Carl-Magnus Mörth, Christoph Humborg, Hanna Eriksson, Åsa Danielsson, Miguel Rodriguez Medina, Stefan Löfgren, Dennis P. Swaney and Lars Rahm

Modeling Riverine Nutrient Transport to the Baltic Sea—A Large-Scale Approach

?1 We developed for the first time a catchment model
?2 simulating simultaneously the nutrient land-sea fluxes from all 105 major watersheds within the Baltic Sea drainage area. A consistent modeling approach to all these major watersheds, i.e., a consistent handling of water fluxes (hydrological simulations) and loading functions (emission data), will facilitate a comparison of riverine nutrient transport between Baltic Sea subbasins that differ substantially. Hot spots of riverine emissions, such as from the rivers Vistula, Oder, and Daugava or from the Danish coast, can be easily demonstrated and the comparison between these hot spots, and the relatively unperturbed rivers in the northern catchments show decisionmakers where remedial actions are most effective to improve the environmental state of the Baltic Sea, and, secondly, what percentage reduction of riverine nutrient loads is possible. The relative difference between measured and simulated fluxes during the validation period was generally small. The cumulative deviation (i.e., relative bias) (Σ(Simulated − Measured)/ΣMeasured $\times$ 100 (%)) from monitored water and nutrient fluxes amounted to +8.2% for runoff, to −2.4% for dissolved inorganic nitrogen, to +5.1% for total nitrogen, to +13% for dissolved inorganic phosphorus and to +19% for total
?3 phosphorus. Moreover, the model suggests that point sources for total phosphorus compiled by existing pollution load compilations are underestimated because of inconsistencies in calculating effluent loads from municipalities.

INTRODUCTION

Nutrient loads to the coastal zone have increased globally during the 20th century (1), including those to the Baltic Sea (2). Not surprisingly the environmental conditions in the Baltic have deteriorated since the Second World War in concert with the increased nutrient loads because of increased industrialization and transportation as well as a more intensive agriculture. Anoxia, a dwindling cod population, and massive cyanobacteria blooms are just a few indications of the problematic conditions in the Baltic Sea (3). To overcome these problems, measures have been taken to reduce the nutrient loads, resulting in slight, but discernable improvements. The Helsinki Commission (HELCOM) identified the largest point sources of pollutants to the Baltic, some of which have been reduced during the last decade (4). Rydberg et al. (5) recently reported decreasing trends in annual primary production for the Kattegat and Belt region after 1980, and Papush and Danielsson (6) found less increasing nutrient trends for the last few decades as compared to the period 1970–1990s (7). These changes might be explained as an effect of improved wastewater treatment and measures in agriculture. On the other hand, many authors (1, 8) have stressed the importance of internal sources, which are only indirectly forced by the external nutrient loads.

The decision support system NEST (9) has been developed to analyze the effect of different management actions of the Baltic Sea. It consists of a marine biogeochemical model of the entire ?4 Baltic Sea linked to a drainage basin model, which handles the various nutrient emissions from land and describes the net export to the sea. The latter model was linked to an emission database that enables the formulation of alternative scenarios for remedial actions. To date, such a model has been lacking on the Baltic Sea scale. The model was applied to the entire Baltic Sea drainage basin divided into separate watersheds. This division was necessary to handle the complex ecosystem, but it required a consistent treatment of emission data from more than 100 watersheds draining into the Baltic Sea. A consistent data handling approach, as performed by CSIM, is urgently needed, because the existing pollution load compilations (PLC) 4 (10) represent a summary of various inconsistent national load and source-oriented approaches to estimating nutrient loads to the Baltic Sea, which thus risk serious misinterpretations. As a ?5 starting point, each watershed was simulated separately, and results were then aggregated for each subbasin of the Baltic Sea to be applicable to the European Union (EU) Water Framework Directive (11). Nutrient [nitrogen (N) and phosphorus (P)] fluxes were described by means of the water flows through various land cover types of a watershed, including surface and groundwater transports. The model simulates different management scenarios to predict the effects of various measures taken in the watersheds. These simulations can also be analyzed from an economical point of view (12). However, the aim of this article is to summarize the basic characteristics of the long-term and short-term model estimates. More detailed applications of the model testing various management scenarios can be found in Wulff et al. in this issue (9).

STUDY AREA

The Baltic Sea drainage basin comprises almost 2 million km^2, which is four times larger than the area of the sea itself (Fig. 1). The net freshwater discharge of the entire drainage basin is about 475 km^3 y^{-1}. The drainage basin of the Baltic Sea can be divided into a northern boreal region that drains into the Gulf of Bothnia (Bothnian Bay and Bothnian Sea) and a southern region that drains into the rest of the Baltic Sea (Fig. 1). Land usage patterns vary significantly between the watersheds (Table 1; Fig. 2). The dominating land cover in the north is boreal forest and wetlands. Cultivated areas and deciduous forest dominate the watersheds of the south. The population is around 83 million people distributed across nine riparian countries and three upstream states (13, 14). The majority of the population is found in the southern, highly industrialized region with intensive agriculture. Only 16% of the entire population lives in the upper, boreal region.

The entire drainage basin was partitioned into 105 watersheds (Fig. 1) following the EU-JRC data compilation for European watersheds, which is also the basis for the water districts in the European Water Framework Directive. The size of the different ?6 drainage basins in this study ranges from 265 km^2 up to 286 000 km^2. A handful of rivers dominate the freshwater discharge, but as they drain the highly populated southeastern region they also dominate the nutrient loads. On the other end of the scale are 22

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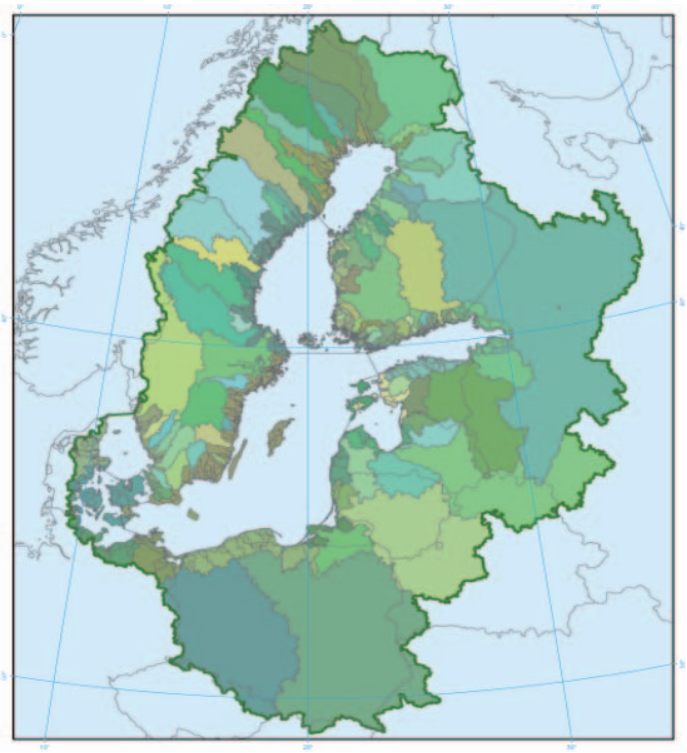

Figure 1. A map of the Baltic Sea catchment and main watershed areas.

small unmonitored coastal drainage basins with mainly diffuse nutrient loads to the coastal zone.

MODEL CONFIGURATION

CSIM is a lumped hydrologic model (Fig. 3) based on the generalized watershed loading function model [(GWLF) 15, 16] originally developed to simulate streamflow, sediment, and nutrient fluxes from mixed-use watersheds in the United States. CSIM and its predecessors, BasinSim (16) and GWLFXL (17) were used successfully in large watersheds of the United States, including the Delaware River (18) and the Choptank River drainage of Chesapeake Bay (19, 20), as well as in other watersheds throughout the world (21–24) to simulate seasonal and interannual nutrient fluxes. The model divides each watershed into a number of land use categories and considers the loads from each category separately. Daily erosion and sediment yields are derived from an event-based variant of the universal soil loss equation (USLE) and a sediment scheduling algorithm (15). The model simulates daily discharge to the streams, sediment load, and nutrient transport from the drainage area. The model is using this daily resolution to enable simulations of event-driven fluxes that, to a high degree, control especially the particulate P transport. These daily fluxes were then aggregated to annual fluxes (and multiannual fluxes) that are the forcing data for the marine model within NEST. The model is based on characteristic concentrations of inorganic and total N and P [dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), total nitrogen (Tot-N), and total phosphorus (Tot-P)] in surface and groundwaters; organic forms of nutrients can be added through erosion and point sources. Atmospheric deposition is not included explicitly, but is parameterized in the concentrations that the model requires to estimate nutrient transport.

Both groundwater and runoff are considered, including the transport of both dissolved and particulate nutrients. These loading functions are specified for each watershed and are used

Table 1. Baltic Sea basin characteristics indicated as population, population distribution, and land class areas to each of the Baltic Sea basins: Bothnian Bay (BB), Baltic Proper (BP), Bothnian Sea (BS), Gulf of Finland (GF), Gulf of Riga (GR), Danish Sounds (DS), Kattegat (KT) and the total Baltic Sea.

Basin	Population	Urban (%)	Rural (%)	Catchment area (ha)	Decidious (ha)	Coniferous (ha)	Mixed forest (ha)	Herbacous (ha)	Wetlands (ha)	Cultivated (ha)	Bare (ha)	Water (ha)	Snow and ice (ha)	Artificial (ha)
BB	1 320 010	47.7	52.3	26 362 519	787 625	11 433 919	7 197 350	1 400 056	2 373 819	1 075 175	609 163	1 412 081	40 306	33 025
BP	54 861 680	56.8	43.2	57 153 463	1 300 206	10 142 531	5 713 819	4 789 506	250 044	32 775 738	2 863	1 369 281	0	809 475
BS	2 393 152	39.4	60.6	22 637 213	452 144	13 487 719	4 440 944	691 863	737 250	1 091 388	168 194	1 458 981	275	108 456
DS	5 220 245	84.6	15.4	2 883 425	34 538	73 606	79 219	135 056	10 550	2 265 781	0	134 538	0	150 138
GF	12 364 198	67.0	33.0	43 110 463	1 282 219	18 592 269	7 614 144	382 238	183 844	8 694 344	0	6 143 138	0	218 269
GR	3 970 124	45.7	54.3	13 378 794	796 344	2 234 406	2 253 125	905 838	58 988	6 794 231	0	255 281	0	80 581
KT	2 920 856	57.8	42.2	7 934 431	156 938	3 410 575	1 225 913	202 656	78 431	1 767 013	7 600	968 381	0	116 925
Sum	83 050 265	57.0	43.0	173 460 306	4 810 013	59 375 025	28 524 513	8 507 213	3 692 925	54 463 669	787 819	11 741 681	40 581	1 516 869

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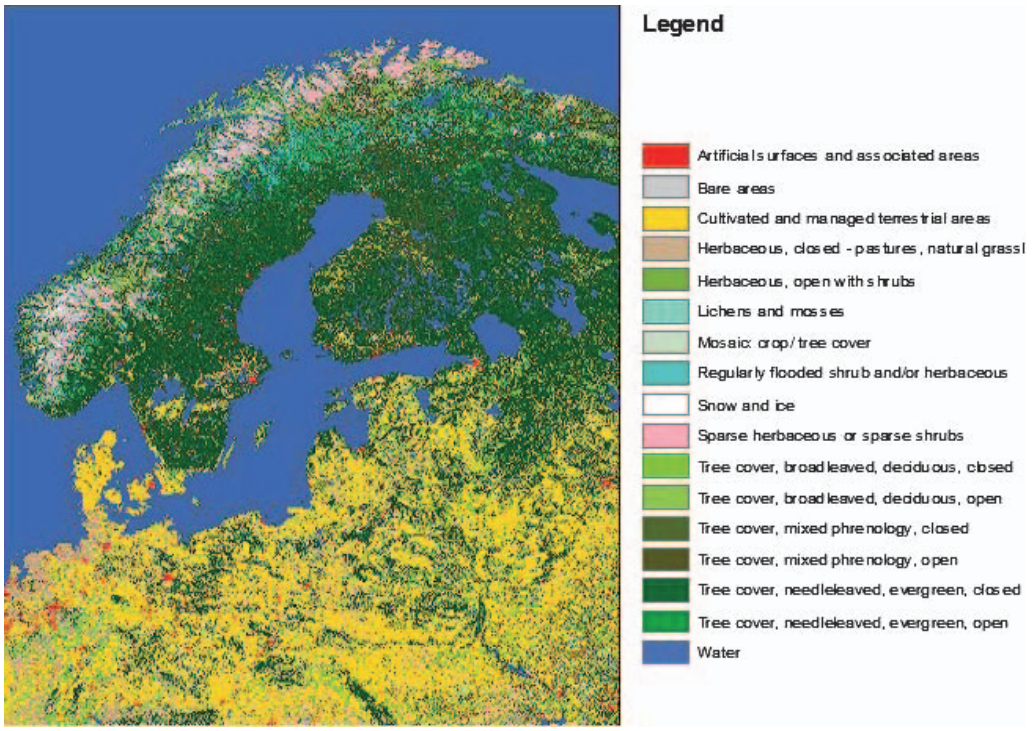

Figure 2. Land classes for the Baltic Sea catchment. For the model simulations, 10 classes were used, and all herbaceous areas were aggregated to one class; tree classes were divided only into deciduous forest, mixed forest, and coniferous forest, leaving us with the following classes: deciduous forest, coniferous forest, mixed forest, herbaceous areas, wetlands, cultivated areas, bare areas, water, snow and ice, and artificial areas.

with the hydrological cycle to estimate nutrient loads from surface and groundwater runoff, manure, point sources, and septic systems. Nitrogen and phosphorus loads in streamflow are calculated as the product of water discharge and the specified nutrient concentrations, with the addition of three types of sources, i.e., handling of manure as well as sewage in rural respectively urban areas. Sewage is calculated from the distribution of urban and rural population, the degree of connection to wastewater treatment plants (WWTPs), and the effectiveness of their waste treatment.

The streamflow consists of total surface runoff from individual land use classes in the watershed and groundwater contributions from two common groundwater compartments handling the discharge from the saturated zone. The uppermost of the two flow paths of groundwater discharge responds to precipitation relatively quickly whereas the lower path has a slow climate response, not substantially affecting the seasonal streamwater discharge pattern. The rationale for this is that during episodic events in forested hill slopes of the boreal watersheds, which dominate the annual streamwater discharge, the main groundwater flow path is a lateral flux in the upper soil horizon because of the high hydraulic conductivity as compared to deeper layers (25, 26). A large proportion of the streamwater during such flow events is generated by "old" water previously held in the unsaturated zone (27, 28), providing the opportunity for biogeochemical processes to modify the groundwater chemistry substantially as compared to the precipitation composition. The characteristic nutrient concentrations specified are independent of land use class, implying similar groundwater concentrations of N and P from arable land and forest.

Precipitation and evapotranspiration is applied to each land cover type and was estimated using the algorithms given in the original GWLF model (15). Water from each land cover type is then routed to streams as both direct surface runoff and indirectly down through subsurface layer compartments as groundwater runoff; each contributes a component of stream baseflow.

CSIM was modified from GWLFXL (17), written in Visual Basic 6.0. To facilitate modeling of the 105 watersheds simultaneously, the CSIM platform is an Access database used to store and retrieve data. It handles input data and results as well as keeping track of the modeling history (files, simulations) to facilitate model analysis and storing of the results. The model is based on a land-use partition of the watershed instead of dividing the catchments into upstream/downstream resolution. This currently excludes individual source apportionment per land cover type and in-stream retention.

DATA MATERIAL

The model requires daily precipitation and temperature data, as well as areas of land use/land cover, soil parameters, and sediment and nutrient concentrations in runoff for each catchment. In addition, validation data, including streamflow, sediment flux, and nutrient fluxes, are necessary for model testing and parameterization. Nutrient emissions are obtained from statistics on human population, livestock, and point sources as well as handling practices of sewage, manure, and fertilizer. To estimate watershed level agricultural loads, all available agricultural statistics for each riparian country in the Baltic basin were aggregated on a national basis and assumed to be proportionally distributed over the arable land of each country (in proportion to the size of cultivated land in each basin; Fig. 2).

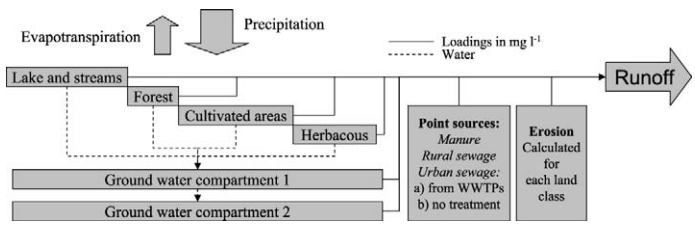

Figure 3. Model architecture for CSIM. Precipitation and evapotranspiration were applied on each of the various land covers. Water from each land cover type was routed directly to the stream flow and down to the soil-water compartment. From the soil-water compartment, water was routed to the stream flow and the groundwater compartment, and from there on to the stream. Four types of point sources were considered. Sewage nutrient load is calculated from the distribution of the urban and rural population, and the degree of connection to WWTP and the effectiveness of the treatment (primary, secondary, and tertiary).

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Table 2. Percentage of the entire population in the respective country connected to a system for collection and treatment of wastewater for years 1996–2000 (mean value). No information is available for Russia and Belarus, and the applied values in the modeling were estimates.

Country	Primary treatment	Secondary treatment	Tertiary treatment	No treatment
Belarus (BEL)	0	0	10	90
Czech republic (CZE)	0	61	0	39
Germany (GER)	2.2	8.4	78.6	10.8
Denmark (DEN)	2	5.2	81.4	11.4
Estonia (EST)	2.2	34.4	33.6	29.8
Finland (FIN)	0	0	79	21
Lithuania (LIT)	33	6	18	43
Latvia (LAT)	2.2	34.4	29	34.4
Norway (NOR)	0	5.8	85.8	8.4
Poland (POL)	5.2	30.6	13	51.2
Russia (RUS)	0	0	10	90
Sweden (SWE)	0	5.2	85.8	9

Hydrology and Nutrient Concentrations

Daily rainfall and temperature are forcing functions for the hydrology of the model. These data are provided in a $1° \times 1°$ meteorological database provided by the Swedish Meteorological and Hydrological Institute, with weather analyzed every 6 hours during the period 1980–1990 and every 3 hours during ?8 1990–2000. These data were aggregated to daily observations for each catchment, i.e., mean temperature and total precipitation per area and day. The groundwater discharge is based on the daily water balance for soil and shallow saturated zones. Cumulative snow and snow melt are estimated using a simple degree-day method (15).

Runoff and riverine nutrient concentrations for the calibration and validation of the model were retrieved from the Baltic Environmental Database (29), which is based mainly on the ongoing monitoring of the riparian Baltic States and represent monitoring sites closest to the river mouth. The riverine export to the Baltic Sea is dominated by a few rivers (Neva, Vistula, Oder, Daugava, and Nemunas). The runoff is estimated using the US Soil Conservation Service's Number Equation (30). For the small coastal watersheds, the water discharge and nutrient supply are estimated in the database from monitored neighboring catchments proportional to their areas.

Catchment Characteristics

The data used for land cover estimates (Table 1) are based on satellite images with a spatial resolution of 0.15 km $\times$ 0.15 km and various reference data sets provided by Metria Miljöanalys and by the EU Joint Research Centre, Ispra, Italy. Percentages of land cover (10 classes) were calculated using ARC VIEW 8.1 (Fig. 2).

Erosion is estimated from the USLE algorithm (31), which gives monthly erosion and sediment yields using monthly rainfall-runoff coefficients. These calculations require input ?9 data (land cover, soil type, and watershed slope) for each land cover type. A sediment delivery ratio based on watershed size and a flow-based transport capacity is applied to the calculated erosion. This gives the sediment yield schedule for each land use class area in response to event-based soil erosion.

Emission Statistics

Population data were based on national census data (EUROSTAT). The distribution between urban and rural population for each watershed was estimated from a proxy, the night light distribution, and intensity as mapped from satellite images (13). Given the distribution of population for each watershed, a more precise distribution of point sources was possible as compared to the one given by the pollution load compilation by HELCOM (10). The population distribution is rather skewed latitudinally, ranging from 850 persons in the Töre Älv watershed in the north to 23.3 million inhabitants in the Vistula drainage basin in the south. Watersheds with a high population density have most of their population in urban areas.

Urban sewage was calculated from the distribution of the population, degree of connectivity to WWTPs, and the efficiency of the treatment process (Table 2). Primary treatment was assumed to reduce the N and P loads by 19% and 15%, respectively, whereas secondary treatment reductions were assumed as 37.5% for N and 35% for P. Finally, tertiary treatment was assumed to remove 80% and 90% of N and P, respectively (values are taken from EUROSTAT). Rural sewage was calculated from the population distribution and per capita emission given by Johnes et al. (32) (Table 3). The retention of both sewage emissions and manure (see below) was assumed to be same. Information on degree of connectivity to WWTPs for Russia and Belarus were lacking, and we assumed that 10% of the population was connected to tertiary treatment. EUROSTAT values for the degree of connectivity were given for the whole population. We assumed that people in urban areas were connected first; in watersheds where the total number of people connected to sewage treatment was higher than the estimated urban population, we assumed that part of the rural population was connected to WWTPs.

National data on livestock was taken from EUROSTAT, and livestock was distributed in proportion to the cultivated areas per watershed. Between the drainage areas there is a large variation, from almost no pigs to 12 000 000 pigs and almost no cattle to 4 350 000 cattle units. However, most of the drainage areas display rather small stocks; $\approx$75% of the areas have less than 60 000 cattle units and 80 000 pigs.

The total N excretion of the various animal types (Table 3)

Table 3. Annual emissions of N and P from cattle (milk cows, other cattle), pigs (slaughter pigs and sows), and humans (kg y–1).

	Milk cows		Other cattle		Slaughter pigs		Sows		Humans	
Country	N	P	N	P	N	P	N	P	N	P
Belarus (BEL)	47.4	9.8	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Czech Republic (CZE)	63.0	11.8	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Germany (GER)	96.1	16.1	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Denmark (DEN)	74.2	13.3	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Estonia (EST)	94.3	15.9	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Finland (FIN)	84.8	14.6	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Lithuania (LIT)	63.5	11.9	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Latvia (LAT)	62.2	11.7	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Norway (NOR)	101.6	16.8	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Poland (POL)	63.0	11.8	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Russia (RUS)	47.4	9.8	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1
Sweden (SWE)	101.6	16.8	34.0	4.5	8.8	3.6	22.0	9.0	3.9	1.1

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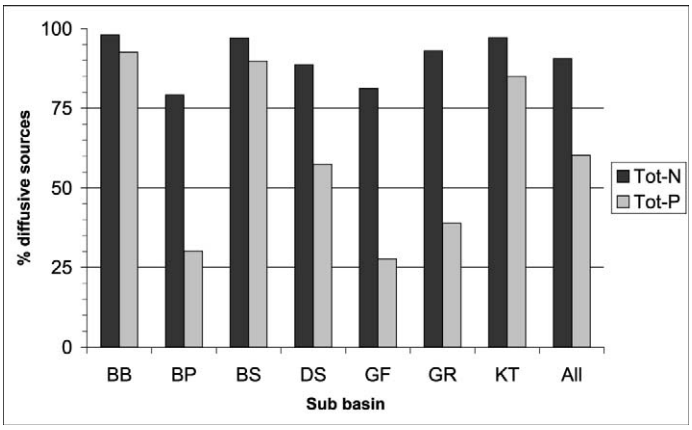

Figure 4. Diffusive sources for Tot-N and Tot-P (%) in the various subcatchments of the Baltic Sea as simulated by CSIM (same abbreviations used for subbasins as in Table 4).

was estimated based on the production level (33). The emission of N and P from each animal to streamwater is estimated on a monthly basis, and we assumed that 83% of N and 97% of P from manure emissions (and rural sewage emissions) is retained in the soils (32). Thus, the model treats manure emissions via tile drainage conceptually as a net input after soil retention and, hence, loads the water in a way similar to point sources from sewage. Nitrogen and P emissions from manure were calculated from national statistics on the number of cattle (dairy cows and other cows) and pigs (slaughter pigs and sows). Emission numbers for individual livestock categories were taken from FOASTAT and reports from the Swedish Agriculture University. Because the primary emission per head is some 10–30 times higher for a livestock unit than for a human unit (Table 3), the distribution of livestock is a significant factor in nutrient load.

ANNUAL AND SEASONAL SIMULATION MODES

As discussed above, the model estimates the annual water balance for all 105 major Baltic watersheds as well as their nutrient loads from natural and anthropogenic sources. Diffuse emissions were parameterized as increased groundwater nutrient concentrations and nutrient inputs from manure and emissions from the rural population not connected to sewage treatment that enter the streamwater after significant soil retention (83% for Tot-N and 97% for Tot-P). Point sources were addressed using information on the proportion of the watershed population connected to sewage treatment and information on the degree of treatment, i.e., primary, secondary, or tertiary treatment. For this analysis, we have essentially ignored seasonal variations of the water and nutrient fluxes to the Baltic Sea because this level of temporal resolution exceeds the current demands of the overall project, which requires lumped long-term average and interannual estimates (34). We may thus characterize this model set-up as an "annual mode" aimed at describing the interannual and longer term variability of net nutrient inputs into the various basins of the Baltic Sea.

Simulations of the seasonal nutrient and water fluxes are possible for selected watersheds for which more detailed information is available on significant nutrient sources, such as the timing of fertilizer and manure applications, which are not evenly distributed through the year as assumed in the annual mode. Moreover, a reasonable parameterization of nutrient uptake by phytoplankton and subsequent sedimentation, redissolution from the sediments, and resuspension in reservoirs, lakes, and river banks might also be included to describe seasonal fluxes well. Currently, including these details is not feasible for all 105 watersheds because of the lack of sufficient environmental data. However, for some eutrophied watersheds with few lakes and impoundments, i.e., watersheds where retention/remobilization processes leading to substantial seasonal time shifts in nutrient concentrations and transport are generally low, it is possible to simulate seasonal nutrient fluxes with the available information. This is also possible for pristine systems such as the subarctic rivers.

IN-STREAM RETENTION

Since in-stream biological uptake is not parameterized dynamically in the model, the in-stream retention was adjusted during model calibration by comparing the net emissions into the streamwaters (i.e., diffuse inputs after soil retention and point sources after treatment) and the observed nutrient loads at the river mouth during the calibration period. The mean in-stream retention for all simulated rivers was about 15% for Tot-N and 19% for Tot-P, i.e., the estimated loads to rivers were about 15–20% higher on average than the measured loads at the river mouth, which is somewhat lower as compared to estimates made by various model approaches complied in the latest PLC [~30% for both Tot-N and Tot-P; (10)] and by estimates in US river systems (35).

RESULTS

Source Distribution

The diffuse sources contributed most to the overall simulated Tot-N river loads. In the boreal watersheds of the Bothnian Bay, Bothnian Sea, and Kattegat the contributions of diffuse sources represent more than 95% of the load (Fig. 4). The contribution of diffuse sources in the heavily populated and cultivated southern watersheds is somewhat lower and ranged between 75% and 85% of the total. In contrast, for Tot-P, the differences in source distributions in watersheds along a latitudinal gradient were much more evident. Whereas in the boreal watersheds of the Bothnian Sea, Bothnian Bay, and Kattegat the diffuse sources were the most significant with >85% of the total load, the simulated contribution of diffuse sources to the overall Tot-P river load in the cultivated watersheds was between only 30% and 60%, i.e., the model results indicate that between 40% and 70% of the Tot-P loads in the cultivated watersheds originated from point sources.

The CSIM estimates of the distribution of sources of Tot-N are similar to those of PLC 4 (10), whereas the CSIM estimates of the contribution of Tot-P from point sources are much higher than those of PLC 4. PLC 4 estimated the contribution of diffuse and point sources to the riverine Tot-N load as 743 601 t y^{-1} and 66 261 t y^{-1}, respectively, whereas CSIM simulations indicated these sources as 769 000 t y^{-1} and 79 600 t y^{-1}, respectively. PLC 4 estimated the contribution of diffuse and point sources to the riverine Tot-P load as 33 004 t y^{-1} and 6 977 t y^{-1}, respectively, whereas CSIM simulations indicated these sources s 29 900 t y^{-1} and 19 700 t y^{-1}, respectively. Note, that the comparison between PLC 4 data and CSIM could only be made for the calibration period, simply because of the fact that a comparable data set has been compiled by HELCOM only for 2000; earlier compilations did not differentiate between point and diffuse emissions in sufficient detail.

Lumped Simulations as Drivers of the Marine Biogeochemical Model within NEST

The calibration of the model was performed on data from 1996 to 2000, as this period had the best data available for comparison with the model (Table 4). Somewhat unconventionally, the validation period was earlier, 1990 to 1994, and we

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Table 4. Simulated and measured river loads for the calibration and validation period, calibration period 1996–2000, and validation period 1990–1994. River loads have been lumped to each of the Baltic Sea basins: Bothnian Bay (BB), Baltic Proper (BP), Bothnian Sea (BS), Gulf of Finland (GF), Gulf of Riga (GR), Danish Sounds (DS), Kattegat (KT) and the total Baltic Sea. Loads are given in tonnes N and P y–1. Measured values are from the Baltic Environmental Database, http://data.ecology.su.se/models/bed.htm.

Tot-N						Tot-P					
Calibration period, 1996–2000			Validation period, 1990–1994			Calibration period, 1996–2000			Validation period, 1990–1994		
Basin	Measured tonne	Simulated tonne	Basin	Measured tonne	Simulated tonne	Basin	Measured tonne	Simulated tonne	Basin	Measured tonne	Simulated tonne
BB	50 850	50 072	BB	46 297	54 836	BB	2712	2708	BB	2868	2975
BP	392 981	359 899	BP	303 527	337 699	BP	23 301	24 387	BP	17 954	23 914
BS	53 658	51 741	BS	49 383	54 713	BS	2397	2410	BS	2376	2550
DS	37 935	37 334	DS	40 364	39 323	DS	1676	1717	DS	1765	1706
GF	97 954	91 566	GF	103 220	94 674	GF	5538	5623	GF	5491	5711
GR	69 967	66 350	GR	73 762	69 626	GR	1976	2132	GR	1918	2173
KT	70 041	64 745	KT	59 120	59 911	KT	1832	1718	KT	1590	1633
Sum	773 387	721 708	Sum	675 673	710 782	Sum	39 434	40 698	Sum	33 961	40 662

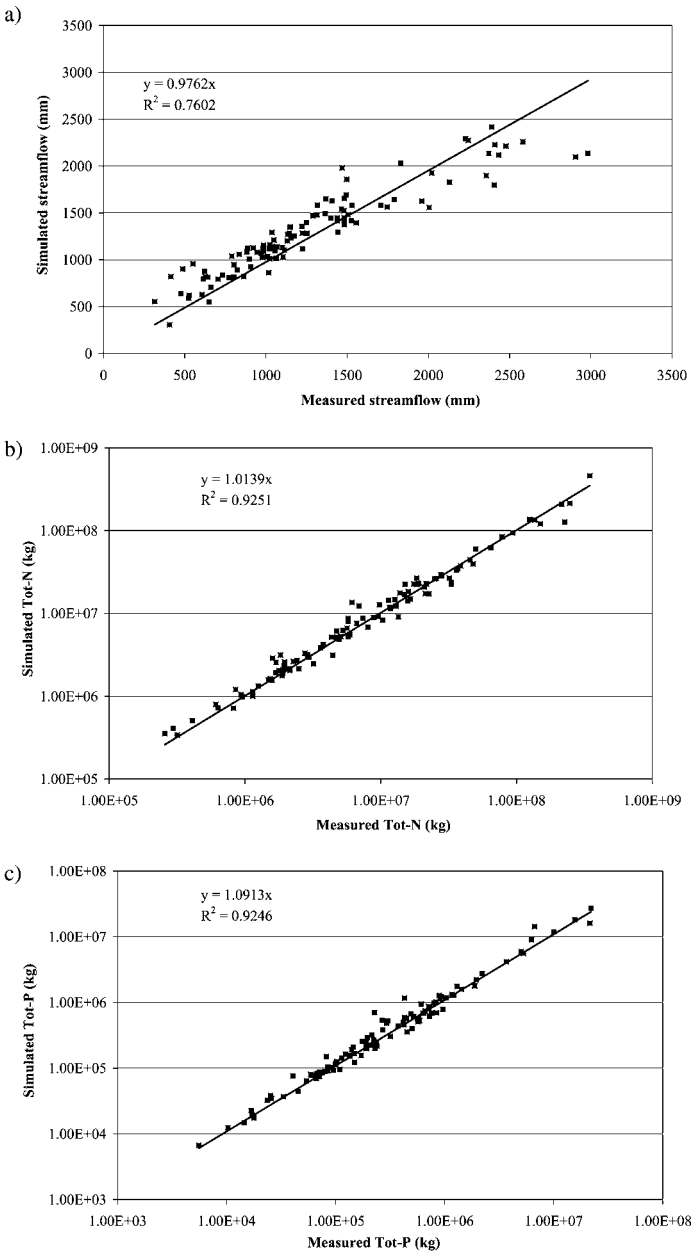

Fig. 5. A multiannual fit of simulated and measured data for the validation period (1990–1994): (a) streamflow, (b) Tot-N, and (c) Tot-P.

assumed that emission data did not change within this rather short period of time between calibration and validation period. These assumptions appear justified, because changes in sewage treatment (as expressed as the proportion of population connected to modern sewage treatment) between the calibration time period and the validation time period that occurred mainly in countries with a transitional economy were only a few percent (EUROSTAT) and major changes in agricultural practices occurred just before (1989/1990 after the political changes). However, the cumulative deviation from monitored water and nutrient fluxes (relative bias) over this 4-year validation period (April 1990 to March 1994) was relatively small $\Sigma(\text{Simulated} - \text{Measured})/\Sigma\text{Measured} \times 100$ (%); +8.2% for runoff, −2.4% for DIN, +5.1% for Tot-N, +13% for DIP, and +19% for Tot-P. The same figures for the calibration period are: runoff, +1.6%; DIN, −3.5%; Tot-N, −6.5%; DIP, +2.6%; and Tot-P, +3.2%. For regression plots of N and P for the validation period, see Figure 5a–c. ?13

Interannual Simulations

The interannual variability of water and nutrient fluxes were reasonably well described for the 105 watersheds (Fig. 6a–c), where, across all watersheds and years of the validation period, 91%, 92%, and 95% of the overall variability in streamflow, Tot-N, and Tot-P, respectively, could be described by the model. Overall, the annual mode of CSIM described the annual streamflow and Tot-N loads fairly well, i.e., these fluxes were overestimated with 4% and 5%, respectively; Tot-P loads were overestimated by 25%. However, interannual correlation coefficients of individual watersheds for the validation period still show temporal discrepancies in some cases. On average, the interannual correlation coefficient per watershed was 0.69 for streamflow, 0.65 for Tot-N, and 0.63 for Tot-P, and for the major watersheds, i.e., the Neva, Vistula, Oder, Daugava, and Nemunas, the interannual correlation coefficients ranged between 0.13 and 0.75 for streamflow, 0.13–0.93 for Tot-N, and 0.48–0.98 for Tot-P. The major reason for the unsatisfying performance for the Oder River (interannual correlation coefficient for streamflow and Tot-N = 0.13) can be explained by the extreme values used both for the calibration and validation period, i.e., the Oder flood 1998 and the extreme dry year in 1991.

Seasonal Simulations

For the simulations of the seasonal variation of streamflow, Tot-N and Tot-P in the unperturbed Råne River and the polluted Oder River from 1996 to 1998 was chosen as the calibration period and 1998–2000 as the validation period, since

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for this period all monthly data were available, whereas for the period 1990–1994 some monthly observations were missing. ?14 The Råne River drains a small catchment area (4000 km^2) in the forested boreal region of northern Sweden, and simulation of streamflow, Tot-N, and Tot-P are shown in Figure 7a–c. The flow patterns were well described, and the spring peak flow in May–June was correctly indicated by the model ($R^2 = 0.72$). The seasonal correlation coefficients of Tot-N ($R^2 = 0.23$) and Tot-P ($R^2 = 0.12$) were lower compared to the streamflow because of missing biological processes not accounted for in the model; however, the order of magnitude of the seasonal variation were well described by the simulations. The Oder River is one of the major eutrophied catchments (117 000 km^2) draining a large part of Poland, and simulation of streamflow, Tot-N, and Tot-P are shown in Figure 7d–f. The flow patterns were again well described, and the spring peak flow in April–May was correctly indicated by the model ($R^2 = 0.44$). The seasonal correlation coefficients of Tot-N ($R^2 = 0.39$) and Tot-P ($R^2 = 0.17$) were lower as compared to the streamflow, again because of the missing biological processes not accounted for in the model.

DISCUSSION

There is a consensus that the environment of the Baltic Sea has deteriorated significantly during the last century and there is an urgent need to improve the conditions. The question is, "How to do it?" Experiences from small-scale remedial actions and pilot experiments dominate our knowledge, but the large catchment scales involved necessitate new approaches. To manage remedial actions involving 83 million people in a dozen countries and a regional system with time scales of many decades, analysis and modeling tools are necessary that can address the full scope of the problem, if initially at only a basic level. This is the purpose of the present model development and applications on the Baltic Sea drainage basin. As a major first result of these model attempts, we may summarize that the current estimates compiled by HELCOM underestimate the Tot-P load from point sources, simply because of the fact that estimates of point source emissions are based on official data from WWTPs and do not take into account the part of the population not connected to wastewater treatment.

Catchment Models

Many drainage basin models have been developed for northern Europe, e.g. INCA (36), HBV-N (37), POLFLOW (38), ?15 MONERIS (39), and RIVERSTRAHLER (40). They vary in their spatial and temporal resolution and differ in their degree of process orientation. None of them has been applied to such a large-scale problem as the entire Baltic Sea catchment. Instead, the HBV-N and the MONERIS approaches have been used together with estimates based on simple semiempirical equations (Latvia, Lithuania, Poland) on nutrient loads in the latest PLC (10) making it difficult to judge whether all emissions were treated in a similar way. In other words, the compilation represents an assemblage of assumptions on what diffuse and point sources essentially are and how much of the point and diffuse emission are retained along the way to the Baltic Sea. It should be emphasized here that the individual national estimates as such are based on sound scientific reasoning; however, the overall conclusions drawn for the entire Baltic Sea catchment might be questioned because of the inconsistency of variable description such as diffuse *vs.* point sources between the various models. Because of the scope of the task, it was essential to keep the model as simple as possible, while retaining the ability to estimate nutrient fluxes from specific watersheds. This will be crucial, as the model will be used interactively in the associated decision support system NEST (9), which requires an efficient model to operate in an interactive mode.

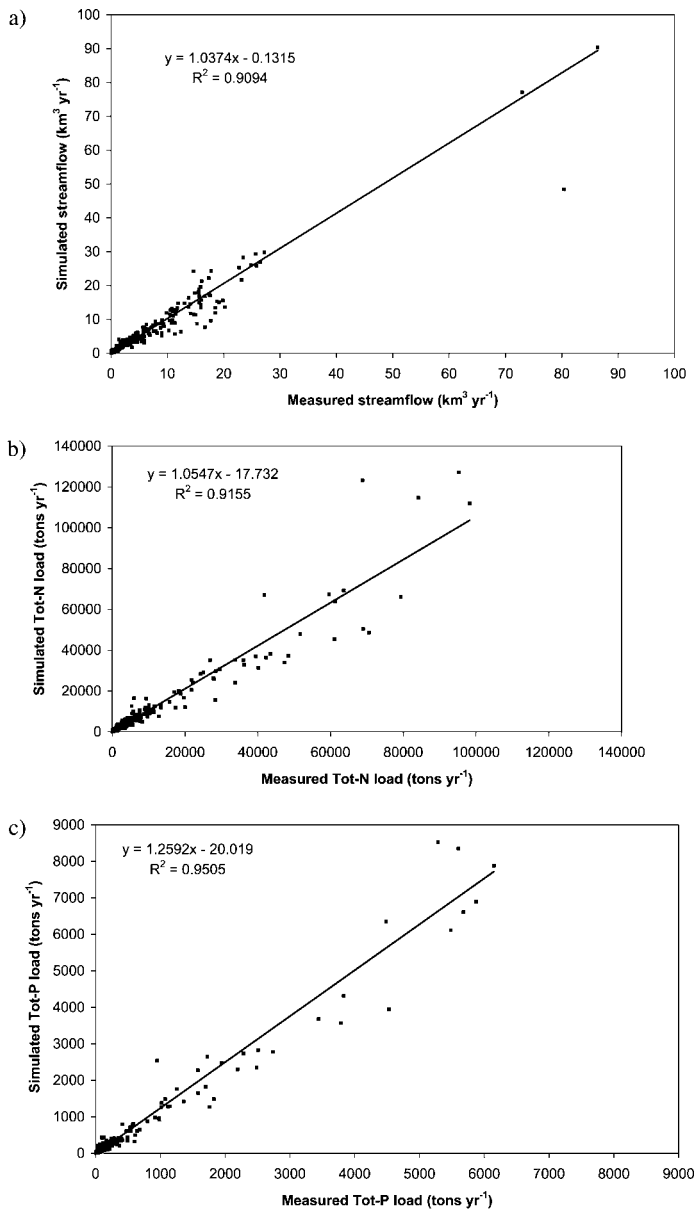

Fig. 6. Interannual fit of simulated and measured data for the validation period (1990–1994): (a) streamflow, (b) Tot-N, and (c) Tot-P.

The main aim of the CSIM large-scale model approach was to simulate the total nutrient transport to the various subbasins of the Baltic Sea and to compare riverine nutrient transport between the Baltic Sea subbasins that differ substantially because of the agriculturally dominated, heavily populated landscape in the southern catchment as compared to the boreal less populated northern catchment. Thus, a model describing the nutrient transport along such a gradient of natural settings should first of all handle the huge differences in the scales of nutrient transports reasonably. Hot spots of riverine emissions, such as from the Vistula, Oder, and Daugava, can be described easily, and the comparison between these rivers and the relatively unperturbed rivers in the northern catchments show decisionmakers where amendment strategies make sense, and, second, what percentage reduction of riverine nutrient loads is possible [see Wulff et al. (9) in this issue]. Obviously, a first step toward a catchment-wide nutrient transport model was to simulate lumped multiannual fluxes, because a time resolution in 4-year steps was required by the marine biogeochemical model within NEST (34). Consequently, the calibration was

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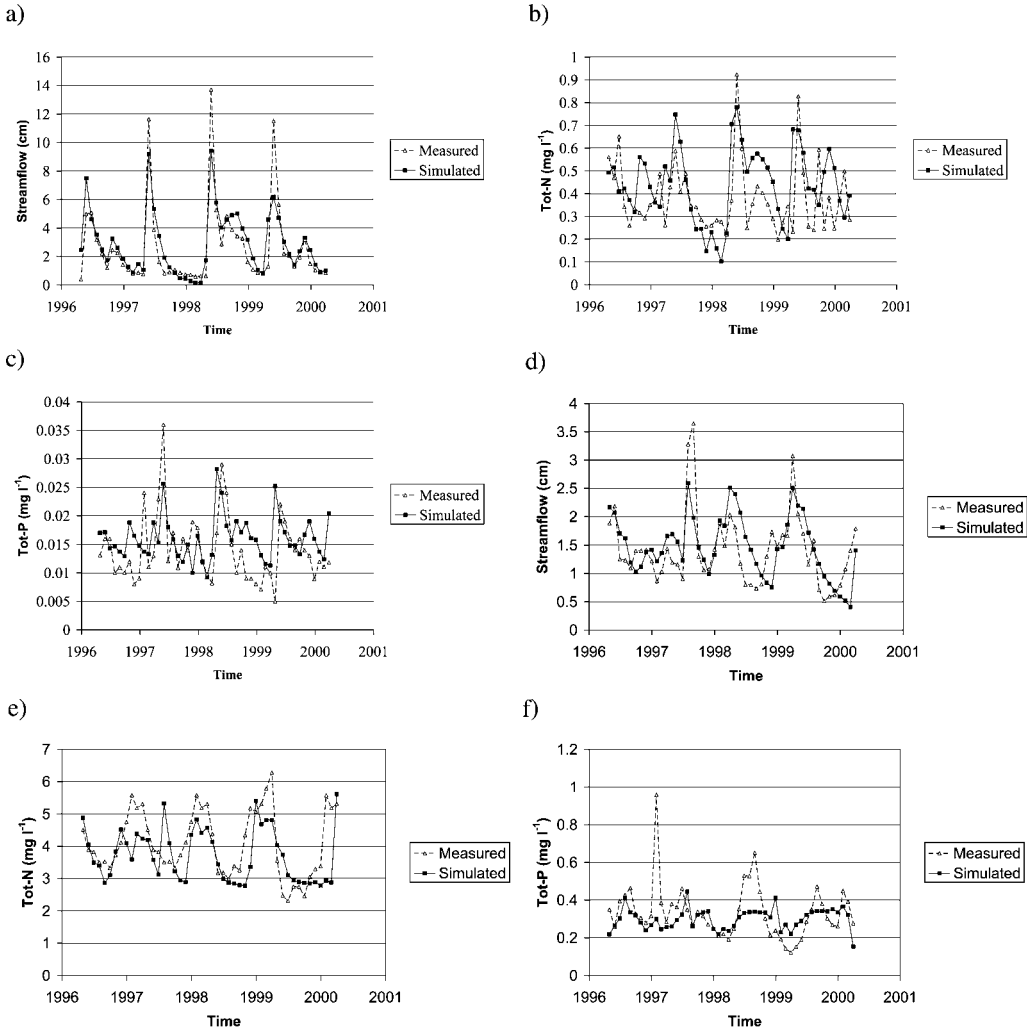

Fig. 7. Seasonal fit of simulated and measured data for two rivers, Råne (unperturbed) (a–c) and Oder (eutrophied) (d–f) during 1996–2000. The period 1996–1998 was used for calibration and 1998–2000 for validation.

performed in a way to match the multiannual averaged fluxes. This explains as well the unsatisfactory performance of the model for some rivers, such as the Oder, showing low interannual correlation coefficients between measured and simulated annual streamflow and nutrient loads, whereas the lumped multiannual simulations for this specific river were much better, i.e., the differences between simulated and measured data were on the order of 10% (Fig. 5). To achieve better interannual correlation coefficients between simulated and measured data, all rivers must be better calibrated for seasonal fluxes, which is though possible as shown in Figure 7 for the rivers Oder and Råne, which represent two end members of the Baltic Sea rivers with respect to anthropogenic emissions and natural settings. However, for most of the rivers the interannual variability could be simulated reasonably well.

Data and Evaluation Consistency as Crucial for Management Options

Because short-term measures, i.e., nutrient reductions to be achieved within <5 years, should be evaluated first, we focused on a robust description of the point sources that are also easier to handle in a simple one-box approach. Diffuse loads, such as nutrient leakages from agricultural and forested areas, are more difficult to simulate. However, the relative contribution from point and diffuse sources will be reasonably correct when the point sources are reasonably described. The new method to distribute populations developed by Hannerz and Destouni (13) was used in our CSIM model. This completely new population data set in combination with the EUROSTAT statistics on connectivity and treatment efficiency of WWTPs is a large step forward to gain a better description of these point sources. As a starting point, we focused on a detailed description of human emissions from urban and rural sources and from livestock emissions, because both of these sources reach the streamwater and eventually the Baltic Sea relatively quickly through direct emissions from WWTPs and tile drainage of human waste and manure. The first interesting result of this rather simple but consistent calculation of source distribution in the Baltic Sea catchment stresses the potential for measures to reduce P loads. Whereas PLC 4 (10) estimated the contribution of total Tot-P emissions from point sources to about 7 000 t y^{-1}, the estimates from CSIM were higher by almost a factor of three, i.e., 20 000 t y^{-1}. In total, primary emissions of Tot-P (point and diffuse) were assumed to be about 50 000 t y^{-1} as compared to 40 000 t y^{-1} as assumed by PLC 4. One might argue that CSIM overestimated Tot-P loads during the validation period by 25% (Fig. 6c) or exactly 10 000 t y^{-1}, i.e., the overestimated Tot-P loads could theoretically be explained by the higher point source estimates in the CSIM calculation. However, as noted earlier, the comparison between source distributions could only be made for the calibration period, and half of the overestimated Tot-P load during the validation period could be explained by the overestimated runoff that was almost 10% higher compared to the measured data. Moreover, the in-stream Tot-P retention (which is discussed in detail below) assumed by CSIM was about 10% lower as compared to other studies (10, 35), giving room for higher primary emissions when assumed to be 30%.

Besides these modeling peculiarities, it appears obvious that a total population of some 83 million people living in the Baltic Sea catchment will generate more than 7000 t Tot-P y^{-1} as

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officially declared by PLC 4 as emissions from point sources. In Poland and Russia, but also in the Baltic States, for example, more than half of the population lives in cities, whereas the percentage of people connected to tertiary sewage treatment was below 30% during the 1990s (Table 2). From a simple calculation, assuming that half of the population and that, on average, 25% of that population had modern treatment during the late 1990s in Poland and Russia (referring to the area that drains into the Baltic Sea), there are 2.4 million inhabitants in Russia plus about 10 million inhabitants in Poland that emitted their wastes with no treatment, amounting to about 14 000 t Tot-P emissions y^{-1}. PLC 4 simply did not account for these emissions in some countries (the Baltic States and Russia) or treated them as diffuse sources in the case of Poland; in those countries where more detailed models with source apportionment have been run, as in the case of Germany (using the MONERIS model) and Sweden (using the HBV-N model), these estimates will be more accurate. However, these inconsistencies in data evaluation lead to a major conclusion that the contribution of point sources to the riverine Tot-P loads to the Baltic was 19% only. CSIM calculations point to a much larger contribution (40%; Fig. 4) of point sources for the riverine Tot-P loads, implying that river loads could be reduced by some several thousand tonnes by modern sewage treatment [for a more detailed analysis of the potential Tot-P load reductions, see Wulff et al. (9) is this issue].

Future Prospects

Any model with our goals requires a large set of data to be operative, but the data available often only describe relevant statistics at the national level; this requires a methodology to properly apportion some data over individual catchments and land use classes. In the present work rather robust proxies were developed for some variables, such as population density linked to night light distribution, etc. Whereas such approaches are debatable, the task of further refining the data set, which describes a total catchment area of almost 2 million km^2 and 83 million people, will necessarily await future research.

The detailed dynamics of in-stream retention of Tot-N and Tot-P were not simulated in the current CSIM version. Rather, in-stream retention coefficients were estimated during the calibration of the model by comparing the measured nutrient loads at the river mouth with the estimated emission from the hydrological pathways, human emissions after treatment in WWTPs, and manure emissions after soil retention. The three major emissions sources were, in general, some 15–20% higher than the observed river load, which is in fairly good agreement with estimates on riverine retention in US rivers (35) and Baltic rivers (10). However, an independent description of the riverine retention, i.e., a constant factor or an empirical function relating riverine retention to water transit time (35) or hydraulic load (41), will give the opportunity to test whether the source apportionment between diffuse and point sources is reasonable. Information on a calculated riverine retention together with the information on point sources, which are relatively easy to estimate, will enable only an adjustment of surface and groundwater concentrations during the calibration of the model, and these concentrations still have to be reasonable and comparable to literature values. However, the overall simulated contribution of diffuse source to the overall nutrient load, which were about 90% for Tot-N and 60% for Tot-P, respectively, is, with the exception of the 20% lower estimates for diffuse Tot-P loads as discussed above, in very good agreement with the overall picture given by PLC 4.

A major challenge in watershed modeling is a sound description of the pathways of diffuse nutrient sources. Only one major diffuse source, i.e., emissions of manure via tile drainage, is considered dynamically in the current model version. Fertilizer use and atmospheric deposition were not considered explicitly, but included through the choice of type concentration. We chose to first describe nutrient emissions by livestock as a function of livestock density and productivity, because these differ significantly between the riparian countries and will change drastically, especially in those countries with a transitional economy. The next step is to simulate the effects of agricultural practices such as fertilizer use or the use of grain types as winter crops. However, nutrient leakage via the root zone can be calculated using the algorithms of soilNDB(42).

Seasonal simulation of streamflow and nutrient concentrations were reasonably performed with the current CSIM set-up for the relative simple river systems, i.e., an unperturbed system as in the case of the Råne River and an eutrophied but essentially undammed system with a few lakes only as in the case of the Oder River. The ability to simulate seasonal variations in water fluxes and nutrient concentrations are central when it comes to estimating the effects of manure handling as requested by the EU nitrate directive, i.e., to analyze the optimal time window when manure can be put on the fields. A temperature-dependent retention coefficient of manure might be an obvious way to simulate, for example, a transport of manure co-occurring with the snow melt when manure is spread during winter time. Moreover, to estimate nutrient loading effects on near-shore marine ecosystems with short water residence times, i.e., in areas most visible for people living along the Baltic coast, a seasonal resolution is required. To estimate time lags between nutrient emissions and peak concentrations because of biological production, especially in the eutrophied and heavily dammed river systems such as the Daugavam a biological submodel as formulated in the RIVERSTRAHLER (43) approach for example can be applied.

CONCLUSIONS

There are many possible remediation strategies to reduce the riverine nutrient loads to the Baltic, each requiring a level of investment. To make such an action politically feasible, it is necessary to evaluate the probable outcome of such investments and even to be able to suggest an optimal choice of watersheds for implementing the remedial actions so as to achieve the desired goals in a reasonable socio-economic way. We believe that the CSIM model applied to evaluate scenarios across the entire Baltic drainage basin is a step forward in this work. We also believe that using a model like CSIM has the secondary benefit of promoting the use of uniform and consistent data across the subbasins of the Baltic, which will increase both the quality of environmental data in the region and our understanding of the processes they represent.

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Carl-Magnus Mörth is an associate professor in environmental geochemistry at the Department of Geology and Geochemistry, Stockholm University. He is working on biogeochemical processes in terrestrial systems, especially on large-scale transport of weathering products, inorganic carbon, and nutrients. His address: Department of Geology and Geochemistry, Stockholm University, SE-10691 Stockholm, Sweden.
magnus.morth@geo.su.se

Christoph Humborg is an associate professor in biogeochemistry. He is working on coastal zone biogeochemistry issues and especially on the effects of river exports of biogenic elements on coastal seas. His address: Department of Applied Environmental Science, Stockholm University, SE-10691 Stockholm, Sweden.
christoph.humborg@itm.su.se

Hanna Eriksson is a PhD student working on source apportionment of nutrients and large-scale nutrient losses from catchments in the Baltic Sea drainage basin. Her address: Department of Applied Environmental Science, Stockholm University, SE-10691 Stockholm, Sweden.
hanna.eriksson@itm.su.se

Åsa Danielsson is an associate professor at the Department of Water and Environmental Studies, Linköping University. She is an environmental statistician working on biogeochemical modeling, with special focus on nutrients and metals in aquatic systems. Her address: Department of Water and Environmental Studies, Linköping University, SE-581 83 Linköping, Sweden.
asada@tema.liu.se

Miguel Rodriguez Medina is working as a research engineer at the Department of Systems Ecology, Stockholm University. He is database manager for the Baltic Environmental Database in the frame of the MARE project. His address: Department of Systems Ecology, Stockholm University, SE-10691 Stockholm, Sweden.
miguel@system.ecology.su.se

Stefan Löfgren is an associate professor working at the Department of Environmental Assessment, SLU, Uppsala. He is working on experimental studies in small catchments but also on assessment of long-term monitoring data of forested catchments and its implications for nutrients, carbon, and metals. His address: Department of Environmental Assessment, P.O. Box 7050, SE-75007 Uppsala, Sweden.
stefan.lofgren@ma.slu.se

Dennis Swaney is a mathematical modeler in the Department of Ecology and Evolutionary Biology at Cornell University. His current focus is on biogeochemical processes and dynamics of watersheds and estuaries. His address: Department of Ecology and Evolutionary Biology, E309b Corson Hall, Cornell University, Ithaca, NY 14853 USA.
dps1@cornell.edu

Lars Rahm is a professor in oceanography at the Department of Water and Environmental Studies at Linköping University. His current focus is on interaction between physical and biogeochemical processes in the aquatic environment. His address: Department of Water and Environmental Studies, Linköping University, SE-58183 Linköping, Sweden.
larra@tema.liu.se

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