Regional overview of nutrient load in Europe – challenges when using a large-scale model approach, E-HYPE

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Abstract The homogenous set-up of the HYPE model for Europe (E-HYPE) gives an overview of riverine nutrient transport from land to sea and surface water concentrations across the continent. Results indicate that loads and concentrations of total nitrogen are highest in the western part of Europe, draining to the North Atlantic Ocean. High phosphorous concentrations were more dispersed and coincided principally with major urban centres. Spatially-consistent moderate total phosphorous loads were also seen across the agricultural regions of Western Europe and north of the Black Sea. By analysing where modelled data and observations agree or disagree it may be possible to identify major knowledge gaps in the model. Spatial variation in results can help contribute to understanding of hydrological and nutrient processes in the wide variety of climates, physiological and anthropogenic conditions represented across the European continent. The predictability is limited by the quality of the continental-scale input data and the optimisation of model parameters to multiple sites.

Key words water; nitrogen; phosphorous; load; concentration; spatial pattern; pan-Europe; open data; model; predictability; knowledge gaps

INTRODUCTION

Nutrients cause eutrophication problems in surface water, and a deeper understanding of sources and pathways may help water managers to improve water quality status more efficiently. Currently, there are rather few monitoring sites across Europe with long time-series of river discharge and nutrient concentrations. In addition, quality and quantity measurement sites are seldom co-located. Many waterbodies and river reaches thus remain practically ungauged and models are deemed necessary to interpolate and extrapolate between observations in both time and space to get a full overview and understanding of the problems. Many catchment-scale models including nutrients have been developed and tested for specific European rivers during recent decades (e.g. Krysanova, 1998; Loos *et al*., 2009), and also on the national scale (Strömqvist *et al*., 2012) or for sensitive regions, like the Baltic basin (e.g. Mörth *et al*., 2007; Arheimer *et al*., 2012). Models are often used for: (i) environmental assessment, (ii) identification of critical areas contributing to the eutrophication problems, (iii) source apportionment for a specific water body to identify main polluters, and for (iv) evaluation of effects of nutrient reduction measures or (v) climate change impact. For such purposes it is important to have a harmonised multi-catchment approach to avoid bias from mixing different databases and model assumptions. It is also important to investigate the agreement between model and observations, to judge the overall reliability of the results. There have been very few attempts to simulate water quality at large multi-catchment scales. Attempts at the continental or global scale include an empirical nutrient leakage model for Europe (Bouraoui *et al*., 2011), a gridded global nitrogen load model (He *et al*., 2011) and a gridded global phosphorous-load model for loads to surface water and seas (Harrison *et al*., 2010). None of these models, however, include an integrated hydrological and nutrient turnover model for both nitrogen and phosphorous to simulate the transport of nutrients from their sources to local waterbodies and the sea.

This study gives a pan-European overview of riverine nutrient transport from land to sea and surface water concentrations across the continent. By analysing where modelled data and observations agree or diverge it may be possible to identify major knowledge gaps in the model processes. Spatial variation in results can help contribute to understanding of hydrological and nutrient processes in the wide variety of climates, physiological and anthropogenic conditions represented across the European continent. The predictability of a large-scale model is limited by the quality of the continental-scale input, forcing data and the fact that parameters are constrained simultaneously to multiple observation sites. Many challenges still remain when using open data sources and harmonised model parameter values for such a large region. Nevertheless, given the level of predictability, the model can provide regional overviews, source apportionment and can highlight hotspots for which more detailed modelling may be required. The homogenous set-up of the E-HYPE model for the European continent can be further used for simulating the impact of changes in climate, environment or society, e.g. as a result of European directives and their implementation. The model also provides input to coastal and oceanographic models around the European coast.

DATA AND METHOD

E-HYPE is a pan-European application of the Hydrological Predictions for the Environment (HYPE) model simulating hydrological and nutrient variables on a daily time-step for 35 447 sub-basins at a median resolution of 215 km^2 across the European continent. The model is set-up using readily available continental or global databases (Table 1), which have recently become available due to open data policies in many countries. The data was tailored to correspond to the division into model sub-basins. The model is forced daily using the ERA-INTERIM re-analysis at 0.75 degrees (about 6800 km^2, Dee *et al*., 2011). Monthly precipitation means were further corrected to match the climatological precipitation means from the GPCC database at 0.5 degrees (about 3000 km^2, Rudolf *et al*., 2005).

The HYPE model is a dynamic, semi-distributed and process-based model based on well-known hydrological and nutrient transport concepts (Lindström *et al*., 2010). Major nutrient

Table 1 Open data used in the set-up of E-HYPE2.1. Full references are given in the Appendix.

Variables	Data source – number refers to reference in Appendix
Areal extent	8.8 million km^2
Median sub-basin resolution	214 km^2
No. sub-basins	35 447
Topography/routing	Hydrosheds [2] and Hydro 1K (for latitude > 60 deg) [1]
Forcing data	ERA-INTERIM (corrected to GPCC for precipitation)
Landcover	CORINE [3] and Globcover 2000 (for areas not covered by CORINE) [4]
Urban Area	Euroland Soil Sealing 2009 [5]
Lake area and spatial distribution	GLWD (Global Lake and Wetland database) [6]
Lake and reservoir information	GLWD (Global Lake and Wetland database) [6] ERMOBST [7] FLAKE-Global [8] International Water Power & Dam Construction yearbook 2011 [9] ILEC World Lake database[10] LEGOS [11] Swedish Water archive (SMHI) [12]
Irrigated area	European Irrigation Map [13] Gmia [14]
Soil types	European Soils Database [15] and DSMW (Digital Soil Map of the World) [16]
Water discharge measurements	GRDC [17], EWA [18], BHDC [19], in total ~1000 stations after cleaning (289 > 5000 km^2; 839 with daily time-series).
Evaporation measurements	NTSG, Fluxnet, Cosmo [20]
Point sources (Urban/Rural)	HYDE population database[21], EEA (treatment level) [22]
Point sources (Industrial)	EPRTR[23]
Agriculture data/statistics	CAPRI [24]
Atmospheric deposition	MATCH model [25]
Nutrient concentration measurements	GEMS water [26], national data sets with time series data (70 stations after cleaning). EEA for annual and seasonal means (1700 stations after cleaning) [27]

sources and sinks are included. In the model, the landscape is divided into classes according to soil type, vegetation and altitude. The soil representation is stratified and can be divided into up to three layers. The flow paths include surface runoff, macropore flow, tile drainage and groundwater outflow from the individual soil layers. Rivers and lakes are described separately with routines for turnover, rating, sinks and sources. Precipitation and temperature force the dynamics of water and nutrient turn-over at each time-step.

The HYPE model contains a number of parameters for which representative values should be given. These parameters represent processes for discharge and nutrients in the model. Initial parameter estimates were taken from the calibrated parameter set of the S-HYPE model application for Sweden (Strömqvist *et al.*, 2012). These parameters were then further tuned by optimising land-use and soil-type specific parameters in groups of representative gauged basins, which are groups of lake-free smaller gauged catchments with dominant areas of the relevant land-use or soil-type in the upstream catchment area. A global potential evapotranspiration parameter was optimised for best fit of simulated evapotranspiration against flux-tower data measurements across the continent. Where gauges were co-located with lakes, individual rating curves were calibrated for 121 lakes and individual regulation schemes fitted to describe the functioning of 46 reservoirs. Other lakes and reservoirs discharge in the model according to general rating curves. Modelled water discharge was evaluated for 181 observation sites of independent catchments and downstream sites, which represent more heterogeneous land cover and soil-type conditions than the representative gauged basins. These sites were well distributed over the model domain, with the exception of eastern Europe north of the Black Sea and in Turkey, where 132 of these gauged sites were regulated by dams and reservoirs.

Some tuning of parameters for water quality was made to match observations in 16 small catchments with good quality monitoring data from the EuroHarp project database (Silgram *et al.*, 2009a,b). The other observation data from the EEA's WISE database (Table 1) were only available on seasonal or annual time-scales and these data was used for an independent evaluation. In this paper, evaluation was made for catchments ≥250 km^2, using annual average concentrations based on observation series of ≥3 years, and removing sites to avoid large portions of overlapping catchment area, which left 276 observation sites for total nitrogen and 309 sites for total phosphorous. These sites were well distributed over central and northern Europe, but sparse in Spain, France and Italy. There were no sites across most of eastern Europe. The observations were compared to modelled flow-averaged concentrations for the period 1990–2008, compiled into annual means. To analyse the correlation between concentration and sources of pollution, the samples were categorised according to catchment characteristics (Table 2).

Table 2 Splitting of EEA water quality monitoring sites into categories based on catchment characteristics.

Variable	Categorisation			
Sample size	S	MS	ML	L
Area (km^2)	<1000	≥1000 and <10000	≥10000 and <50 000	≥50 000
No obs. sites	*86*	*152*	*40*	*13*
Agriculture (%)	<0.01	≥0.01 and <0.25	≥0.25 and <0.5	≥0.5
No obs. sites	*39*	*89*	*91*	*72*
Lake area (%)	<0.001	≥0.001 and <0.01	≥0.01 and <0.05	≥0.05
No obs. sites	*90*	*79*	*80*	*42*
Population (km^{-2})	<10	≥10 and <100	≥100 and <150	≥150
No obs. sites	*78*	*137*	*33*	*43*

The HYPE model is based on the assumption that sources contributing to riverine nutrient load are mainly agriculture, fertile soils (mineralization), plant residuals, atmospheric deposition, nitrification, and emissions from rural households, industry and wastewater treatment plants. Sinks are mainly plant up-take and harvest, adsorption in soils and sediments, phytoplankton growth in freshwater, denitrification and burial. To check if some dominant sources/sinks could explain spatial variability in the observed concentrations and model results, Pearson correlations were calculated.

RESULTS AND DISCUSSION

Pan-European nutrient loads

Spatial analysis of nutrient fluxes simulated by using E-HYPEv2.1 indicate that loads and concentrations of total nitrogen are highest in the western part of Europe (Fig. 1), e.g. Denmark, Germany, the Netherlands, Belgium, northwest France and the southern UK, all draining to the North Atlantic Ocean. High phosphorous concentrations were more dispersed and coincided principally with major urban centres, e.g. south of England and the Netherlands. Spatially consistent moderate total phosphorous loads were also seen across the agricultural regions of Western Europe and north of the Black Sea. Lowest nutrient concentrations are found in the forested and sparsely populated northern part of Europe.

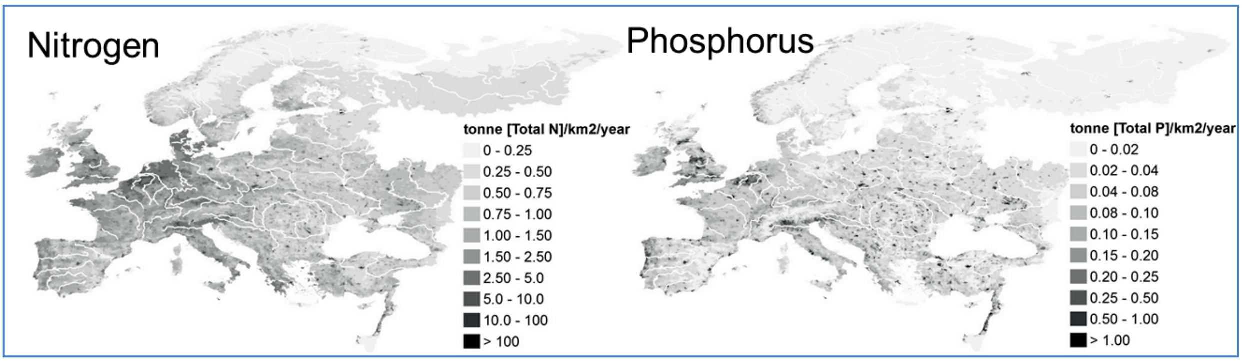

Fig. 1 Total nitrogen (left) and total phosphorous (right) load on surface water (white lines) across continental Europe, based on calculations in sub-basins with a median size of 214 km^2.

The largest nitrogen load from land to marine basins (Fig. 2) was found for agricultural sources, except for the Arctic Sea where forest leakage dominates and the Celtic Sea where point sources dominate. For phosphorous, the results show a more diverse picture, with large contributions from point sources in all catchments, and a south–north gradient in contributions from agricultural sources, which are probably connected to erosion processes during flood events in Mediterranean climates.

The source apportionment of nutrient load from land to sea was made for net transport by rivers (after transformation in rivers and lakes) and coastal areas with direct drainage. Figure 2 clearly shows that agriculture is also the main contributor of nitrogen after removal processes in rivers and lakes. It should be noted that arable land is often more fertile than forested soils, which means that it is prone to leaching also in a natural state. For calculating cost efficiency among

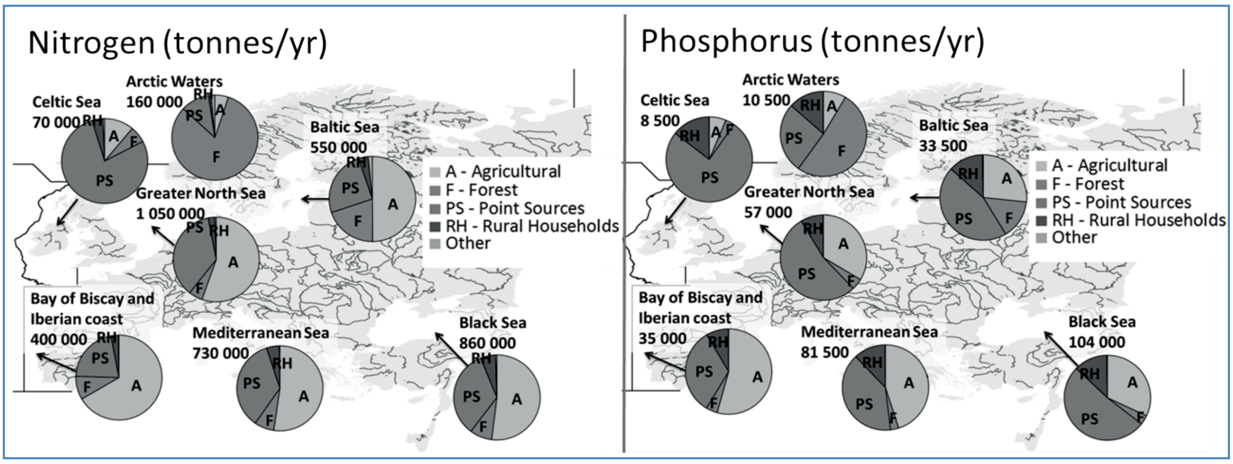

Fig. 2 Total load and source apportionment of nitrogen and phosphorous flow from land to the seas surrounding Europe.

measures it is important to separate the anthropogenic contribution from the natural background load (i.e. Arheimer *et al*., 2005), which has not been done here. Nevertheless, it is interesting to note the spatial variability among polluters of European seas.

Model evaluation

When examining the impact of a few catchment characteristics on riverine nutrient concentrations, similar correlations were found between observations and model results (Table 3). This strengthens the assumptions used in the model concept. Among the studied variables, agricultural land was most strongly correlated to high nutrient levels, especially nitrogen. However, the model gave higher correlation to agricultural land for both nitrogen and phosphorous than could be seen for the observations. This can be attributed to the process simplifications taken in the model, which result in a reduction of variability compared to the observed time-series. Lake percentages were negatively correlated to concentration levels. This indicates that the impacts of retention and removal processes on surface water are of higher magnitude than the atmospheric deposition onto lakes; however, the correlations are not very strong, indicating regional variation of lake effects on riverine nutrients. Average upstream population density showed a positive correlation with nutrient levels at the studied sites. This confirms the relevance of point-source pollution on river systems, which is also illustrated in the loads to marine basins across the whole of Europe. Specific runoff was negatively correlated to nutrient concentrations, which might be an effect of dilution caused by higher water discharge in some rivers.

Table 3 Pearson correlation coefficients for annual average concentration of total P and total N, averaged over modelled period 1991 to 2010.

Riverine nutrient concentration	Catchment area	% Agri-culture	% Lake area	Population density	Specific runoff
$totN_{annual}$, observed	–0.002	0.67	–0.39	0.72	–0.25
$totN_{annual}$, simulated	–0.04	0.77	–0.39	0.69	–0.31
$totP_{annual}$, observed	0.04	0.51	–0.31	0.49	–0.23
$totP_{annual}$, simulated	0.005	0.59	–0.38	0.61	–0.25

The E-HYPE model managed to capture some of the spatial variablity in water and nutrient discharge across Europe for the 276 discharge and 309 nutrient observation sites available (Fig. 3). The median of the mean absolute errors per station, normalized by the observed mean over the evaluation period was 34% for daily water discharge, 36% for yearly nitrogen concentrations and 53% for yearly phosphorous concentrations. The model shows best performance for water discharge (most sites < 10% volume error), followed by nitrogen, and the spread in results is largest for phosphorous. This is in line with previous finding from Sweden (Strömqvist, 2012) and the Baltic Sea region (Arheimer *et al*., 2012); however, it should be noted that the modelled concentrations were flow normalised, which was not the case for the observed data. Furthermore, the observed values of annual means are often based on rather few measurements for some of the observation sites. Water discharge was most difficult to model for rivers with low flow (Fig. 3(a)).

Analysis of the spatial variation of model performance shows that the largest volume error of water discharge occurred in the northern as well as in the southern parts of Europe (Fig. 4(b)). In the north, water discharge is generally underestimated, which may be a result of too low precipitation in the ERA-interim data. In southern Europe the water discharge is overestimated, which is likely due to underestimated evapotranspiration rates in the E-HYPE model at southern latitudes. There is an urgent need for more research on improved ET algorithms and validations against several sources of measurements for more accurate estimates.

Looking at the model's capacity to capture water dynamics, the NSE performance, while generally positive, tends to be poorer for southern Europe, as well as for mountainous areas. This may again be caused by evapotranspiration estimates, but is probably also an effect of the dynamics of the precipitation data. The Mediterranean weather patterns are difficult to capture in

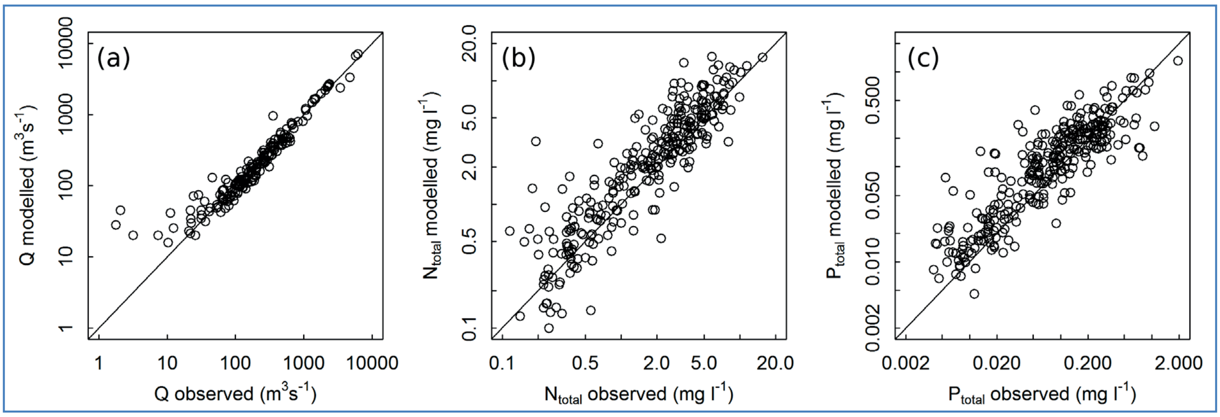

Fig. 3 Observed *vs* modelled annual averages at evaluation sites across Europe for: (a) discharge, (b) total nitrogen, and (c) total phosphorous.

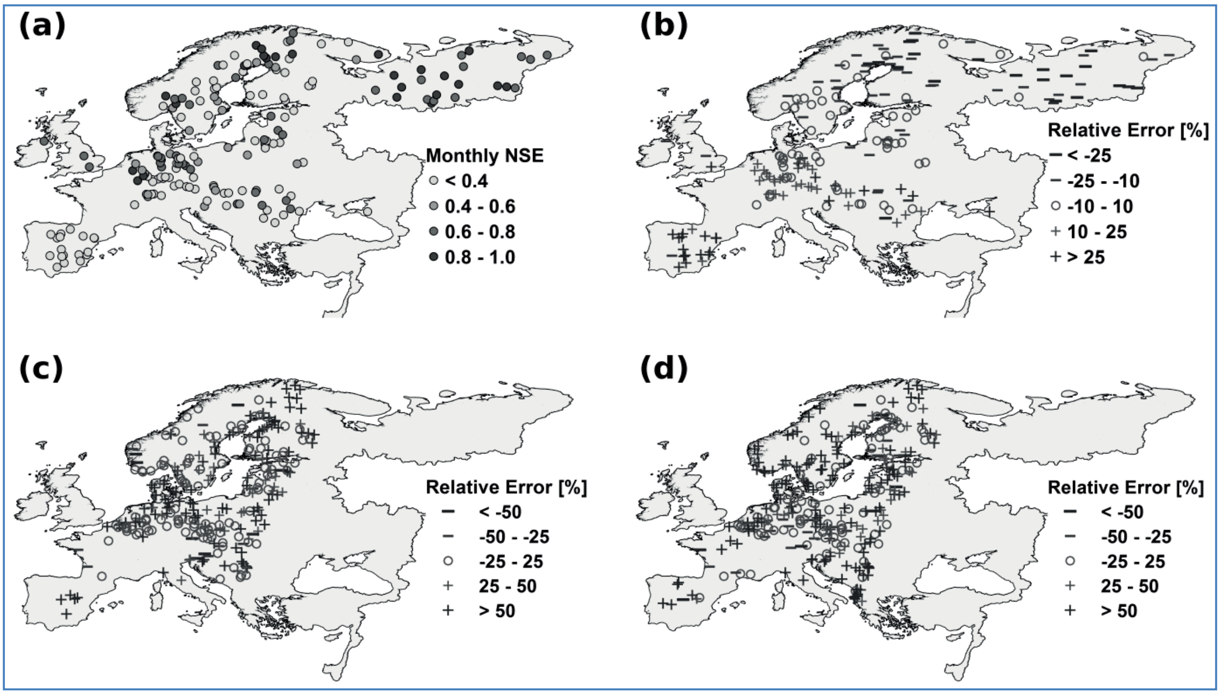

Fig. 4 Model performance for water discharge: (a) NSE and (b) relative volume error; and for annual nutrient concentration levels of (c) nitrogen and (d) phosphorous (both: relative volume error).

meteorological forecast models, which is the basis for the precipitation forcing used. Precipitation in mountains is also difficult to estimate and the grid size used is rather large for catchments in the mountains, where water divides between rivers may be found within short distances. The evaluation of nutrients levels shows no clear spatial trend across Europe (Fig. 4(c) and (d)).

Model performance under different physiographical conditions across Europe was also examined by dividing the observation sites into categories based on catchment characteristics. The results show that the dynamics of water discharge were much easier to reproduce under natural conditions than regulated ones (Fig. 5(a)). This was expected as general regulation routines seldom reflect short-term fill and spill practices, although E-HYPE separates between irrigation reservoirs and hydropower dams. Monthly NSEs were higher than performance based on daily values, which could also be expected as errors tend to even out when they are aggregated in time. The effect of aggregation in space was examined by separating the results into different sizes of river basins, and for NSE an increase in performance with size could be seen. However, the relative volume

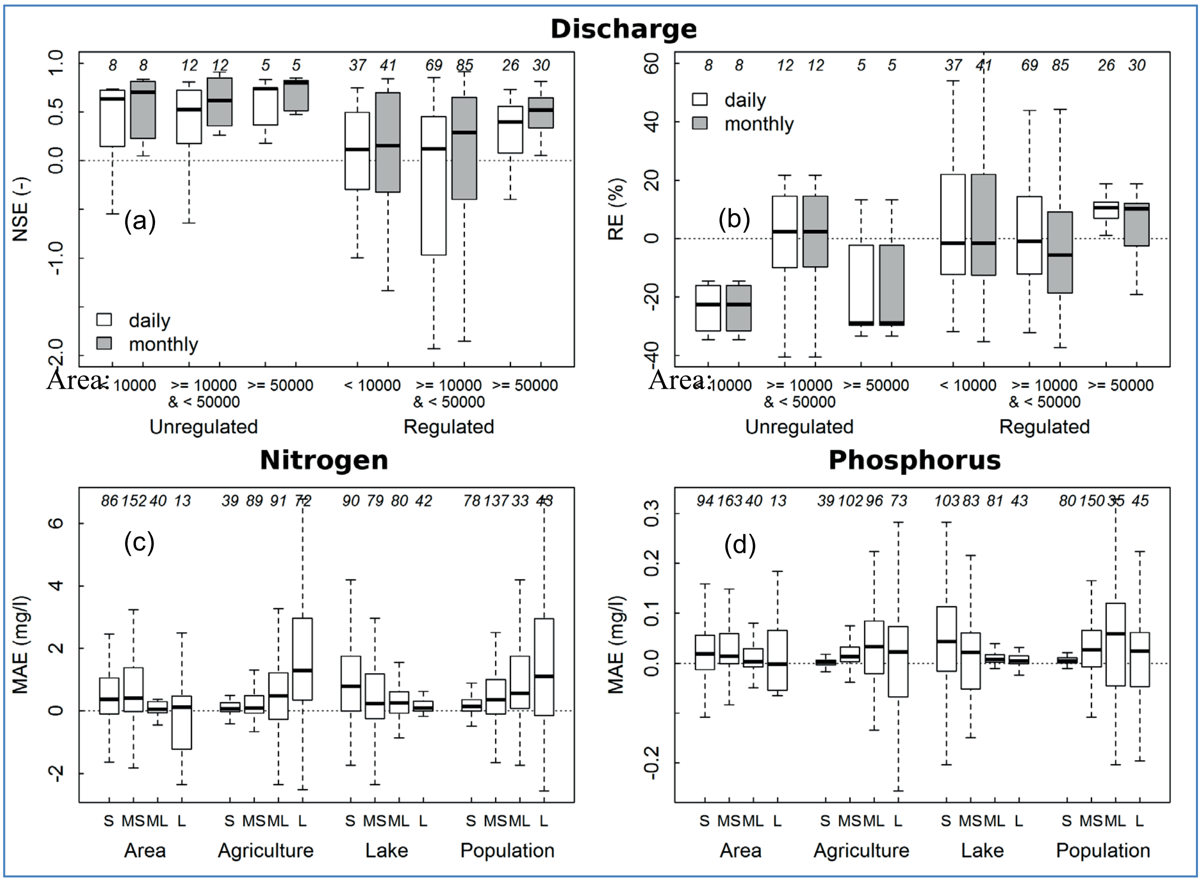

Fig. 5 Model performance in the different categories of monitoring sites representing different upstream conditions, according to Table 2. Water discharge was evaluated both for daily (157 sites) and monthly observations (181 sites), nitrogen and phosphorous for annual observations (260 and 309 sites, respectively). Boxes represent 50% of the values, bold lines medians, and whiskers extend to 1.5 times of the interquartile range. Observation-site counts for each category are given in italics above each plot.

error showed little correspondence with the catchment area, and fewer volume errors were found in regulated rivers (Fig. 5(b)). As seen in Fig. 3, there was a correlation of low discharge with poor model performance. The correlation of error with low discharge indicates the poorer ability of the model to reproduce discharge in dry regions, most likely where extractions affect the water balance.

For nutrients, mean absolute errors were normally within 2 mg L^{-1} for nitrogen and 0.2 for phosphorous (Fig. 5(c) and (d)). The relationship between model performance and catchment characteristics was not very distinct. However, both nitrogen and phosphorous showed a decrease in model performance as population density or arable land percentage increased, and an increase with higher lake percentage. Anthropogenic impacts on nutrient levels are thus difficult to describe properly in the model. Probably more detailed information is necessary for treatment levels in wastewater plants and emissions from rural households. This information was received from very coarse general information at the national level. Also, agricultural practices are based on the large NUTs regions (Britz *et al.*, 2007), which vary significantly in size depending on European country, and may therefore not be relevant on the local scale. For arable land, soil information including soil drainage should probably also be more detailed for better estimates on turnover processes causing nutrient leakage.

In summary, the results indicate that there is some predictability in this attempt to make pan-European simulations of water discharge and nutrients. There will, however, always be some limits in the predictability that can be achieved with a model at this scale based on open source input data. The input data covers many political entities and large areas. It therefore becomes impractical, for example, to manually fit regulation curves to every reservoir, define every irrigation canal or the location and emissions from every single urban wastewater treatment plant.

Model performance was poorest in regions where anthropogenic interference with the natural water and nutrient cycle is greatest. It is difficult to simulate the effects of human decision-making on short-term regulation, yearly crop choices, whether or not to irrigate those crops, and fertilization and management of the crops. Nevertheless, by exploiting data from open sources, approximate representations of these features averaged over time can be made.

Further research could be directed to improving model inputs related to anthropogenic influences as open access to relevant data increases, for example, as a result of the INSPIRE directive (Infrastructure for Spatial Information in the European Community). Dynamic nutrient forcing, i.e. changing land use and management with time, could improve the model hindcast performance for nutrients, and could improve the ability to simulate the effects of future land-use change and remedial measures for reducing nutrient loading. There is also a large potential for improvement in the discharge simulations by reducing bias in the precipitation data, which in turn will positively affect the nutrient simulations. The quality of the simulated pan-European riverine nutrient concentrations and loads is constrained by the quality of the water fluxes, both in terms of available input data and model performance, and the results shown here clearly illustrate the continuing need to improve the underlying hydrological model.

CONCLUSIONS

- The regional overview of modelled pan-European nutrient loads and concentrations show that:
  – total nitrogen loads to watercourses are highest in the western part of Europe, e.g. Denmark, Germany, the Netherlands, Belgium, northwest France and the southern UK, all draining to the North Atlantic Ocean;
  – high phosphorous concentrations were more dispersed and coincided principally with the major urban centres, e.g. south of England and the Netherlands. Spatially consistent moderate total phosphorous loads were also seen across the agricultural regions of Western Europe and north of the Black Sea. Lowest nutrient concentrations are found in the forested and sparsely populated northern part of Europe.
- Source apportionment for contribution to the seas around Europe shows that:
  – the largest nitrogen load from land to marine environment originates from agricultural sources, except for the Arctic sea where forest leakage dominates and the Celtic Sea where point sources dominate;
  – results for phosphorous show a more diverse picture, with large contributions from point sources and a south–north gradient in contributions from agricultural sources.
- The pan-European model (E-HYPE) could reproduce the variability in concentrations occurring as a result of land cover, population, lake effect and catchment size.
- The E-HYPE model shows best performance for water discharge (most sites <10% volume error), followed by nitrogen (median = 36% of absolute mean error) and the spread in results is largest for phosphorous (median = 53% of absolute mean error).
- Challenges and scope for future research come from the representation of anthropogenic impacts on the hydrological and nutrient cycles. Another significant source of improvement is the accuracy of currently available European-scale daily precipitation and temperature data sets.

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APPENDIX

Open data sources used for the homogenous catchment model set-up across the European continent, E-HYPE2.1 (see Table 1).

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10. (http://wldb.ilec.or.jp/LakeDB2/) (ILEC= International Lake Environment Committee Foundation).
11. LEGOS (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales) http://www.legos.obs-mip.fr/en/.
12. Swedish water archive (SVAR) http://svarwebb.smhi.se/.
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15. JRC: http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB/index.htm European Soils Database.
16. http://www.fao.org/geonetwork/srv/en/main.home, http://www.fao.org/nr/land/soils/digital-soil-map-of-the-world/en/.
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18. BHDC: Baltex Hydrological Database. http://www.smhi.se/sgn0102/bhdc/.

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