentrations of nutrients close to natural levels, clear water, natural level of algal blooms, natural distribution and occurrence of plants and animals, and natural oxygen levels. The new EU Marine Strategy from 2008 and BSAP are complementary and compatible with each other (Backer et al. 2010).

The inland water quality of the Baltic Sea Drainage Basin is primarily regulated by the EU Water Framework Directive (WFD), which was introduced in 2000 (e.g., Moss 2008; Hering et al. 2010) with the purpose to *establish a framework for the protection of inland surface waters, transitional waters, coastal waters, and ground-water* (EC 2000). The directive requires that inland waters to be monitored and characterized through a classification, in which ecological and chemical statuses are used for surface waters. Unless the conditions are at least classified as good, remediation measures must be taken during subsequent stages in the WFD management cycle. A good ecological status cannot be reached unless a water body deviates only slightly from a pristine state with no or minimal human impact, in the directive called “undisturbed conditions” (EC 2000). Reducing the effects of eutrophication of inland waters, estuaries and coastal waters are, therefore, of great importance to achieve good ecological status according to the WFD (Cherry et al. 2008).

Problem Statement and Research Question

Both the WFD and the BSAP use region-specific action plans as means for fulfilling their requirements. For instance, in addressing the eutrophication problem, demands are formulated on how much anthropogenic P and N loads should be reduced per sub-catchment of the considered region. If the WFD goals in the Baltic Sea Drainage Basin could be fully achieved, the conditions for fulfilling

the requirements of the BSAP/Marine Directive for the ecological status of the Baltic Sea would also be met. However, it is clear that the goals cannot be fulfilled, at least not within the coming decade, as required by the WFD and the BSAP. A failure to fully meet these goals will occur for three main reasons: (i) Relatively radical measures are needed, such as extensive land use change (e.g., Wulff et al. 2007), which are not feasible from a socio-economic perspective (Volk et al. 2009). For example, in the most populated river basin district (RBD) of Sweden, the Northern Baltic Sea (NBS) RBD, the reduction demand of P from the RBD authority (RBDA) of 100 tons per year is larger than the estimated anthropogenic load contribution from agriculture within the RBD to the Baltic Sea (Larsson and Pettersson 2009). (ii) Retention processes and slow transport through the subsurface water systems (Darracq et al. 2008, 2010; Destouni et al. 2010; Persson et al. 2011) can delay targeted effects of mitigation measures considerably. Furthermore, ecosystems need to respond to measures taken, which may considerably prolong the time it takes to reach WFD targets (Hering et al. 2010). (iii) WFD implementation requires involvement at many administrative levels. Not least at the local (municipal) level, awareness of WFD targets is still relatively limited (Andersson et al. 2012), which indicates that it may take time to address them in an effective way. The implementation also causes changes in the structure of water management and in e.g., Sweden this may cause tensions between different levels (Lundqvist 2004; Andersson et al. 2012).

Since WFD and BSAP goals cannot be fully met in the near future, it is clear that there is a need to prioritize. Considering P-loads and eutrophication, our main research question is: What are the spatial implications of using different possible criteria for reducing water-borne P-loads in the NBS-RBD? In particular, we hypothesize that some regions (catchments) have a high need of reducing P-loads due to multiple nutrient-related water quality problems. They could in such case be robustly identified as priority catchments in action plans for remediation.

Study Area: Northern Baltic Sea River Basin District (NBS-RBD)

The Northern Baltic Sea River Basin District (NBS-RBD) is one of five WFD-related RBDs in Sweden. Of these five RBDs, four completely drain into the Baltic Sea (Fig. 1a) and its sequence of sub-basins and sills. In addition to land areas, the NBS-RBD is composed of lakes, estuaries, adjacent coastal waters of the Baltic Sea, and islands (including the Stockholm Archipelago; Fig. 1b). In this study we spatially analyze the degree of eutrophication,

Fig. 1 **a** The Baltic Sea drainage basin (green and yellow) and its countries. Numbers refer to the five River Basin Districts, RBDs, of Sweden: (1) Bothnian Bay, (2) Bothnian Sea, (3) Northern Baltic Sea, (4) Southern Baltic Sea, (5) Skagerrak and Kattegat. GIS data from UNEP/GRID-Arendal (2001) **b** Characteristics of the NBS-RBD. Data source SMHI (2010) ©Lantmäteriet Gävle 2010. Permission I 2010/0056

and P-load contributions to inland and coastal waters from 27 different catchments¹ of the NBS-RBD, which covers 44 000 km². From a hydrological viewpoint, the NBS-RBD is dominated by the drainage basin of Lake Mälaren which has a surface area of 1100 km², and is also known as the Norrström drainage basin. Lake Mälaren discharges to the Baltic Sea through the towns of Stockholm (98 % of the discharge) and Södertälje. The lake could be described as a freshwater archipelago with several different glacially overdeepened basins, separated by shallow thresholds, between which the exchange is small. The NBS-RBD has 2.9 million residents, 2.6 million of whom live in urban areas, and the lake Mälaren supplies freshwater to about two million. According to Stockholm County Council, the population of the region is also expected to grow by 20–35 % from 2005 to 2050. The land use pattern follows the soil distribution. Forests (61 % of total catchment area) mainly cover till soils, and arable land (22 %) is located in the vicinity of rivers and lakes where clay and fine-grain soils dominate (NBS-RBDA 2009). In 2012 wheat, barley, and oat were the dominating crops; however, 33 % of arable land is used for haymaking and pasture, and approximate 10 % lie fallow. Diatom analyses have shown

that the lake Mälaren was culturally eutrophicated already in the medieval time (Renberg et al. 2001). Phosphorus has been monitored in Lake Mälaren since the 1960s, and the monitoring shows that the introduction of chemical precipitation to the sewage water treatment process led to large improvements in the 1960s and 1970s, reducing the P input to the lake by 60 %. Nevertheless, despite various mitigation measures, most of the water bodies of the NBS-RBD are currently eutrophicated, and 97 % of the anthropogenic P-load comes from agricultural land, waste water, and storm water (Appendix S1 for further details). Given the current situation, it is clear that the WFD-related goals cannot be fully met in NBS-RBD in the near future, for the same main reasons as in many river basin districts of the EU.

MATERIALS AND METHODS

Data sources

The quantifications and analyses conducted in this study are primarily based on data from the pollution load compilation 5(PLC5)-reporting to HELCOM (Brandt et al. 2008) combined with data from the Swedish Water Information System (Water Information System Sweden 2009)

¹ River Basin Districts in Sweden contain several (smaller) river basins that are referred to as catchments in this study.

and from the River Basin District Authority in the Northern Baltic Sea (NBS-RBDA 2008). These data include anthropogenic P-load contributions from different sources within the NBS-RBD to catchment outlets and the Baltic Sea, as well as land use and eutrophication of water bodies within these catchments RBDA (Appendix S1). The 27 catchments considered here comprise all catchments of the NBS-RBD for which PLC5 data are reported, including those located in the Norrström Drainage basin (gray-lined catchments in Fig. 1b) and all adjacent catchments that drain directly into the Baltic Sea (black-lined catchments in Fig. 1b). Data are not presented for smaller coastal discharge areas that lack well-defined surface runoff, or for islands of the Stockholm archipelago.

P-Load Estimations in the PLC5

The reported PLC5 data on the net loads of nutrients are based on field measurements of discharges and nutrient concentrations. Data gaps have been filled with calibrated results obtained from the HBV-NP model, which is a transient, deterministic hydrological model that can be spatially resolved to the scale of relatively small sub-catchments. It was developed considering Swedish conditions, and has additionally been applied to many catchments across Europe, including catchments in Nordic countries, Estonia, and Germany (e.g., Arheimer 2006). It includes hydrological routines for storage changes in snow, other surface waters including lakes, and subsurface waters. It also contains nutrient routines that account for soil surface erosion, soil leaching, point sources, atmospheric deposition, and retention-transformation processes (see Andersson et al. 2005).

A main part of the direct monitoring data of (net) loads at basin outlets that are available for approximately 40 % of the Swedish PLC5-basins (from 470 monitoring stations) has been used to calibrate the HBV-NP model, and a smaller part of it has been used for evaluating the overall uncertainty in the P-load results of the model (Appendix S1). This overall uncertainty is mainly due to uncertain P-retention parameters, and uncertain input data on point sources of P, soil type, and land use (Andersson et al. 2005). Its magnitude was evaluated from the average difference between the direct monitoring data that were not used for calibration and blind model predictions of associated P-loads. Results showed that this difference was on average 25 % (Naturvårdsverket 2008; Appendix S1). In contrast, main conclusions in this study are drawn from characteristics of identified high P-load catchments, which on average have 55 % higher P-loads than other considered catchments. This relatively large P-load difference indicates that our conclusions should be robust.

Reduction Demands in the Program of Measures

The program of measures (set up by the Water District Board of the NBS-RBD) specifies the required P (and N) reductions (in tons per year) that each catchment has to meet to reach the WFD goal of good status. The demands are based on estimates of current, catchment-specific loads of P (and N), taken from the above described PLC5 load estimations. The required reductions regard the mass flows of P at the catchment outlets, which in the case of the considered catchments are located at either Lake Mälaren or the Baltic Sea. The catchment-specific demands were related to the measured or modeled P concentrations in the furthest downstream water body of the catchment, and were taken to be representative of the entire catchments with the goal of achieving good ecological status in the entire catchment.²

Data Compilation

The 27 here considered WFD catchments are the same size as or larger than the PLC5-basins, containing up to 15 PLC5-basins. Both the gross loads (emitted at the source location) and the net loads (i.e., load contributions to recipients following potential retention and degradation along transport pathways) are in the PLC5 reporting divided into a natural and an anthropogenic part. The latter consists of known primary point sources (waste water treatment plants, industries, septic tanks in rural areas, forest clear cuts, storm water drainage, and agricultural practices; Brandt et al. 2008). In the present study, we combined data from the PLC5-reporting on the (net) contribution of each PLC5-basin to the Baltic Sea with data describing the loads to Lake Mälaren reported in the program of measures of the NBS. The reporting from HELCOM-PLC5 and NBS-RBDA is based on the same observational and HBV-NP modeling material. However, the NBS-RBDA reports do not explicitly give the relative source contributions (from agriculture, waste water, etc.) to the loads of Lake Mälaren. These were instead estimated by multiplying HELCOM-PLC5 data on relative source contributions to the Baltic Sea with NBS-RBDA data on absolute loads to the basin outlets in Lake Mälaren (Fig. 1b). This is consistent with assuming that the P-retention in Lake Mälaren is the same regardless of original source.

² The values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity, and deviate only slightly from those normally associated with the surface water body type under undisturbed conditions (EC 2000).

Spatial Analysis: Different Perspectives on Surface Water Status

We rank the ecological status of surface waters and coastal waters of the 27 considered catchments, focusing on P-loads and eutrophication. Three alternative ways of ranking are considered, based on different perspectives of the actual status. A main difference between the perspectives is that different parameters are considered. The different perspectives are

- (A) Anthropogenic P-load contribution per arable area to the catchment outlet.
- (B) Anthropogenic P-load contribution per arable area to the Baltic Sea.
- (C) Percentage of eutrophicated water bodies in the catchment.

Rank 1 out of 27 is assigned to the catchment with the highest parameter value, representing the most polluted catchment, having then the highest need of reducing loads, according to the considered perspective. For each perspective A–C, the rankings of the different catchments within NBS-RBD are analyzed spatially. The rankings are also compared to the spatial distribution of actual reduction demands of NBS-RBD given in the program of measures (see “[Reduction Demands in the Program of Measures](#)” section).

More specifically, perspective A considers agricultural areas that have high anthropogenic P-load contributions to the catchment outlet, located either at Lake Mälaren (Norrström) or to the Baltic Sea (coastal discharge). Hence, from this perspective, a more “polluting” agricultural area will get more highly ranked than a less polluting one. This is in contrast to the load reductions suggested by the Program of Measures, which are based on evaluation of total anthropogenic loads per sub-catchment (not normalized by agricultural area). Perspective B is identical to perspective A, except that it considers the load contribution to the Baltic Sea, which sub-catchments without direct Baltic Sea discharge are influenced by retention processes in Lake Mälaren. Perspective C considers environmental impacts within the target catchment, in contrast to perspectives A and B that focus on pollution export to downstream water systems. Perspective C hence targets local eutrophication problems, which is possibly the most WFD impregnated perspective.

RESULTS

The reduction demands from the program of measures for the NBS-RBD vary considerably between its 27 considered catchments (Fig. 2; y-axis). Most of the demands vary

between 0 % (no demand) and 40 % of the net anthropogenic P-load. Five of the 27 catchments have high reduction demands between 45% and 85% of the net anthropogenic P-load. These areas are referred to as high reduction demand areas in the remainder of the paper. As shown in Fig. 2 (x-axis), the main part of their anthropogenic P-load (>70 %) comes from the agricultural sector.

More generally, Fig. 3a shows that catchments that have relatively high P-loads of anthropogenic origin at their outlets ($>10 \text{ kg year}^{-1} \text{ km}^{-2}$) are characterized by a relatively high percentage of arable land (>20 %). Notably, all of the high reduction demand areas are located in catchments with at least 20 % arable land (Fig. 3a; red symbols). However, the scatter is considerable; there are also agricultural catchments (>20 % arable land) with lower P-loads ($<5 \text{ kg year}^{-1} \text{ km}^{-2}$). The outlier catchment Tyresån/Trosaån, which has a very high P-load of $28 \text{ kg year}^{-1} \text{ km}^{-2}$, contains a waste water treatment plant that cleans water for about 300 000 individuals that mainly live outside of the catchment area.

Figure 3b shows that there is some scatter in the expected positive relationship between the percentage of arable land and the percentage of eutrophicated water bodies within a catchment. This can in part be due to anthropogenic nutrient loads from sources other than agriculture, such as loads from storm water, and private and municipal waste water solutions. In the high reduction demand areas (red symbols), 50 % or more of the water bodies are eutrophicated. However, Fig. 3b reveals that this state is shared with a main part (about 2/3) of the considered catchments.

While Figs. 2 and 3 show the anthropogenic P-loads to the catchment outlets, Fig. 4 shows the estimated anthropogenic load contributions to the Baltic Sea. The direct influence on the P-loading of the Baltic Sea from the coastal catchments is illustrated by the 1:1 Baltic Sea P-load—catchment outlet P-load relationship shown in Fig. 4 (circles and diamonds). The modeled additional P-retention for the Norrström catchments that discharge into Lake Mälaren is shown by their considerably reduced Baltic Sea loadings (squares and triangles). The resulting P-loading to the Baltic Sea is estimated between 26 and 72 % of the loading to the outlets at Lake Mälaren (Fig. 4).

Table 1 (column 2) shows the top 10 catchment-specific reduction demands from the Program of Measures, in percent of the catchments’ anthropogenic P-load. The demand of the Rank 1 Örsundaån catchment corresponds to 85 % of the anthropogenic P-load at the catchment outlet. The Tyresån/Trosaån has a reduction demand of 32 % of its anthropogenic P-load at the catchment outlet, which corresponds to Rank 10 in Table 1. The table also introduces alternative rankings of the NBS-RBD catchments, based on the considered perspectives (A, B, C) on surface water

Fig. 2 The reduction demand in the NBS-RBD as part of anthropogenic P-load versus anthropogenic P-load from agriculture. The ellipse marks the five catchments with the highest reduction demand

status. Specifically, the top 10 agricultural P-load contributions per arable area to the catchment outlet (Table 1; perspective A) range between $48 \text{ kg km}^{-2} \text{ year}^{-1}$ in the Sagån catchment (Rank 1) and $27 \text{ kg km}^{-2} \text{ year}^{-1}$ in the Tyresån/Trosaån catchment (Rank 10). The top 10 contributions per arable area to the Baltic Sea (Table 1; perspective B) range between $45 \text{ kg km}^{-2} \text{ year}^{-1}$ in the Svärtaån catchment (Rank 1) and $18 \text{ kg km}^{-2} \text{ year}^{-1}$ in the Åkerströmmen catchment (Rank 10). Finally, the relative amount of eutrophicated water bodies ranges between 93 % in the Örsundaån catchment (Rank 1) and 67 % in the catchments of Svärtaån and Köpingsån (both share Rank 10). These results show that the four Rank 1 positions in Table 1 are held by three different catchments.

The colored catchments of the four panels of Fig. 5 show the geographical locations of the top 10 ranked catchments in the program of measures and the three alternative perspectives A–C. Their names are given in the corresponding columns of Table 1. The color coding of Fig. 5 is the same as in the first column of Table 1; the non-colored catchments of Fig. 5 have ranks below 10. The figure shows that the geographical distribution of the top 10 ranked catchments is relatively different between the considered cases. For example, only 5 out of the 10 catchments with the highest reduction demand according to the program of measures also appear on the perspective A top 10 list (shown in bold characters in Table 1). This reappearance of 50 % of the catchments is only slightly higher than the reappearance of 37 % of the catchments

that would be expected on average, if 10 catchments were randomly selected for a top 10 list, out of the 27 considered catchments.

The perspective B list has the lowest reappearance of catchments from the reduction demand top 10 list, with four reappearing catchments (bold characters in Table 1) out of 10. All of the top 10 catchments of perspective B discharge directly into the Baltic Sea (blue-colored row in Table 1) and are located relatively close to the Baltic Sea coast (Fig. 5; perspective B). By contrast, the (inland) catchments that discharge into Lake Mälaren have relatively small anthropogenic P-load contributions to the Baltic Sea, owing to the estimated retention of Lake Mälaren. Perspective C, referred to as the most WFD impregnated, contains relatively many (seven) catchments from the top 10 list of high reduction demand areas. However, it differs considerably from perspective B; the catchments of perspective C are located relatively close to Lake Mälaren, as opposed to those of perspective B.

DISCUSSION

Present results show that NBS-RBD catchments that have high reduction demands in the program of measures do not contain highly polluting agricultural regions (with high contribution per agricultural area) in a number of cases. Such catchments can have extensive arable areas that add to relatively high total loads, however, with below-average

Fig. 3 Percentage of arable land in catchments of the NBS-RBD, versus **a** anthropogenic P-load to the catchment outlet per unit catchment area, and **b** percent eutrophicated water bodies

contributions per arable area. Reducing loads in those catchments can come at high costs, since reducing the total agricultural area has been found to be much more expensive than the cutting of excess nutrient surpluses from relatively polluting farms (Volk et al. 2008). The fact that

environmental studies addressed to managers and decision makers often neglect prevailing heterogeneity in farm contributions (Balana et al. 2011) can, therefore, have negative environmental and economic consequences. Furthermore, these results raise the general question of how

Fig. 4 Anthropogenic P-load contributions from catchments of the NBS-RBD to their outlets (*x*-axis) and to the Baltic Sea (*y*-axis). Differences from the 1:1 relation occur for catchments within Norrström (*squares* and *triangles*) due to P-retention in Lake Mälaren

reasonable it is to achieve the WFD goal of equally good ecological status in all catchments, regardless of population pressures, production outputs, valued landscape characteristics, downstream impacts, and costs for abatement measures (Glavan et al. 2012; Gren and Destouni 2012). The difficulties involved in the definition of undisturbed conditions and the WFD ambition of achieving them are further discussed by Moss (2008) and Bishop et al. (2009).

In contrast to the WFD, the BSAP is primarily concerned with load contributions to the Baltic Sea. From the coastal and marine perspective of BSAP, areas with high estimated load contributions to the Baltic Sea should be prioritized, at least in the short run (Larsson and Pettersson 2009). Present results show that downstream impacts of P-loads differ considerably depending on the catchment outlet location relative to the considered recipient. For example, although 60 % of the catchments with high P-load at their outlets are located in the Lake Mälaren Basin, none of them are highly ranked regarding load contributions to the Baltic Sea. Hence, strict prioritizing from a Baltic Sea and BSAP perspective implies that the P-loads of catchments that discharge directly to the Baltic Sea must primarily be reduced. From the same strict Baltic Sea perspective, the high P-loads to Lake Mälaren can be maintained due to the estimated high retention along the remaining transport pathway from Lake Mälaren to the Baltic Sea. This is despite possible adverse inland effects. Conversely, a strict prioritizing from a WFD perspective would imply that the identified high P-loads in the Norrström–Lake Mälaren drainage basin must be reduced, despite expected small effects on total loads to the Baltic Sea. One can note that WFD is legally binding in

Sweden and that the overall goal of the RBDs is to fulfill WFD requirements.

These examples show more generally that quite different target areas and measures can be needed to address WFD and BSAP goals, in contrast to implicit assumptions of common measures made by regulators and authorities (Andersson et al. 2012). Since the goals cannot be fully met in the near future (Larsson and Pettersson 2009; Hering et al. 2010), prioritization is needed as stated earlier. However, the present results specifically show that strict prioritization according to BSAP goals yields unacceptable consequences for inland waters. The same is true for WFD and coastal waters. Furthermore, since catchments with high total P-loads do not necessarily have high internal eutrophication (and vice versa), many catchment-specific measures could most likely not simultaneously address P-load and eutrophication problems in an efficient way. There is, therefore, a need to find reasonable compromises, which for instance can be obtained through shifting focus further toward regionally adapted goals and solutions (Volk et al. 2009; Glavan et al. 2012; Friedland et al. 2012), supported by dialogs between politicians, scientists, managers, stakeholders, and non-governmental organizations (Bishop et al. 2009; Ioris 2012).

The present results also show that estimated P-load contributions to the coast are strongly influenced by lake retention processes, particularly in the Lake Mälaren region. Due to inherent complexities of coupled subsurface–surface water systems (Jarsjö et al. 2008; Destouni et al. 2010; Persson et al. 2011), effective remediation measures need to be underpinned by a relatively detailed understanding of nutrient transport processes, and not least

Table 1 Reduction demands of high priority catchments according to the Program of Measures, and values of parameters considered in alternative perspectives A–C (absolute values shown within brackets; corresponding ranking shown in column 1). Blue-colored cells contain basins with direct Baltic Sea discharge. Uncolored cells: discharge to Lake Mälaren. Bold characters: top 10 highest reductions demands. Basins marked with * lack well-defined surface runoff

Rank	Reduction demand in the Program of Measures for NBS-RBD	Perspective A	Perspective B	Perspective C
	High reduction demand areas	Anthropogenic P-load from agriculture per arable area: Contribution to catchment outlet	Anthropogenic P-load from agriculture per arable area: Contribution to the Baltic Sea	Part of water bodies being eutrophicated within the catchment
	% of anthropogenic P load	kg km ⁻² year ⁻¹	kg km ⁻² year ⁻¹	% of water bodies
1	Örnsundaån (85)	Sagån (48)	Svärtaån (45)	Örnsundaån (93)
2	Sagån (80)	Hedströmmen (46)	Olandsån/Skeboån* (32)	Tyresån/Trosaån* (88)
3	Olandsån (77)	Svärtaån (45)	Kilaån (28)	Svartån (83)
4	Tämnarån (69)	Örnsundaån (44)	Tyresån/Trosaån* (27)	Tyresån (83)
5	Svärtaån (51)	Fyrisån (40)	Olandsån (26)	Åkerströmmen (80)
6	Köpingsån (39)	Arbogaån (36)	Tämnarån (26)	Oxundaån (78)
7	Mälarens Närområden* (37)	Olandsån/Skeboån* (32)	Skeboån (24)	Trosaån (77)
8	Kolbäcksån (36)	Kolbäcksån (29)	Tyresån (20)	Sagån (73)
9	Oxundaån (36)	Kilaån (28)	Nortäljeån/Åkerströmmen* (19)	Mälarens närområden* (72)
10	Tyresån/Trosaån* (32)	Tyresån/Trosaån* (27)	Åkerströmmen (18)	Svärtaån (67)
				Köpingsån (67)

Fig. 5 Ranking of high priority catchments within the NBS-RBD corresponding to Table 1. The four panels show the top ten high reduction demand areas according to the program of measures and perspectives A–C. Geographic data: SMHI (2010) ©Lantmäteriet Gävle 2010. Permission I 2010/0056

retention processes in such systems. For example, a possible continued slow leaching of P through the subsurface water systems may need to be considered in predictions of P-load to the surface and coastal waters (Darracq et al. 2008). Results from the Swedish Environmental Protection Agency, which is responsible for the PLC5-reporting show deviations between measured and simulated loads in the river mouths, imply that the P-modeling can be further refined (Brandt et al. 2008). For instance, the P-retention has been observed to decrease with increasing water flow and watercourse depth (e.g., Olli et al. 2008). Accordingly, development of additional (site specific) models and relevant remediation measures will be dependent on relatively detailed monitoring data. The current problem of available monitoring data being insufficient has been discussed by

e.g., Hannerz and Destouni (2006) and Hering et al. (2010). Although the WFD has increased the amount of data, ongoing monitoring programmes frequently yield data that cannot be used for evaluating water body status according to WFD methods and standards (Ullrich and Volk 2010). Furthermore, available data are not yet centrally stored and, therefore, not easily accessible for research and model development purposes (Hering et al. 2010; Hammer et al. 2011).

CONCLUSIONS

Based on spatial analysis of P-loads, P concentrations, and eutrophication status of 27 sub-catchments in the Northern

Baltic Sea River Basin District of Sweden, we conclude that

- The set of catchments that have high reduction demands in the WFD-related program of measures (due to high total P-loads) only partially overlaps with the set of catchments that have high P-load contributions per arable area.
- Most catchments that have a high degree of internal eutrophication do not express high export of P from their outlets to downstream water systems.
- The set of catchments that had the highest P-load contributions to the Baltic Sea shows remarkably small overlap with any of the considered sets that had considerable issues from the inland water perspective of the WFD.

Impacts from specific (P) sources and associated reduction needs can hence differ considerably on local to regional scales, and between upstream (inland) and downstream (lake, sea) water systems. This shows more generally that priority removal of key P sources contributing to inland water pollution cannot at the same time be expected to effectively mitigate P-loads to downstream coastal waters, and vice versa; emphasizing a need for adaptation of partially conflicting objectives of the WFD (inland water) and the BSAP (coastal water) to region-specific conditions.

Acknowledgments This study was funded by the Ministry of Education and Research and conducted within the Research School for Teachers on Climate Evolution and Water Resources. It was part of the project Ecosystems as common-pool resources: Implication for building sustainable water management institutions in the Baltic Sea region, funded by the Foundation for Baltic and East European Studies. The second author acknowledges support from the strategic research project EkoKlim at Stockholm University.

REFERENCES

- Aarnio, T., V Jormalainen, J. Kuparinen, F. Wulff, S. Johansson, S. Laakkonen, and E. Kessler. eds. 2007. Science and governance of the Baltic Sea, *AMBIO* 36(2–3): 424–431.
- Andersen, J. H., S. Korpinen, M. Laamanen, and U. Wolpers, eds. 2010. Ecosystem Health of the Baltic Sea 2003–2007. HELCOM Initial Holistic Assessment. Helsinki Commission, Baltic Marine Environment Protection Commission, Baltic Sea Environment Proceedings No. 122, Helsinki, Finland.
- Andersson, I., M. Petersson, and J. Jarsjö. 2012. Impact of the European Water Framework Directive on local-level water management: Case study Oxunda Catchment, Sweden. *Land Use Policy* 29(1): 73–82.
- Andersson, L., J. Rosberg, B.C. Pers, J. Olsson, and B. Arheimer. 2005. Estimating catchment nutrient flow with the HBV-NP Model: Sensitivity to input data. *AMBIO* 34(7): 521–532.
- Arheimer, B. 2006. Evaluation of water quantity and quality modelling in ungauged European basins. In *Predictions in ungauged basins: Promises and progress*, ed. M. Sivapalan, et al., 103–107. Wallingford: IAHS Publication 303.
- Backer, H., J.-M. Leppänen, A.C. Brusendorff, K. Forsius, M. Stankiewicz, J. Mehtonen, M. Pyhälä, M. Laamanen, et al. 2010. HELCOM Baltic Sea Action Plan—A regional programme of measures for the marine environment based on the ecosystem approach. *Marine Pollution Bulletin* 60: 642–649.
- Balana, B.B., A. Vinten, and B. Slee. 2011. A review on cost-effectiveness analysis of agri-environmental measures related to the EU WFD: Key issues, methods, and applications. *Ecological Economics* 70(6): 1021–1031.
- Bishop, K., K. Beven, G. Destouni, K. Abrahamsson, L. Andersson, R.K. Johnson, J. Rodhe, and N. Hjerdt. 2009. Nature as the “natural” goal for water management: A conversation. *AMBIO* 38(4): 209–214.
- Brandt, M., H. Ejhed, and L. Rapp. 2008. The nutrient load to the Baltic Sea and Skagerrak and Kattegat 2006. Swedish EPA, Report 5815, Stockholm, Sweden, 96 pp (In Swedish, English Summary).
- Cherry, K.A., M. Shepherd, P.J.A. Withers, and S.J. Mooney. 2008. Assessing the effectiveness of actions to mitigate nutrient loss from agriculture: A review of methods. *Science of the Total Environment* 406: 1–23.
- Conley, D.J., H.W. Paerl, R.W. Howarth, D.F. Boesch, S.P. Seitzinger, K.E. Havens, C. Lancelot, and G.E. Likens. 2009. Controlling eutrophication: Nitrogen and phosphorus. *Science* 323: 1014–1015.
- Darracq, A., G. Lindgren, and G. Destouni. 2008. Long-term development of phosphorus and nitrogen loads through the subsurface and surface water systems of drainage basins. *Global Biogeochemical Cycles* 22: GB3022.
- Darracq, A., G. Destouni, K. Persson, C. Prieto, and J. Jarsjö. 2010. Quantification of advective solute travel times and mass transport through hydrological catchments. *Environmental Fluid Mechanics* 10(1–2): 103–120.
- Destouni, G., K. Persson, C. Prieto, and J. Jarsjö. 2010. General quantification of catchment-scale nutrient and pollutant transport through the subsurface to surface and coastal waters. *Environmental Science and Technology* 44(6): 2048–2055.
- Diaz, R.D., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321: 926–929.
- EC. 2000. European Parliament and the Council of the European Union. Directive 2000/60/EC establishing a framework for the Community action in the field of water policy. *Official Journal of the European Communities* L327: 1–72.
- Ferreira, J.G., J.H. Andersen, A. Borja, S.B. Bricker, J. Camp, M. Cardoso da Silva, E. Garcés, A.-S. Heiskanen, C. Humborg, L. Ignatiades, C. Lancelot, A. Menesguen, P. Tett, N. Hoepffner, and U. Claussen. 2011. Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive, Estuarine. *Coastal and Shelf Science* 93(2): 117–131.
- Friedland, F., T. Neumann, and G. Schernewski. 2012. Climate change and the Baltic Sea Action Plan: Model simulations on the future of the western Baltic Sea. *Journal of Marine Systems* 105–108: 175–186.
- Glavan, M., S.M. White, and I.P. Holman. 2012. Water quality targets and maintenance of valued landscape character—Experience in the Axe catchment, UK. *Journal of Environmental Management* 103: 142–153.
- Gren, I.M., and G. Destouni. 2012. Does divergence of nutrient load measurements matter for successful mitigation of marine eutrophication? *AMBIO* 41(2): 151–160.
- Hammer, M., B. Balfors, U. Mörtberg, M. Petersson, and A. Quin. 2011. Governance of water resources in the phase of change: A case study of the implementation of the EU Water Framework Directive in Sweden. *AMBIO* 40(2): 210–220.

- Hannerz, F., and G. Destouni. 2006. Spatial characterization of the Baltic Sea drainage basin and its unmonitored catchments. *AMBIO* 35(5): 214–219.
- Hering, D., A. Borja, J. Carstensen, L. Carvalho, M. Elliott, C.K. Feld, A.-S. Heiskanen, R.K. Johnson, et al. 2010. The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. *Science of the Total Environment* 408: 4007–4019.
- Ioris, A.A.R. 2012. The political geography of environmental regulation: Implementing the Water Framework Directive in the Douro River Basin, Portugal. *Scottish Geographical Journal* 128(1): 1–23.
- Jarsjö, J., Y. Shibuo, and G. Destouni. 2008. Spatial distribution of unmonitored inland water flows to the sea. *Journal of Hydrology* 348: 59–72.
- Larsson, M., and M. Pettersson. 2009. *Dominating areas and sources for eutrophication within the Northern Baltic Sea RBD*. Sweden: Account of Governmental Commission and County Board of Västmanland. [In Swedish].
- Lundqvist, L. 2004. Integrating Swedish Water Resource Management: A multi level governance trilemma. *Local Environment* 9(5): 413–424.
- Moss, B. 2008. The Water Framework Directive: Total environment or political compromise. *Science of the Total Environment* 400: 32–41.
- Naturvårdsverket (The Swedish Environmental Protection Agency). 2008. *Näringsbelastningen på Östersjön och Västerhavet 2006*. Sveriges underlag till HELCOMs femte Pollution Load Compilation. Naturvårdsverkets Rapport 5815, 95 pp. ISBN 978-91-620-5815-9, (In Swedish).
- NBS-RBDA. 2008. Preliminär kartläggning och analys i Norra Östersjöns vattendistrikt. Northern Baltic Sea River Basin District Authority, Västerås, Sweden (In Swedish).
- NBS-RBDA. 2009. Förvaltningsplan Norra Östersjöns vattendistrikt 2009-2015. Northern Baltic Sea River Basin District Authority, Västerås, Sweden (In Swedish).
- Olli, G., A. Darracq, and G. Destouni. 2008. Field study of phosphorus transport and retention in drainage reaches. *Journal of Hydrology* 365: 46–55.
- Persson, K., J. Jarsjö, and G. Destouni. 2011. Diffuse hydrological mass transport through catchments: scenario analysis of coupled physical and biogeochemical uncertainty effects. *Hydrology and Earth System Sciences* 15: 3195–3206.
- Pitkänen, H., and T. Tamminen. 1995. Nitrogen and phosphorus as production limiting factors in the estuarine waters of the eastern Gulf of Finland. *Marine Ecology Progress Series* 129: 283–294.
- Renberg, I., R. Bindler, E. Bradshaw, O. Emteryd, and S. McGowan. 2001. Sediment evidence of early eutrophication and heavy metal pollution of Lake Mälaren, Central Sweden. *AMBIO* 30(8): 496–502.
- SMHI. 2010. GSD river basin data, Swedish water archive. SVAR 2008. <http://produkter.smhi.se/svar/svar2008.htm>. Accessed March 18, 2010.
- Ullrich, A., and M. Volk. 2010. Influence of different nitrate-N monitoring strategies on load estimation as a base for model calibration and evaluation. *Environmental Monitoring and Assessment* 171(1–4): 513–527.
- UNEP/GRID-Arendal. 2001. Baltic Sea ArcView GIS data from Baltic Drainage Basin Project (BDBP). Retrieved July 7, 2010 from <http://www.grida.no/baltic/htmls/maps.htm>.
- Volk, M., J. Hirschfeld, A. Dehnhardt, F. Schmidt, C. Bohn, S. Liersch, and P.W. Gassman. 2008. Integrated ecological-economic modelling of water pollution abatement management options in the Upper Ems River. *Ecological Economics* 66: 66–76.
- Volk, M., S. Liersch, and G. Schmidt. 2009. Towards the implementation of the European Water Framework Directive? Lessons learned from water quality simulations in an agricultural watershed. *Land Use Policy* 26: 580–588.
- Water Information System Sweden. 2009. <http://www.viss.lst.se>. Accessed December 1, 2013 (in Swedish).
- Wulff, F., O.P. Savchuk, A. Sokolov, C. Humborg, and C.-M. Mörtz. 2007. Management options and effects on a marine ecosystem: Assessing the future of the Baltic. *AMBIO* 36(2–3): 243–249.

AUTHOR BIOGRAPHIES

Ingela Andersson (✉) is PhLic in Physical Geography at Stockholm University. Her research interests include the Water Framework Directive and its implications on Physical planning and management. *Address:* School of Natural Sciences, Technology and Environmental Studies, Södertörn University, 141 89 Huddinge, Sweden. *Address:* Department of Physical Geography and Quaternary Geology, Stockholm University, 106 91 Stockholm, Sweden. e-mail: ingela.andersson@stockholm.se

Jerker Jarsjö is an Associate Professor in Hydrogeology at Stockholm University. His research interests include hydrological and hydrogeological model interpretations of contaminant transport, groundwater–surface water interactions, and water quality trends. *Address:* Department of Physical Geography and Quaternary Geology, Stockholm University, 106 91 Stockholm, Sweden.

Mona Petersson is a Lecturer in Physical Geography at the School of Natural Sciences, Technology and Environmental Studies, Södertörn University. Her research interests are landscape processes related to river basins and coastal areas, and the considerations taken within planning and management. *Address:* School of Natural Sciences, Technology and Environmental Studies, Södertörn University, 141 89 Huddinge, Sweden.