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Modelling Nutrient Load Changes from Fertilizer Application Scenarios in Six Catchments around the Baltic Sea

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Abstract: The main environmental stressor of the Baltic Sea is elevated riverine nutrient loads, mainly originating from diffuse agricultural sources. Agricultural practices, intensities, and nutrient losses vary across the Baltic Sea drainage basin (1.75×10^6 km^2, 14 countries and 85 million inhabitants). Six "Soil and Water Assessment Tool" (SWAT) models were set up for catchments representing the major agricultural systems, and covering the different climate gradients in the Baltic Sea drainage basin. Four fertilizer application scenarios were run for each catchment to evaluate the sensitivity of changed fertilizer applications. Increasing sensitivity was found for catchments with an increasing proportion of agricultural land use and increased amounts of applied fertilizers. A change in chemical fertilizer use of ±20% was found to affect watershed NO_3-N loads between zero effect and ±13%, while a change in manure application of ±20% affected watershed NO_3-N loads between zero effect and −6% to +7%.

Keywords: agricultural management scenarios; Baltic Sea; environmental modelling; SWAT

1. Introduction

The ecological state of the Baltic Sea has been under pressure over the past few decades due to elevated nutrient inputs [1–3]. Hypoxia, which has serious negative ecological implications, occurs frequently. Hypoxia in sheltered marine areas is often associated with increased nutrient levels, and nutrient loads are recognized as the main driver of hypoxia in the Baltic Sea [4–9].

The elevated nutrient inputs originate predominantly from increased river nutrient loads [10]. Nitrogen loads have primarily increased due to augmented use of agricultural fertilizers, compared with preindustrial levels [11]. A source apportionment for the total riverine nutrient loading of the Baltic Sea in 2000 revealed that for total nitrogen (TN), natural background losses accounted for 28%, diffuse losses for 64%, and point source discharges for 8% of the riverine TN input to the Baltic Sea [12]. Agriculture accounted for 70–90% of the diffuse TN load [13]. For phosphorous, Mörth et al. [14] estimated that 15% to 70% of the total phosphorous (TP) load originated from point sources in sparsely populated boreal catchments and densely populated temperate catchments respectively between 1996–2000. Atmospheric deposition of nitrogen from land-based combustion of fossil fuels amounts to between 25% and 33% of the total nitrogen input to the Baltic Sea [15]. Ship traffic contributes 4–5% of the total atmospheric nitrogen deposition through fuel combustion [16].

The rising incidence of eutrophication has led policy makers and researchers to focus on the development of tools to reduce the nutrient input to the Baltic Sea and thus prevent further deterioration of ecological quality [17]. The most complex strategy developed is the Baltic Sea Action Plan [15,18,19], which includes an eutrophication segment aiming "to have a Baltic Sea unaffected by eutrophication" and in "good ecological status" [18]. However, knowledge-based assessment tools and management solutions are needed to achieve the objectives of the Baltic Sea Action Plan. With respect to agricultural nutrient losses, the potential impact of various management strategies needs to be assessed. According to the Helsinki Commission (HELCOM) pollution load compilation [20], the required reduction in TN load (total TN load) is 118,000 tons N, compared to the 1997–2003 reference period. By 2010, approximately 69% of this reduction was archived (90,000 tons N), but with large variation between the seven marine basins of the Baltic Sea. The remaining requirements after the 2008–2010 period are varying between zero and approximately 62,000 tons N (26% of the 2008–2010 total load) to the Baltic Proper (the main central part of the Baltic Sea).

Development of strategies aiming at reducing the nutrient loads to the Baltic Sea must be multi-faceted and comprehensive as the success of the applied strategies depends on multiple processes. Surface runoff, soil erosion, and nutrient retention/transport between the root zone and the catchment outlet are complex processes that are influenced by several environmental and anthropogenic factors. Process-based models describing both the hydrology and the sediment and nutrient transport within catchments are useful tools for describing such complex processes, and for evaluating the impact of measures and management strategies. Such models are capable of handling large amounts of data, combined with theoretical and expert knowledge, to integrate all available information about the system of interest.

Several studies involving modelling of river water and nutrient loads to marine areas with different purposes, and using different types of models, have been published [21–28]. Specifically addressing the Baltic Sea, the hydrological model HBV was set up for the entire Baltic Sea drainage basin to estimate runoff [29], with a preliminary study on scale effects [30]. The HBV model applied a rather crude spatial distribution approach, based on variability parameters, to model soil moisture dynamics and runoff in each individual sub-basin. The variability parameters were found to be relatively stable over a wide range of scales. Therefore, the HBV model could be applied at macro scale [30]. The "Hydrological Predictions for the Environment" HYPE model was set up and tested for both Sweden and the entire Baltic Sea catchment, reporting a water balance error of <10% and <25%, respectively [31,32].

Concerning the modelling of nutrient transport, a large-scale model "Catchment Simulation software" (CSIM) was set up for the entire Baltic Sea basin, aiming to describe the substantial differences in nutrient loads between the various catchments relative to geographical conditions, land use, population density, climate, etc. [14]. This was the first modelling work of its type conducted for the Baltic Sea catchment, and the main challenge was to capture the huge scale differences in nutrient transport [14]. Therefore, the model was kept relatively simple, focusing on key processes. The CSIM model describes inter-annual and seasonal variability of water and nutrient fluxes for 105 catchments. However, large-scale lumped models, such as CSIM, set up for entire regions are not capable of describing the impact of various mitigation measures applied at small/semi-distributed scale. Thus, to develop cost-effective adaptation strategies, models that can handle processes at small/semi-distributed scale, are needed.

In this study, the semi distributed (SWAT) was set up for six type catchments within the Baltic Sea watershed. Models like SWAT permit working on a fine spatial scale and addressing catchment and agricultural management in a detailed way [33]. Several individual SWAT models have been set up for areas within the Baltic Sea watershed with a focus on different objectives [17,34–43]. Ekstrand et al. [34] calibrated the SWAT model to five river basins in Sweden (tributaries to Lake Mälaren) to improve the modelling of phosphorus losses relative to the rainfall-runoff coefficient-based Watershed Management System (WATSHMAN) model. Francos et al. [36] applied the SWAT model to the Kerava watershed (South Finland) and found a good agreement between the measured and predicted values of runoff, total N, and total P concentrations at the outlet, especially when using precipitation data with fine spatial resolution. Lam et al. [38] performed an assessment of point and diffuse source pollution of nitrate in the Kielstau catchment (North German lowlands). Marcinkowski et al. [42] modelled combined climate, land use change, and fertilizer application scenarios for the Reda catchment in northern Poland. Abbaspour et al. [44] constructed a continental scale model covering Europe and thereby also the Baltic Sea catchment. All these studies focused, however, on certain geographical areas and were not representative of the entire Baltic Sea watershed. Also, these studies dealt only with hydrological processes, or had little to no emphasis on agricultural management.

This study focuses on modelling the effect of changes in agricultural fertilization practices on nutrient loads in different river catchments around the Baltic Sea. Similar SWAT studies have previously been performed, for example, Santhi et al. [45] evaluated the long-term effects of Water Quality Management Plans on non-point source pollution in a Texas catchment. Schilling and Wolter [46] examined a suite of measures, among these fertilizer application reductions, to meet regulatory limits for public water supplies. White et al. [47] modelled nutrient loads from six Oklahoma catchments, also identifying critical source areas for sediment and phosphorous. Thodsen et al. [41] used SWAT to identify high risk and low risk areas for diffuse nutrient losses in the Odense Fjord catchment, Denmark.

We ran four agricultural fertilization scenarios. These were ±20% chemical fertilizer application and ±20% manure fertilization. In the southern part of the Baltic Sea catchment, in Poland, the Baltic countries, Russia, and Belarus, it is likely that agriculture will intensify with higher fertilizer and manure application rates as a consequence of an expansion in meat and dairy production, leading to increased diffuse nutrient losses [48,49]. The scenarios increasing chemical and manure fertilization were based on this prediction, and on the possibility of water quality, not being the top priority of decisions made in all countries around the Baltic Sea. Along the northern and western rim of the Baltic Sea, in Germany, Denmark, Sweden, and Finland, application rates were likely to be stable or decline following political regulations. There is a continuous need to reduce nutrient loads to meet reduction needs in marine areas and lakes. The 20% reduction scenarios were based on this prediction.

We hypothesised that the effect of altered fertilizer/manure application would vary according to differences in the fraction of agricultural land use and agricultural fertilization practices in the Baltic catchments. The findings of our study will be of use for decision makers in targeting mitigation measures.

The aim of this study was to evaluate the effect of changed agricultural chemical fertilizer and manure application rates on nutrient loads in six type catchments within the Baltic Sea drainage basin.

2. Materials and Methods

2.1. Study Areas

The Baltic Sea drainage basin covers an area of 1.75×10^6 km^2, and the climate ranges from sub-arctic conditions in the north to temperate conditions in the south (Figure 1). The south-western part has a relatively humid Atlantic climate, while the eastern and northern parts have a dryer and more continental climate.

The six type catchments included in this study were: River Kalix, representing the boreal forested northern catchments: River Pärnu, Estonia, and River Nevezis, Lithuania, representing the eastern catchments with both forest and medium intensity agriculture; the Norrström catchment (only including the land area and thus not Lake Mälaren), Sweden, representing the eastern Swedish catchments with both agriculture (medium-high intensity), forest and urban areas; River Plonia, Poland, representing the high intensity agricultural southern catchments; and River Odense, Denmark, representing the high intensity agricultural catchments in the south-western part of the Baltic Sea basin. The combined area of the six pilot catchments was about 55,000 km^2, i.e., approximately 3% of the total Baltic Sea catchment area. The six type catchments represented ranges in climate, land use, and agricultural practices (Table 1).

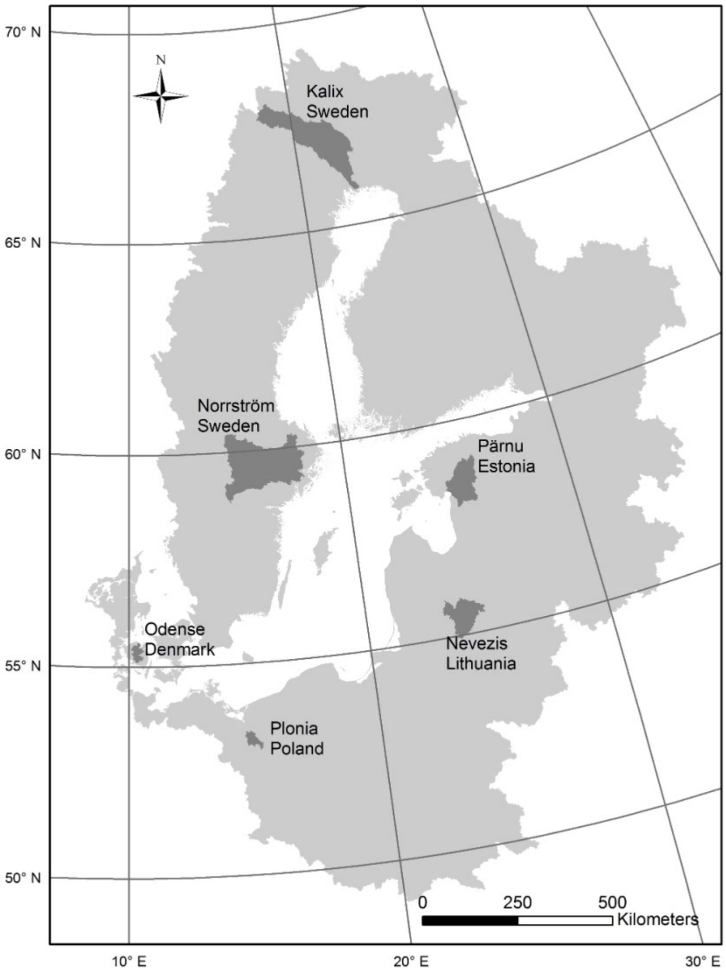

Figure 1. Map of the six type catchments around the Baltic Sea.

Table 1. Catchment characteristics. P is the mean annual precipitation for the period 1995–2006. T is the mean temperature for the period 1995–2006.

Catchment/Country	Area (km^2)	Agriculture (Area %)	P (mm year^{-1})	T (°C)	Catchment Type
Odense/Denmark	1059	71	704	8.7	Intensive agriculture—west
Pärnu/Estonia	6721	33	650	6.5	Agricultural-forested
Nevezis/Lithuania	6142	63	597	6.9	Agricultural-forested
Plonia/Poland	1034	78	550	8.4	Intensive agriculture—south
Kalix/Sweden	18,108	0.5	712	−0.5	Boreal forest
Norrström/Sweden	21,872	26	680	6.4	Forest/intensive agriculture

2.2. Data

Harmonised methods and data for the individual models were used. In some cases, national or local data of better quality than the common data source were chosen in order to optimise model performance. The common data sets on soil (see below) and land use (see below) were aggregates of national maps and differed between countries [50,51].

Climate data on all catchments derived from the data set belonging to the European Joint Research Centers (JRC) MARS50 data set were used, in some cases supplemented with better quality national or local data [52]. The MARS50 data set is a 50 km grid data set that includes all climate data necessary for setting up the SWAT model. MARS50 is available online. For the River Odense catchment, national 10 km gridded daily precipitation was used [53]. For the Pärnu catchment, precipitation and air temperature (minimum and maximum) data for six stations (Koodu, Kuusiku, Massumõisa, Parnu Türi and Viljandi), provided by the Estonian Environment Agency, were used. SWAT uses five different climate variables with daily resolution: temperature (minimum and maximum), precipitation, wind speed, relative humidity and short wave solar radiation, all derived from the MARS50 data set [54].

The Kalix, Nevezis, Plonia and Pärnu catchments were set up using the "Advanced Spaceborne Thermal Emission and Reflection Radiometer" ASTER Digital Elevation Model (DEM) [55]. The Odense catchment was set up using a 32 m resampled version of a 1.6 m LIDAR DEM [56]. The Norrström catchment was set up with a local DEM, with a resolution of 25 m.

The Corine land use map was applied to all catchments [51]. The soil map that was applied to all models except the Odense catchment model, was obtained from the Harmonized World Soil Database (HWSD). This soil map is an aggregation of nationally developed Food and Agriculture Organization of the United Nations (FAO) soil maps [50]. SWAT soil parameters were applied either directly from the HWSD, or estimated using the Hypress soil physics model [57]. For the Odense catchment, a national scale three-layer soil map was used because its quality was deemed superior to the HWSD [58].

Inputs on agricultural management included in the six different SWAT models originated from both national and European statistical sources on crop distribution, crop yields and fertilizer application rates and from local knowledge of agricultural practices [41]. The agricultural management data primarily represented the year 2005. Since the data were collected by different institutions in the various countries, some represented other years/periods. The agricultural area of each catchment was split into a number of rotations reflecting the complexity of the agricultural management in each catchment (Table 2). Increasing complexity, a rising percentage of agricultural area and enhanced knowledge about local agricultural conditions resulted in a higher number of agricultural rotations. The rotations aimed to be realistic with respect to the succession of crops and the application of chemical fertilizers and manure to individual crops, and to ensure that the annual application of chemical fertilizers and manure application was identical between years. Each rotation included dates for tillage/soil treatment, sowing, fertilizer applications and harvesting. Fertilizers were applied as either chemical fertilizers or manure (in many cases both) in accordance with the type of farming represented, for example cereals, pigs and cattle (beef or dairy). The amount of each fertilizer type (e.g., chemical, manure, pig slurry, cattle slurry) applied corresponded with the amounts typically used in the geographical region for the type and the intensity of the agricultural type in focus.

Table 2. Soil and Water Assessment Tool (SWAT) model setup information.

Catchment	Sub-Basins	HRUs *	Soil Types	Slope Classes	Calibration Period	Validation Period	Warm-Up Years	Agricultural Rotations/Years
Odense	31	2734	11	3	1997–2001	2002–2006	2	14/5
Pärnu	130	5271	12	4	1999–2002	2003–2006	7	2/7
Nevezis	102	1936	16	3	2000–2003	2004–2005	5	4/5
Plonia	66	2479	17	3	1997–2002	2005–2006	2	8/3
Kalix	23	280	2	3	1998–2000	2001–2006	2	2/1
Norrström	39	867	8	3	1997–2000	2001–2006	2	4/5

* Hydrological Response Unit (HRU).

In each SWAT model, atmospheric nitrogen deposition was provided as values of both dry and wet deposition based on gridded data from "the European Monitoring and Evaluation Programme" EMEP [59,60].

2.3. Model Setup

The complexity of the individual SWAT models (number of sub-basins and HRUs) reflected the aim of creating comparable models, and was influenced by catchment size, level of detail of basic input data (land use classes, soil classes, slope classes), number of monitoring stations and larger lakes/reservoirs, and the homogeneity of the catchment, as well as the number of rotations into which the agricultural area was split. The number of sub-basins in each SWAT model was thus primarily determined by the number of "points of interest" and not by the threshold of stream initialisation in the delineation of the models, as many of the auto-generated river confluence sub-basins were deleted in the delineation process. Jha et al. [61] evaluated the effect of average relative catchment sizes in SWAT (earlier version) on NO_3 and MinP loads for similar sized catchments in Wyoming, US. They found that loads had no effect on NO_3 loads when the sub-basin size was <2% of total catchment and <5% for MinP. In all models except the River Kalix model, the number of HRUs was limited by applying thresholds to the percentage area of a sub-basin that the soil type/land use/slope class should occupy. The thresholds depended on the number of soil types and land uses present in the maps covering the watershed, thereby determining the initial number of HRUs in each model. However, the number of HRUs depended greatly on the number of splits that the agricultural HRUs were divided into (Table 2). For example, in the River Odense SWAT model the agricultural HRUs were split into 14 different kinds of agriculture, meaning that the number of HRUs with agricultural land uses was multiplied with 14. The number of splits was determined by the range of farming intensity, management practices, and knowledge about local farming practices. Basic SWAT statistics for comparing model setups are shown in Table 2. For example, the spatial resolution of the HWSD soil map was very coarse for Sweden, and only provided two soil types for the Kalix catchment, while there were 11 soil types for the much smaller River Odense catchment. This difference naturally resulted in more HRUs for the Odense catchment than for the Kalix catchment. Agricultural catchments had more HRUs than other catchment types since special emphasis was put on agriculture by splitting this land use type into specific rotations for different kinds of agriculture and agricultural management practices [41]. The upper limit of complexity was set by the computation time for running the SWAT models, and thus for performing the calibration procedure.

2.4. Calibration Data

Recording of river runoff (Q), nitrate (NO_3), and reactive soluble phosphorus/mineral phosphorous (MinP) (using SWAT nomenclature) loads for calibration and validation were collected for at least one location in each catchment (Table 3). All data were collected from national monitoring sources that converted individual nutrient concentration sample values into daily, monthly and bi-weekly load values using approaches complying with the HELCOM requirements of using either "Daily flow and daily concentration regression" or "Daily flow and daily concentration interpolation" methods [62–64].

Table 3. Overview of available calibration data (Q = River runoff, NO_3 = Nitrate river loads, MinP = Mineral phosphorous river loads). + = Crop yield data available.

Catchment	Q (#Stations)	NO_3 (#Stations)	MinP (#Stations)	Crop Yield
Odense	Daily (4)	Daily (4)	Daily (4)	+
Pärnu	Daily (7)	Bi-weekly (6)	Bi-weekly (6)	+
Nevezis	Monthly (3)	Monthly (3)	Monthly (3)	+
Plonia	Daily (2)	Monthly (2)	Monthly (2)	+
Kalix	Daily (3)	Monthly (1)	Monthly (1)	+
Norrström	Daily (2)	Daily/Monthly (2)	Monthly (2)	+

Observations of organic forms of N and P were not available for all catchments; hence, in order to allow cross-catchment comparisons, we chose to include only inorganic N and P. Organic N comprises only a minor fraction of the total N loads in the southern agriculturally dominated part of the Baltic Sea drainage basin [14,65]. In the northern part of the Baltic Sea drainage basin, organic forms of nutrients are dominant [66]. This is, however, mainly due to the land use (forests, extensive peatlands) which was not changed in the applied model scenarios.

2.5. Calibration Procedure

A common calibration procedure was applied to all six catchments. The models were calibrated sequentially in two steps, as previously done [67], with a possible pre-calibration adjustment of crop base temperature (T_BASE) to ensure crop yields and growth rates were at realistic levels for all major crops and vegetation types [44]. This was to ensure that vegetation was growing properly and thereby ensuring that evaporation and nutrient uptakes were not biased by unrealistic vegetation growth [68]. In Step One, river runoff was calibrated against observations on a daily or monthly scale, according to the time step of the observational data. Not all calibration parameter ranges were closed during Step One, as some parameters were sensitive to calibration of both hydrology and nutrient dynamics. Therefore, some parameters were left with a small range to be exploited during the NO_3 and MinP calibration. In Step Two, river NO_3 and MinP river loads were calibrated against observations (Table 3). NO_3 and MinP were calibrated sequentially with NO_3 as primary nutrient and thus calibrated first in each calibration iteration. Where a calibration parameter was sensitive to both NO_3 and MinP, its calibration range was primarily narrowed regarding NO_3 (Table 4).

Table 4. Parameters used during each of the two calibration steps.

Runoff	NO_3 and MinP
ALPHA_BF.gw	ANION_EXCL.sol
ALPHA_BNK.rte	CDN.bsn
CH_k2.rte	CMN.bsn
CN2.mgt	HLIFE_NGW.gw
DEP_IMP.hru	N_UPDIS.bsn
EPCO.hru	NPERCO.bsn
ESCO.hru	SDNCO.bsn
GW_DELAY.gw	
GW_REVAP.gw	
GWQMN.gw	
LAT_TTIME.hru	CH_OPCO.rte
OV_N.hru	GWSOLP.gw
RCHRG_DP.gw	P_UPDIS.bsn
REVAPMN.gw	PHOSKD.bsn
SFTMP.bsn	PPERCO.bsn
SMFMN.bsn	PRF.bsn
SMFMX.bsn	PSP.bsn
SMTMP.bsn	USLE_P.mgt
SOL_AWC.sol	
SOL_BD.sol	
SOL_K.sol	
SURLAG.bsn	
TDRAIN.mgt	
DDRAIN.mgt	
GDRAIN.mgt	

Model calibration of river runoff and nutrient loads was performed based on the Sequential Uncertainty Fitting Algorithm (SUFI2) that uses a global search procedure through Latin Hypercube Sampling [69–71]. All parts of the calibration were optimised by running at least 1000 simulations through SWAT calibration and uncertainty program (SWAT-CUP) software using multiple iterations where parameter ranges were gradually narrowed. Only sensitive parameters were considered after the first few rounds of calibration. The Nash-Sutcliffe model efficiency value was chosen as the primary objective function [72,73].

2.6. Scenarios

Four scenarios of agricultural management relating to application rates of fertilizers or manure were run. Regulation of nutrient inputs in agriculture is the most important measure adopted for nutrient loss mitigation, and is applied in all the EU member states in the Baltic Sea drainage basin (e.g., maximum allowable inputs of fertilizer and maximum allowable livestock densities [74]). The model scenarios included changes in chemical fertilizer use by ±20% and changes in livestock number by ±20%, respectively. The changes in livestock numbers were implemented in SWAT as changes in the manure application amount. The scenarios were introduced to SWAT by changing the amount of fertilizer (chemical or manure) applied to a given agricultural crop at any given time. The scenarios thus had the highest effect in sub-basins with a large fraction of agricultural land. Livestock scenarios were implemented without counterbalancing changes in manure application with chemical fertilizer application. No combinations of altered chemical fertilizer and manure applications were used. A 20% increase in fertilization was also used as a scenario for catchments in central Germany [75].

3. Results

3.1. Model Validation

All models were validated with respect to river runoff (Q), NO_3, and MinP against observations covering at least one-third of the period with observations. Model validation statistics for the six SWAT models are shown in Table 5.

Table 5. Model calibration/validation statistics for the six SWAT models on river runoff, river NO_3 loads and river MinP loads. (calibration/validation) Nash-Sutcliffe [72]. BR^2 is described in [70]. Daily runoff values are used, except for Nevezis where runoff is given as monthly values. All NO_3 and MinP values are derived from monthly data, except for Odense where NO_3 and MinP is given as daily values.

Statistical Parameter		**Odense Denmark**	**Norrström Sweden**	**Kalix Sweden**	**Pärnu Estonia**	**Nevezis Lithuania**	**Plonia Poland**
Run off	Water balance error (%)	14/4	−13/−11	−1/4	−10/−2	4/−2	0/−8
	Nash-Sutcliffe	0.85/0.82	0.61/0.57	0.87/0.87	0.61/0.65	0.84/0.82	0.73/0.57
	R^2	0.89/0.84	0.77/0.70	0.88/0.89	0.68/0.71	0.88/0.84	0.74/0.58
	BR^2	0.87/0.80	0.69/0.66	0.91/0.89	0.33/0.46	0.76/0.59	0.57/0.34
	Error 25 percentile (%)	−21	−71	−31	104	41	21
	Error 75 percentile (%)	34	−2	7	−8	19	20
NO_3	Mass balance error (%)	18/37	−4.3/−8.2	12/−10	−25/−25	−36/−48	3.0/−8.0
	Nash-Sutcliffe	0.52/0.48	−0.53/−0.67	0.33/0.31	0.76/0.72	0.69/0.67	0.61/0.34
	R^2	0.78/0.69	0.36/0.32	0.49/0.45	0.68/0.84	0.82/0.80	0.62/0.34
MinP	Mass balance error (%)	7.0/8.1	5.7/−0.40	8.6/1.6	−23/−26	21/24	13/16
	Nash-Sutcliffe	0.33/0.29	0.11/−0.20	−1.4−1.7	0.52/0.45	0.32/0.34	0.38/0.39
	R^2	0.57/0.61	0.62/0.56	0.23/0.23	0.53/0.48	0.32/0.35	0.38/0.39

The River Pärnu model was initially run with MARS50 precipitation, which resulted in a Nash-Sutcliffe value of −0.24, compared with a value of 0.61 when using local station data. It was obvious that flow peaks did not correspond well with high MARS50 precipitation events.

The time series of observed and simulated river water discharge for both the calibration and the validation period are shown for the River Plonia in Figure 2 by way of example.

As displayed in the figure, the simulated curve followed the observed curve quite well during most of the period. The simulated curve did not systematically over- or underestimate the annual spring peak flow events or the summer low-flow conditions.

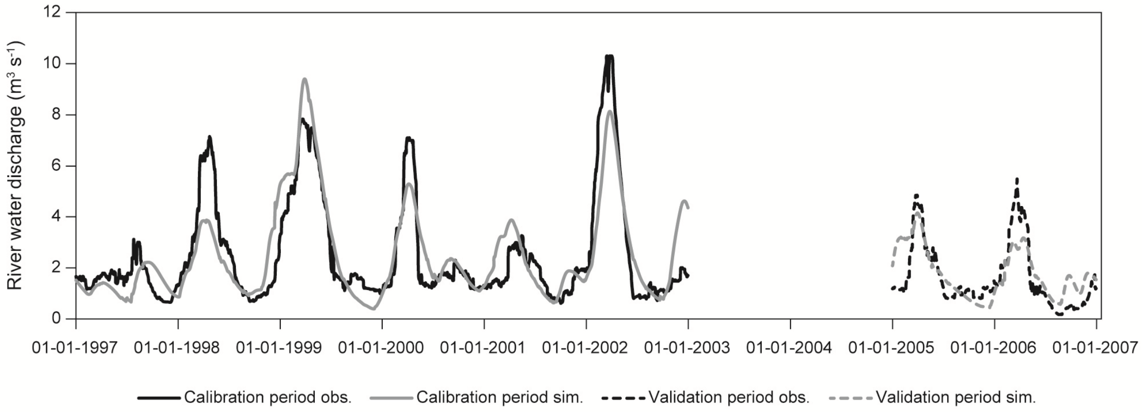

Figure 2. Time series of observed and simulated river water discharge for the calibration period (1997–2002) and the validation period (2005–2006) in the Plonia catchment, Poland.

3.2. Fertilizer Application

Both the total amount of fertilizers applied in a catchment and the amount applied in agricultural areas were important in order to elucidate the nutrient dynamics of catchments (Table 6).

Table 6. Applied annual fertilizer amounts (kg N ha^{-1}) in the SWAT model for each of the six catchments (N/P). The manured area of the Pärnu catchment is very small and therefore not included.

		Odense Denmark	Norrström Sweden	Kalix Sweden	Pärnu Estonia	Nevezis Lithuania	Plonia Poland
Chemical fertilizer	kg N ha^{-1} per catchment area	67/6	14/1.6	0.15/0.03	33/8	35/0.5	115/15
Manure	kg N ha^{-1} per catchment area	62/13	5/1.0	0.3/0.06	-	10/3	5/2
Chemical fertilizer	kg N ha^{-1} per agricultural area	94/8	55/6	30/5	98/23	64/1	147/19
Manure	kg N ha^{-1} per agricultural area	87/18	20/4	60/11	-	19/6	6/2.5

Large differences existed in the amounts of fertilizers used in the different catchments, and were most pronounced between the amounts used per ha^{-1} in the total catchment, primarily reflecting the fraction of the catchment used for agricultural purposes (Table 1). Additionally, there were relatively marked variations between the amounts of fertilizers used per ha^{-1} in the agricultural areas, reflecting the differences in agricultural intensity (Table 6). For the northern boreal catchment, Kalix, the agricultural nutrient input to the catchment of 0.45 kg N ha^{-1} was much smaller than the atmospheric N deposition of about 7 kg N ha^{-1}.

3.3. Scenario Results

Changes in modelled mean annual NO_3 and MinP loads resulting from the scenario runs are presented in Table 7.

The baseline nutrient losses from the River Plonia catchment were low, considering the size of the catchment, the relatively high fraction of agricultural land use, and the amount of fertilizer used. The low load can be explained by the presence of the 36 km^2 large Lake Miedwie a short distance upstream of the monitoring station used for calibration and validation. Therefore, the Plonia catchment nutrient loads were not directly comparable with those from the other catchments.

Table 7. Changes in NO_3/MinP (%) load from catchments in chemical fertilizer and manure application scenarios.

Scenario		**Odense Denmark**	**Norrström Sweden**	**Kalix Sweden**	**Pärnu Estonia**	**Nevezis Lithuania**	**Plonia Poland**
Baseline	Ton year^{-1}	1926/30.3	5704/181	436/30	384/16	3910/228	28.5/2.0
ChemicalFertilizer	−20%	−7.5/−0.2	−1.1/−1.1	−0.02/−0.03	−0.3/−0.6	0.3/−0.1	−13/2
	+20%	7.8/0.2	1.1/1.1	0.02/0.03	0.0/0.0	2.1/−0.1	13/−1
Manure	−20%	−6.3/−0.2	−0.1/−0.6	−0.06/−0.05	−0.1/0.0	0.8/0.1	−0.5/0.0
	+20%	6.8/0.2	0.1/0.0	0.06/0.05	0.2/0.0	0.8/0.1	0.5/0.0

The differences in scenario responses to NO_3 between the catchments were large. The effect of reducing fertilizer application was negligible for the boreal River Kalix, which has a very low fraction of agricultural land use. The largest effects were found for the River Plonia and the River Odense catchments, the latter having the largest fraction of agricultural land and relatively large fertilizer application rates. The River Nevezis catchment also has a comparatively large percentage of agricultural land, but a weaker response in river loads to the scenarios was found, reflecting the lower fertilizer application in this catchment than in the Odense and Plonia catchments. The Pärnu and Norrström catchments both have an agricultural land use around 30%, and showed small responses to the scenarios.

3.4. Model Sensitivity

The most sensitive model parameters for each modelling objective in each of the six SWAT models are given in Table 8. The most sensitive parameters were chosen based on the SWAT-CUP global sensitivity analysis, utilising the Nash-Sutcliffe objective function, at an early stage of the calibration procedure [69,70,72].

Table 8. Most sensitive model parameters.

	Odense Denmark	**Norrström Sweden**	**Kalix Sweden**	**Pärnu Estonia**	**Nevezis Lithuania**	**Plonia Poland**
Water discharge	GW_DELAY EPCO	SMTMP	SMTMP	GW_DELAY ALPHA_BF CH_N2	SMTMP CN2	GW_DELAY CANMX
NO_3 load	SDNCO HLIFE_NGR	NPERCO HLIFE_NGR	NPERCO	NPERCO CDN N_UPDIS	NPERCO	SDNCO HLIFE_NGW
MinP load	GWSOLP PPERCO	GWSOLP PPERCO	PSP	PSP PPERCO	GWSOLP	GWSOLP

GW_DELAY is groundwater delay time (days), ALPHA_BF is Baseflow alpha factor (1 day^{-1}), ESCO is soil evaporation compensation factor, CANMX is maximum canopy storage, CN2 is curve number, SMTMP is snow melt temperature, CH_N2 is Manning channel roughness "*n*" for the main channel, HLIFE_NGR is half-life of nitrate in shallow aquifer (days), SDNCO is denitrification threshold water content, NPERCO is nitrate percolation coefficient, N_UPDIS is nitrogen uptake distribution parameter, CDN is denitrification exponential rate coefficient, GWSOLP is concentration of soluble phosphorous in groundwater contribution to stream flow from sub-basin (mg L^{-1}), PPERCO is phosphorous percolation coefficient and PSP is phosphorous availability index [54].

The parameters shown in Table 8 mostly reflected the overall conditions of the catchment. The northern and eastern catchments with a spring flood flow regime are very sensitive to the snowmelt temperature, and the base flow-dominated southern and western catchments are sensitive to groundwater parameters such as the groundwater delay time. For base flow-dominated catchments, the half-life of nitrate in the shallow aquifer tended to be sensitive.

4. Discussion

In model comparison studies, it is important that the inputs to the different models are as comparable as possible. However, some inputs to the six SWAT models in this study differed, and for instance the soil data were derived from different sources because no uniform single source exists. The HWSD is a collection of national maps that vary in terms of spatial resolution; thus, the HWSD is detailed for Estonia and Lithuania but very crude for Sweden. Therefore, we decided that the best available soil map would be used for each catchment. MARS50 climate data were used in all catchments for all parameters except for precipitation (Odense and Pärnu) and temperature (Pärnu), which were in these cases available at a better spatial scale from other sources. For the Pärnu catchment, the replacement of the MAR50 precipitation with data of better spatial resolution resulted in noticeable improvements to the model; the Nash-Sutcliffe value was improved from -0.24 to 0.61 for runoff during the calibration period. The importance of good precipitation data for calibrating hydrological models is also emphasised by Chaibou et al. [76] and by De Almeida Bressiani [77], who tested a range of precipitation data. The Corine land use map is another aggregation of national maps, but as these are made from a common standard, harmonisation is greater than that of the HWSD, and the Corine map was therefore used in all catchments. The agricultural management and crop yield data used in setting up the models were obtained from national and EU statistics, and were therefore comparable. The expertise of the modellers with agricultural statistics differed as knowledge about local agricultural practices varied from extensive to sparse. Availability of calibration data differed in terms of the amount of data (spatial and temporal), quality of the data, and parameters of the data. All stages of the modelling process are subject to uncertainties and errors, and uncertainty is even stronger in a study comparing conditions in different geographical areas and different countries. As described above, some of the basic input data to the SWAT model, such as the soil maps, differed, increasing the uncertainty related to the soil maps, and implying higher uncertainty in our study than in a study dealing with just one homogeneously produced soil map. The same increase in uncertainty associated with a "total study" was added from all other input data. However, the six catchments were primarily chosen based on the extensive available data, and we therefore believe that the quality was the best possible for the aim of this study. Furthermore, the catchments represented the variations in geographical and agricultural management conditions in the Baltic Sea watershed. For modelling of river runoff, the quality of the climate forcing data, particularly precipitation, is important [69]. The spatial scale of the precipitation data is highly significant. SWAT uses a time series of daily precipitation from the nearest station (in this case the centre point of a grid) and applies this precipitation to a sub-basin, implying that a single value is used for lumped areas of varying size. Potentially, this could induce certain scale problems. For example, a single-station value is applied to a large catchment, the problem being that, for example, a single thunder storm shower (>100 mm day^{-1}) affecting 1% of a large catchment, including the precipitation gauge location, would simulate an extreme high-flow event not occurring in reality, and would not be representative of the entire catchment when applied to the hydrological model. A similar problem may arise if gridded precipitation data is averaged over too few stations. On the other hand, the spatial scale of the gridded observations could be too large, and the variation in water discharge caused by differences in precipitation would therefore not be reflected in the model. In this study, a 50 km grid resolution (2500 km^2) was used for four of the six catchments, while a finer resolution was available for the latter two. The average sub-basin size in the four catchments ranged from 16 km^2 for the River Plonia to 787 km^2 for the River Kalix. Thus, it is obvious that the grid scale of the precipitation data fitted the average sub-basin size of the River Kalix better than that of the River Plonia. That is, if the River Plonia catchment had a substantial geographical precipitation gradient, the 50 km gridded data would presumably be too coarse to capture this. Potentially, the entire River Plonia catchment could be covered by only one grid cell.

By choosing SWAT to model all six catchments, the problem of comparing results from different models was avoided and a consistent modelling approach was applied, lending credibility to the comparison of calibration/validation and scenario results between the six watersheds.

The most sensitive parameters for each SWAT model at an early stage of each calibration step are shown in Table 8. We chose not to quantify parameter sensitivity, as the sensibility of single parameters depends on a number of circumstances—for instance, choice of objective function, temporal resolution of calibration data, calibration procedure, spatial resolution of input data, conceptual model uncertainty, modeller's knowledge of the modelled catchment, chosen initial calibration parameter range, climate of the chosen calibration, and validation period—at the stage of the calibration procedure during which the sensitivity analysis is performed as well as on the model output in focus [69]. For example, the modeller's knowledge about the catchment and experience in calibrating models for a particular area may strongly influence parameter sensitivity. In this study, the modelling team had extensive experience in modelling the River Odense catchment, leading to knowledge about parameter setting for the modelling of NO_3, where the denitrification threshold water content (SDNCO) should be between 0.75 and 0.99 and the denitrification exponential rate coefficient below 1 to produce realistic denitrification rates, thereby avoiding non-uniqueness problems [69]. Extensive knowledge reduced the sensitivity of these parameters compared with a situation where calibration was initiated with a full range. Similar knowledge was not available for the River Kalix, Norrström, Nevezis and Pärnu, and the range of these parameters therefore had to be larger, producing a potentially greater sensitivity. Where calibration data were available with daily resolution, parameters addressing fast-responding parameters were more sensitive than where calibration data were available with monthly resolution.

Model uncertainties relative to reproduction of observational values of Q, NO_3 and MinP are evaluated in Table 5. Moriasi et al. [78] states that Nash-Sutcliffe efficiency values > 0.75 for monthly time steps of runoff are "very good" (Rivers Odense, Kalix, Nevezis), values between 0.75 and 0.65 are "good" and values between 0.65 and 0.50 are "satisfactory" (Rivers Norrström, Pärnu, Plonia) (Table 5). Nash-Sutcliffe values calculated from daily values are usually lower than values calculated from monthly values. Mass balance "percent BIAS" (PBIAS) (%) for N and P estimates of ±25% were considered "very good" (River Odense NO_3 & MinP, River Kalix NO_3 & MinP, River Pärnu NO_3, River Nevezis MinP and River Plonia NO_3 & MinP), ±25% to ±40% as "good" (River Pärnu MinP) and the interval ±40% to ±70% as "satisfactory" (River Nevezis NO_3). Overall, the validation statistics were considered adequate.

The total water balance error of the six SWAT model validations was relatively good, with a maximum error of 11%, but when evaluated according to the 0.25 percentile (25% of all values are smaller than this) and the 0.75 percentile, the models had larger biases (Table 5).

The scenario simulations showed that the effect of altered fertilizer application was strongest in catchments with a large fraction of agricultural land use and with intense agriculture like the River Odense and River Plonia catchments (Tables 1 and 6). River Norrström and River Nevezis exhibited a stronger response to the scenarios than River Pärnu, although the combined agricultural pressure in the three catchments was about the same. River Kalix showed a negligible response to the scenarios, which was expected, as agriculture only occupies 0.5% of its catchment area.

For the Kalix, Norrström, Pärnu and Nevezis catchments, the modelled effects of the scenarios on MinP were of the same magnitude as the effect on NO_3, and were an order of magnitude smaller on MinP than on NO_3 for the River Odense and Plonia catchments. This reflected the higher NO_3 input to these intensely farmed catchments. Besides this, the effects on MinP were rather linked to soil erosion processes than to leaching processes. Therefore, catchments with a relatively continental climate and, consequently, relatively large erosive spring snow melt events, showed a stronger response than catchments with a more Atlantic climate having milder winters and a smaller build-up of snow. Additionally, SWAT did not simulate leaching of dissolved phosphorous from the soil to the groundwater and into the river [54].

The results presented in this paper for the Baltic Sea catchments suggest that the effect of changed agricultural nutrient applications on riverine nutrient loads will be strongest in areas with relatively intensive fertilizer application. Therefore, decision makers should focus on mitigation methods in these areas if they are aiming at maximum impacts per hectare of agricultural land. Large differences in nutrient loads in the high intensity agricultural areas remain, though, due to differences in, for instance, fertilizer application procedures and crop yield and notable differences in retention found primarily for nitrogen [79]. A study running a +20% fertilization scenario for catchments in central Germany found NO_3 river load increases from 2% to 6% [75].

Along the southern rim of the Baltic Sea, in Poland (despite the fact that the Polish Plonia catchment has the highest chemical fertilizer application rates among the six catchments included in this study), the Baltic countries, Russia and Belarus, it is very likely that agriculture will be intensified, with higher fertilizer and manure application rates, as a consequence of an expansion of meat and dairy production, leading to increased diffuse nutrient losses [48,49]. Along the northern and western rim of the Baltic Sea, in Germany, Denmark, Sweden and Finland, application rates are likely to be stable, or will decline following political regulations.

The loads of organic nitrogen and phosphorous make up a substantial part of the total nutrient input to the Baltic Sea, and a primary part of total nutrient inputs in northern boreal forest areas [14]. The organic fractions were not considered in this study for two reasons: (1) data were not available for all six catchments; (2) the scenarios were not thought to substantially influence the load of organic N and P.

5. Conclusions

Four fertilizer application scenarios were run for each of the six watersheds to evaluate the sensitivity of changed fertilizer application rates. Increasing sensibility was found for catchments with an increasing proportion of agricultural land use, and enhanced amounts of fertilizer application. A change in chemical fertilizer use of ±20% affected watershed NO_3-N loads between zero effect and ±13%. A change in manure application of ±20% affected watershed NO_3-N loads between zero effect and −6% to +7%.

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