Joint European Research Infrastructure network for Coastal Observatories

Demonstration of the feasibility of joint trans-regional product production - Transports and E-HYPE
D2.4

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1. Document description

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2. Executive Summary

This report summarises the development and setup of an operational hydrological forecast tool for delivering high-resolution real-time and forecast fluxes of water and nutrients to European Seas. Furthermore we demonstrate a possible approach to a pan-European transport product. More specifically this comprises estimates of sea water transports between different basins in the Baltic and Skagerrak Sea. The hydrological data is intended as an improvement to the discharge climatologies and constant nutrient concentrations traditionally used by oceanographers as input to physical and biogeochemical ocean models. The transport calculations are useful for customers interested in movement of water masses e.g. oceanographers, environmental organisations or fisheries.

E-HYPE

The pan-European hydrological model E-HYPE was developed and set up to provide continental-scale river discharge and riverine nutrient flux inputs to oceanographic models. E-HYPE is a conceptual hydrological model which builds on hydrological response units, and produces simulations of discharge and nutrient variables at daily time steps for sub-catchments with a median size of 215 km^2 across the European continent and includes a routing scheme for simulating daily fluxes from coastal basins to European seas. E-HYPE was used to simulate a hindcast of discharge and nutrients across Europe, and is run operationally by SMHI to produce daily real-time simulations and forecasts of up to 10 days. The model's performance in terms of hindcast discharge and riverine nutrient level simulations is validated against observation data, and a preliminary validation of discharge forecasts is made.

E-HYPE discharge hindcasts were evaluated for long-term means, inter-annual, seasonal, and daily variability, as well as reproduction of extreme events. Observed data was compiled from GRDC, EWA, and BHDC databases, using 181 stations in total. The results show that the model is able to reproduce the inter-annual and seasonal variation of discharge in most locations, however there are some biases in simulated discharge for some distinct regions. Namely, discharge volumes are systematically underestimated in Northern Europe due to systematic biases in the forcing data, leaving large scope for improvement with new, improved data sets. The E-HYPE model was further utilized to simulate riverine concentrations of nitrogen (N) and phosphorus (P). The simulations were evaluated for inter-annual and seasonal dynamics against observation data from several databases. Water quality validation attempts are particularly challenging because measured data are typically scarce and measured with much lower frequencies than e.g. discharge. Moreover, transnational databases often report aggregated data in form of longer-term averages, which leads to uncertainty in the resulting time series. Continental scale models, as shown here with E-HYPE, therefore have the potential to fill a large knowledge gap for decision-makers in that they have the potential to provide model estimates of nutrient transport at scales where measured data cannot be provided. The validation of annual averages of N and P showed a wide performance spread using Pearson correlation as performance measure. No clear spatial bias was detected. Promisingly, the majority of 310 evaluated sites showed positive correlations. A more detailed seasonal evaluation of select sites revealed varying shortcomings of the modelled nutrient concentrations, e.g. time lags or systematic biases throughout the seasons, possibly caused by erroneous model assumptions in E-HYPE's crop growth regimes or pollution source loads.

A preliminary validation of E-HYPE discharge forecasts using real-time forcing data from SMHI (March 2012 to March 2013, with 11 forecast time series from day 0 to day 10 per site) indicates a mixed performance in daily discharge dynamics. In particular, river regulation (e.g. hydropower dams) and water abstraction for irrigation affect model performance, as seen with the hindcast forcing data. However, the preliminary data indicate only small performance deterioration with forecast days from initialization (day 0 to day 10). However, these results are considered preliminary because of the short length of the available forecast time series and the biases identified in the hindcast analysis, and require further evaluation in the future.

Demonstration of a pan-European transport product: SMHI – HIROMB Sea water transports

A system for estimating sea water transport between different regions are made available online 2013-04-18, here http://www.smhi.se/hfa_coord/BOOS/Transports.html

The www page referred to above is not guaranteed to be 100% operational (uptime 24/7) and may be shut down at the end of this project. Examples of the results are also available in this report.

The transport of sea water has, for example, implications for the exchange of oxygen in the Baltic Sea. In the event of a large inflow of oxygen rich water, the situation in the Baltic may improve for a period.

3. Introduction

E-HYPE

Daily discharge and nutrient fluxes from rivers are necessary inputs to oceanographic models. Nearly all countries have networks of daily discharge observation stations which to some extent are used as forcing to oceanographic models. In Europe, international databases, such as NOOS (NOOS 2013), GRDC (GRDC 2009b) and EWA (GRDC 2009a) make some of this data available; however availability of observation data to determine river discharges to the sea is insufficient both temporally and spatially. Public availability of these observations from national and regional authorities varies from country to country and real-time availability of observations online is even more seldom (Hannah et al. 2011).

International availability of water quality (e.g. nutrient) observations from river mouths is even poorer and a network of real-time observations which could be used operationally simply doesn't exist due to the lag times for processing water samples. Given the limited availability of discharge observation data and the desire to use forecasts of hydrological land fluxes in oceanographic models, simulated discharge and nutrient concentrations may be useful as input data to oceanographic models.

There have been very few attempts to simulate water quality at continental or global scale. For pan-European assessments of nutrient loads, Bouraoui et al (2011) set up a model to assess Nitrogen loads on surface waters for medium and large catchments across Europe. This model used a regression equation to calculate the leakage of nutrients from agriculture. He et al. 2011 simulated global Nitrogen concentrations and loads in rivers using a at 0.5 degree grid scale including routing to river mouths; runoff generation was simulated using a land surface model. The simulated inorganic Nitrogen (IN) concentrations compared well to observed for 61 major global river basins. Harrison et al. (2010) simulated global soluble Phosphorous loads to surface water and seas with similar results.

In this study, a pan-European model, E-HYPE aims to bridge the gaps in observation data by simulating discharge and nutrients at high enough resolution to include all major rivers, but also the small coastal subbasins between them which can be significant for coastal agriculture emissions and near coast point sources with little retention. The E-HYPE model includes a hydrological catchment model based on hydrological response units (HRUs) for which hydrological processes in the soil are calculated. Unlike the previously mentioned large-scale models, the E-HYPE model is process based and simulates both concentrations and loads in leachate, in local water bodies and to the sea. The model has been used to simulate a hindcast of discharge and nutrient fluxes to European Seas and has been put operationally into production of daily real-time data and forecasts of up to 10 days. This report outlines the data and methods used to set up the model and evaluates the model's ability to reproduce observed discharge and nutrients both over Europe and to European Seas, as well as a preliminary evaluation of the model's forecast ability.

European sea water transport products

Sea water transport calculations are made available for the Skagerrak and the Baltic Sea, at the BOOS webpages, and the North West shelf - North Sea area, at the NOOS webpages. To add to these products, to enable comparisons and to demonstrate the feasibility, a similar system is built here. Examples of existing presentations are shown in Figure 1 and Figure 2. The method and modelling tool chosen in this study will be further introduced in chapter 5.1.

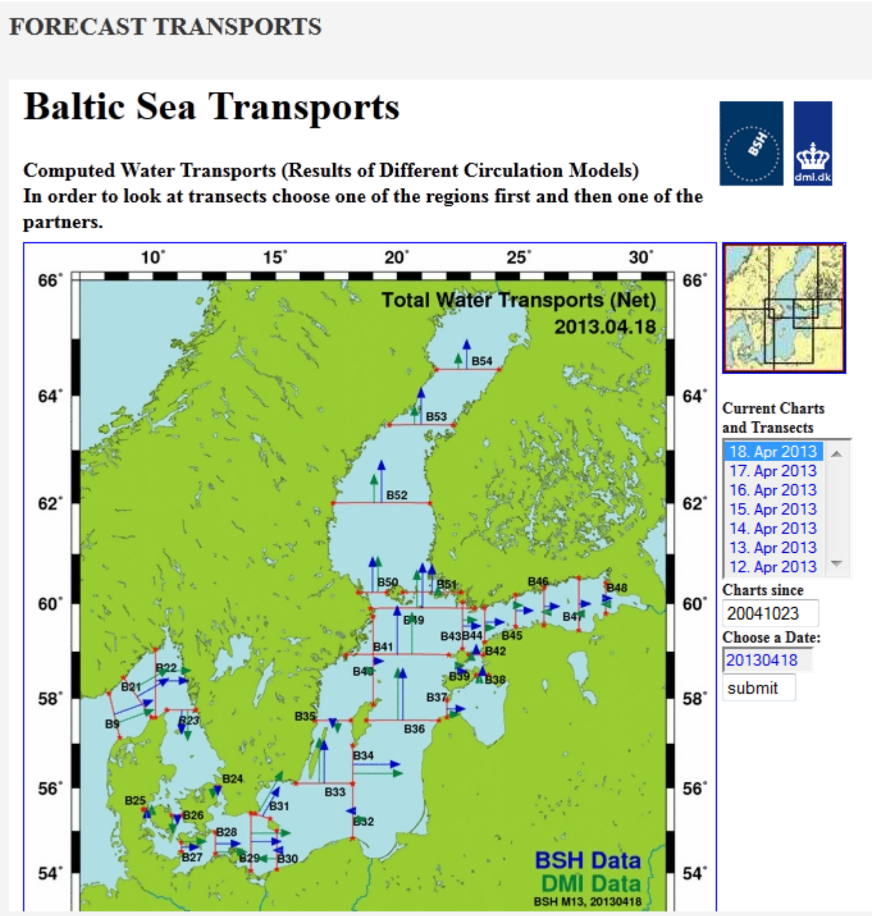
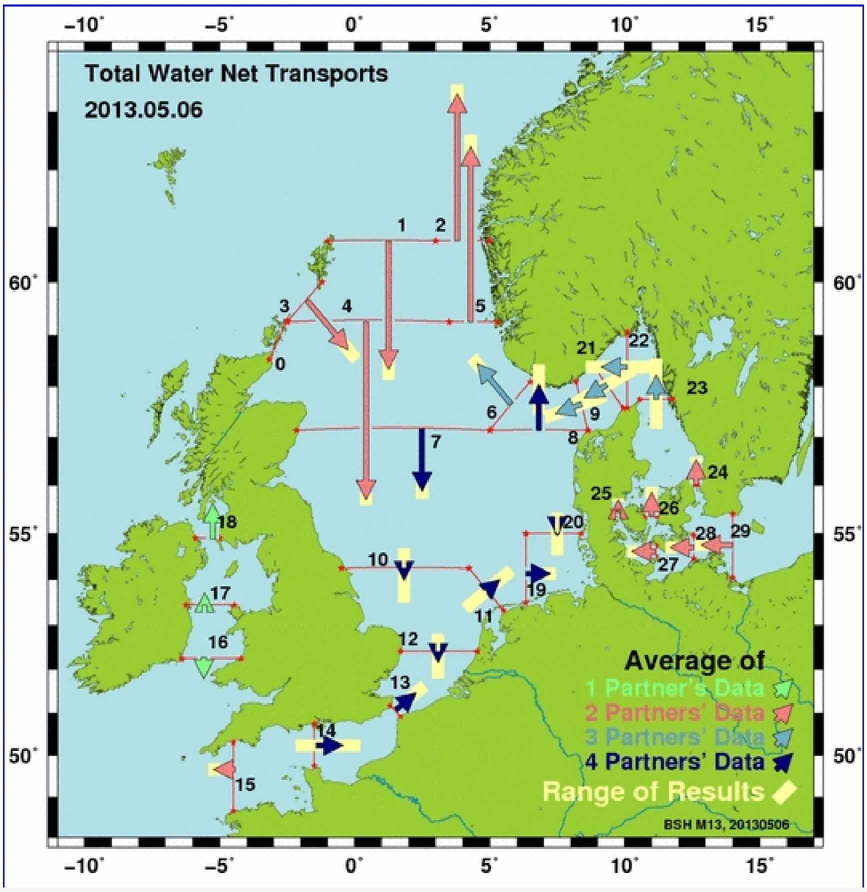


Figure 1 - "BOOS transport calculations" as presented 2013-04-18 on http://www.boos.org/index.php?id=24

North Sea Transports

Computed Water Transports (Average Results of the BSH, MUMM, DMI and MetOffice Circulation Models)



Current Charts and Transects

7. May 2013
6. May 2013
5. May 2013
4. May 2013
3. May 2013
2. May 2013
1. May 2013

time series of 4 partners' data

Online Archive: (Type a Date)

20130507

submit

Overview

BSH

MUMM

DMI

MetOffice

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Figure 2 NOOS transport calculations as presented 2013-05-07 at http://www.noos.cc/index.php?id=151

4. E-HYPE

4.1. The E-HYPE hydrological model

E-HYPE is a pan-European application of the HYPE hydrological model, Hydrological Predictions for the Environment (Lindström et al. 2010) which calculates hydrological and nutrient variables on a daily time-step. The E-HYPE model simulates 35000 subbasins at a median resolution of 215 km2 across the European continent (Fig. 1). The model is set up using readily available continental or global databases and is forced daily using the ERA-INTERIM reanalysis at 0.75 degrees (approximately 6800 km2, Dee et al. 2011) where monthly precipitation means have been corrected to match monthly precipitation means from the GPCC database at 0.5 degrees (approximately 3000 km^2, Rudolf et al. 2005). Subbasin delineation and direction of flow network is taken from the HydroSHEDS (Lehner 2006) river routing network (RRN) for most of the model, but north of 60 degrees, where HydroSHEDS was not available, the HYDRO1K (Verdin and Greenlee 1996) RRN is used. Given the resolution of the forcing data and the accuracy of the subbasin delineation, predictions are deemed most useful for catchments > 5000 km2. Daily discharge data from the Global Runoff Data Centre (GRDC, 2009b), the European Water Archive (GRDC, 2009a), and the Baltex Hydrological Database Centre (BHDC, 2009) were used to calibrate and evaluate discharge in the E-HYPE model for catchments exceeding this threshold area.

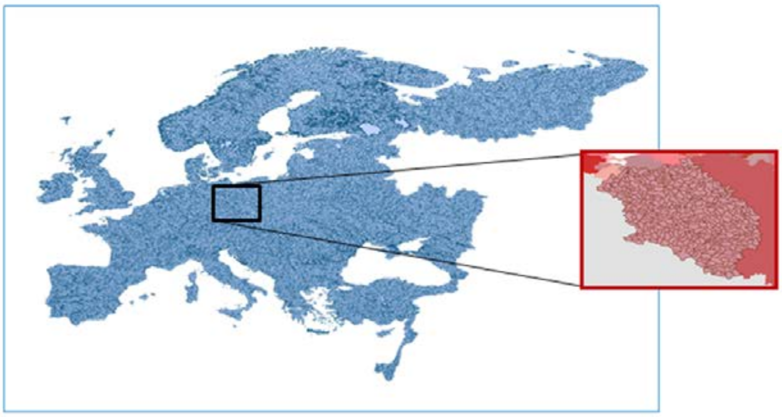


Fig 3. E-HYPE domain showing model resolution

For inputs used to describe water quality and irrigation, the agricultural land cover class was divided into 9 crop groups based on data from the MIRCA2000 database (Portman et al. 2010) and agricultural behaviour such as the timing and amount of fertilisation was taken from the CAPRI model (Britz et al 2007). Urban and rural wastewater emissions were estimated as a function of population from the HYDE database (Goldewijk et al. 2010), and proportional sewage treatment level from the EEA Wise database (EEA 2010). Atmospheric deposition of N was taken from the MATCH atmospheric model (Andersson et al.2007). Note that although E-HYPE is a dynamic model, the definitions of land cover, crops and point sources were static due to data availability limitations.

The HYPE model contains a number of parameters for which a value should be calibrated in order to fit data observations. For discharge, these parameters represent processes including evapotranspiration; snow storage and melt; soilwater storage, recession and runoff; lake processes, routing etc. The potential evapotranspiration parameter was optimised for a best fit of simulated evapotranspiration against flux tower data measurements across the continent. For the rest of the parameters, initial estimates were taken from the calibrated parameter set from the S-HYPE model application over Sweden (Strömqvist et al. 2011). These parameters were then further calibrated by optimising land cover and soil-type specific parameters in groups of Representative Gauged Basins (RGBs) which are groups of lake-free smaller gauged catchments with dominant areas of the relevant land cover or soil-type in the upstream catchment area. Further model calibration included fitting of individual rating curves for the largest 121 lakes and fitting of individual regulation schemes for 46 reservoirs. The resulting model performance was evaluated at independent catchments not used in calibration and at downstream catchments which represent more heterogenous land cover and soil-type conditions.

Some calibration of parameters for water quality was made to match observations in 16 smaller river basins with good quality monitoring data from the EuroHarp project database (Silgram et al. 2009a&b). The other available observation data from the EEA's WISE database (EEA 2010) was only available on seasonal or annual time-scale so this data was used to evaluate the simulated water quality from the model. Note that in general, the effort given to calibration was considerably less than the effort given to model setup and testing, as errors in input data are the more considerable source of error when modelling at this scale.

The E-HYPE hindcast data is available for free public download using the E-HYPEweb system at SMHI (www.ehypeweb.smhi.se).

4.2. The daily forecast production system using E-HYPE

The E-HYPE model started producing live, publicly available forecasts in December 2012. This was done by implementing the E-HYPE model setup and the hype code into the AEGIR production system at SMHI.

An initial model spin-up for the hindcast run is done by running the model with Erainterim from 1979-01-01 to 2012-07-31, saving a model state, then using this saved model state as the state at 1979-01-01 to initiate the actual hindcast run. This is done to ensure equilibrium in starting pools of nutrients for actual hindcast, 1979 to 2012. To transition between the hindcast forcing and today's initial state, the model saves the state at 2012-03-02 (i.e. the end of the available ERAINTERIM hindcast forcing data) and then makes another model run using saved ECMWF deterministic model data as forcing data from 2012-03-03 to the end of the spin-up period (i.e. today's date).

For the daily model run, the model uses the last saved state and the ECMWF global deterministic model as forcing data. The model is run for the period "yesterday" and until "today+9", so a total of 11 days are calculated every day. A new model state is saved every day at the "today" time step and is used by the model run for the next day.

The ECMWF global deterministic model is transferred to E-HYPE forcing data by calculating the mean temperature and the accumulated precipitation for each time step for the centre coordinate of each E-HYPE subbasin. Thus, the temperature and precipitation for the centre coordinate of each subbasin represent the whole subbasin.

The time step used for the daily model runs is 06:00 to 06:00 and represent the start of the time step. So the time step for "today" is forced by data extracted for the period today 06:00 to tomorrow 06:00.

Note that the operational forcing data, ECMWF global deterministic model, has a different resolution to the hindcast forcing data (about 22 km), Erainterim, and is based on a different atmospheric model and therefore any systematic biases shown in hindcast model validation may be different for the forecast period.

Currently the forecasts are made available to requesting oceanographic groups via daily ftp transfer; however, during 2013, it is planned to make the forecasts more publicly available via the E-HYPEweb system (www.e-hypeweb.smhi.se)

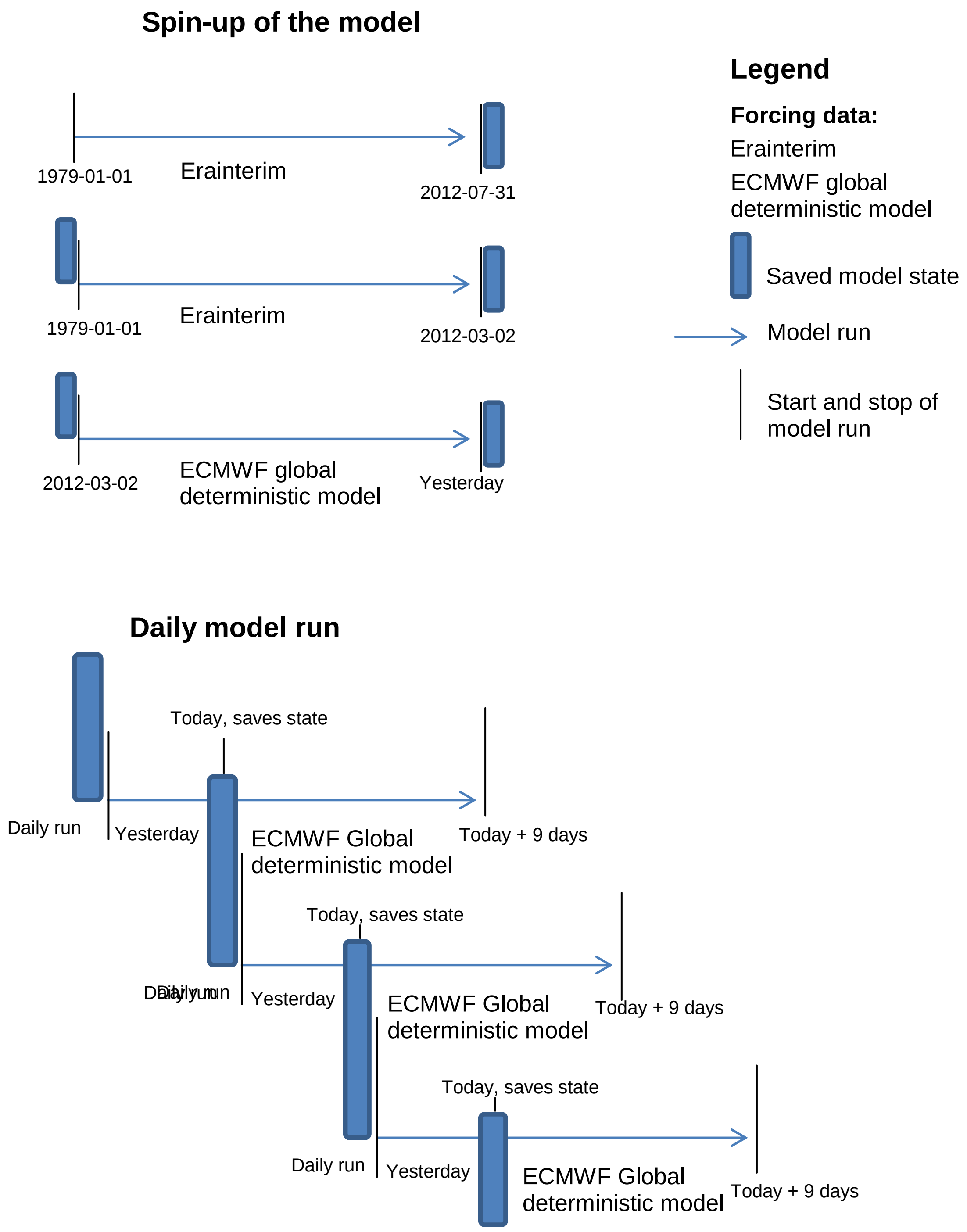


Fig 4. Overview of Hydrological Production system with E-HYPE

4.3. E-HYPE - Results

The ability of the E-HYPE model to reproduce discharge and nutrients in Europe, both in catchments at varying scales and at river mouths discharging to European Seas, was assessed.

4.4. Validation of E-HYPE Discharge

The E-HYPE model was validated for its ability to reproduce long-term discharge means, the inter-annual variability of discharge, the seasonal variability of discharge, daily variability of discharge, ability to reproduce extreme events and performance as compared to a climatological mean. A database of observed discharge data was created using data downloaded from the GRDC, EWA and BHDC databases. Data was filtered for catchment area > 5000 km^2, availability of data in the period 1981 to 2000, as well as removing stations with large portions of missing data, or highly unusual hydrographs. Finally, stations with shared catchment area were removed, so that each gauging station represents at least 90 % unique upstream area. This gave a total of 181 stations with either daily or monthly data and 157 stations with just daily data.

Long-term discharge means

A first test of the model's ability to reproduce discharge across Europe, is to assess how well the model reproduces levels, or long-term discharge means. The relative error is used to indicate the ability of the model to reproduce long-term discharge means. It is calculated as the difference between the simulated mean discharge and the observed mean discharge divided by the observed mean discharge. Fig 5 shows how the relative error varies across Europe for 181 stations varying in catchment size, climatic conditions and catchment properties. The results indicate a negative bias in discharge for northern Europe which is believed to be caused by underestimated precipitation in the forcing data set. There is mainly a positive bias over southern Europe, believed to be caused by underestimated irrigation, town water, and other extraction volumes.

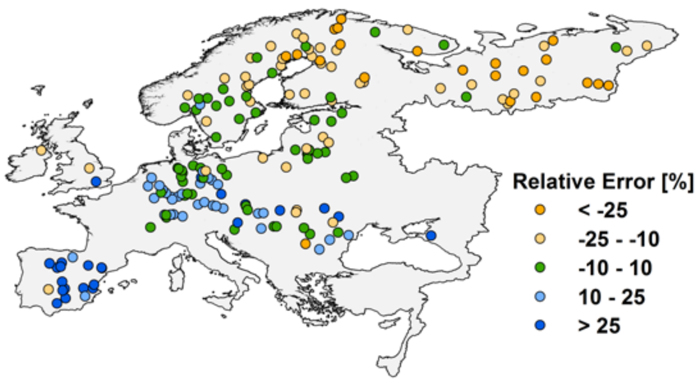


Fig 5. Variation in relative error across Europe for 181 gauging stations

The histogram shown in Figure 6 indicates how many stations achieve relative errors of different sizes. About 32 % of stations could be estimated to within 10 % of the correct mean discharge and 75 % to within 25 % of the correct mean discharge. The remaining 25 % of stations had relative errors exceeding 25 %.

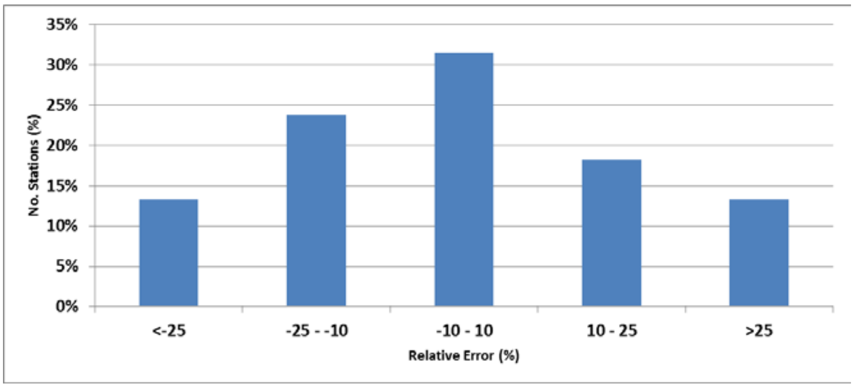


Figure 6. Histogram of Relative Error for 181 European gauging stations

The E-HYPE model was also validated for its ability to simulate long-term discharge means to seas at 45 discharge stations at river mouths around Europe. In total, the model underestimates discharge to European Seas by about 10 %, but with a wide variation in results between stations. Fig. 7 shows that the model performs better in rivers with < 10 % irrigation than in rivers with more significant amounts of irrigation even though there is a negative bias in these stations (caused by the underestimation of precipitation in northern Europe where most unirrigated basins lie).

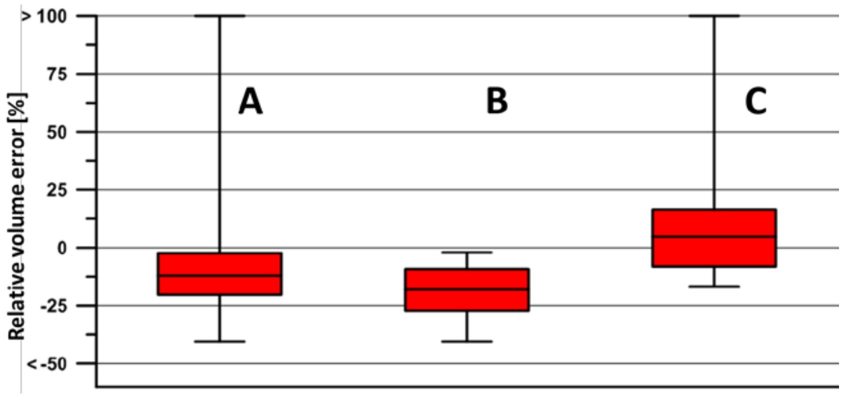


Fig 7. Variation in relative error for discharge stations near to the European coastline. A: All 45 stations, B: 31 with less than 10% irrigated upstream area, C: 14 with more than 10% irrigated upstream area.

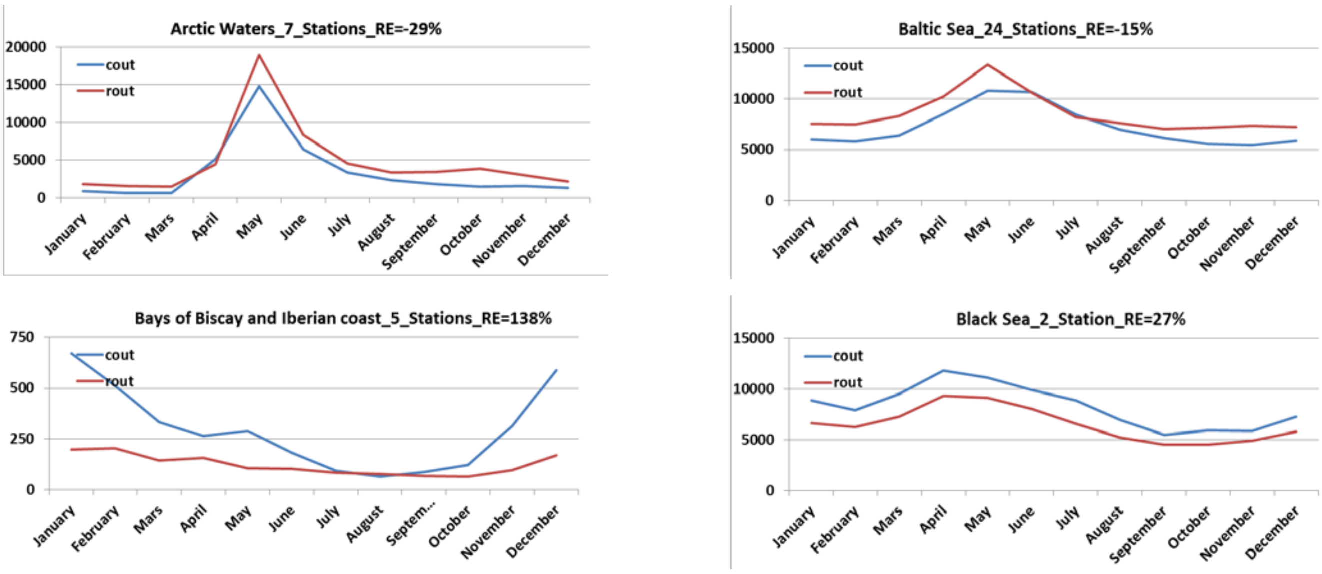
Interannual variability of discharge

The model's ability to reproduce interannual variability of discharge is one important argument for why simulated discharge from model such as E-HYPE could be used rather than climatological means. The Pearson correlation coefficient between observed and simulated yearly mean discharge was calculated for each station to give an indication of the model's ability to capture the inter-annual variability of discharge, without taking into account whether or not the model captures the level or volume of discharge, Fig 8. A majority of stations had correlation coefficients exceeding 0.6 and nearly all exceeding 0.4, indicating the model's ability to reproduce inter-annual variability. There were some regional patterns in the correlation coefficients, with many poorer correlation results on the Iberian Peninsula and Northern Sweden and Finland and in Eastern Europe. This could possibly be due to the model not capturing regulation in very large reservoirs which redistribute discharge across years for hydropower or irrigation.

Fig. 8. Variation in correlation of yearly discharge means across Europe for 181 gauging stations

Seasonal variability of discharge to European Seas

It is also important to assess whether or not the model can reproduce the seasonality of discharge. This was assessed here for the sum of observed discharge to European Seas (Fig. 9). The seasonality of discharge to the Arctic, Greater North Sea, Celtic Sea and Black Sea is well reproduced (not taking into account variations in total volume). For the Baltic Sea, the spring flood peak is somewhat late. For the Mediterranean, Bays of Biscay and Iberian coast, model performance is rather poor, with an exaggerated seasonality as well as the overestimation of discharge. Again, this is thought to be due to the insufficient representation of extraction volumes for irrigation and the seasonable redistribution of water in reservoirs for irrigation purposes. Note that the number of stations used to represent discharge to each sea varies significantly.



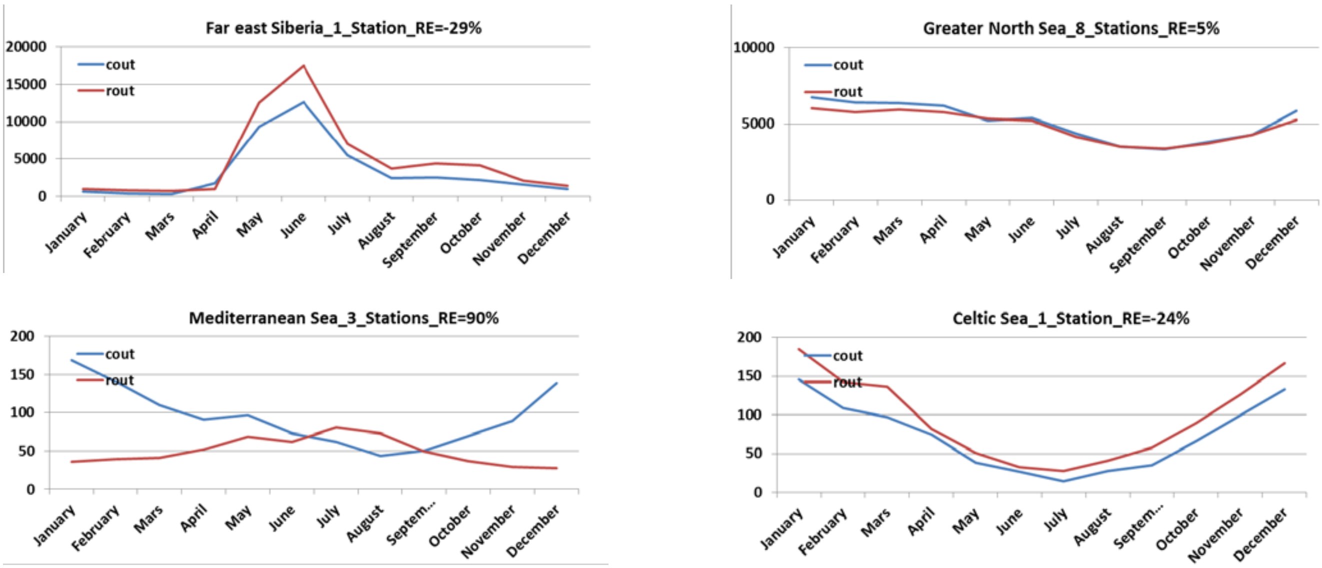


Fig. 9. Seasonal variability of discharge to European Seas

Daily Variability of Discharge

The ability of the model to reproduce the daily variability of discharge is assessed here using the Nash-Sutcliffe Efficiency (NSE, Eq 1):

Eq (1) $$NSE = 1 - \sum(c_i - o_i)^2 / \sum(o_i - \bar{o})^2$$

Where c_i = calculated discharge at timestep, *i*

o_i = observed discharge at timestep, *i*

*o_*= mean observed discharge

This performance measure takes into account the model's ability to simultaneously reproduce the volume of discharge (bias), the relative variability of the flow and the correlation between observations and simulated values. Best NSE values are seen in Western and Northern Europe, despite the volume errors in northern Europe. Very poor NSE values are seen for all of the Iberian Peninsula (where the aforementioned problems with volume and seasonality have been seen), and in parts of central Europe. For all stations across Europe, 66 % had NSE greater than 0 and 39 % of stations have a NSE greater than 0.4. Figure 11 shows that for the 45 river mouth stations, the majority of NSE values exceed 0 and that the regulated rivers were more difficult to simulate than the non-regulated rivers, an expected result given the difficulties in predicting the human factor in daily reservoir operation.

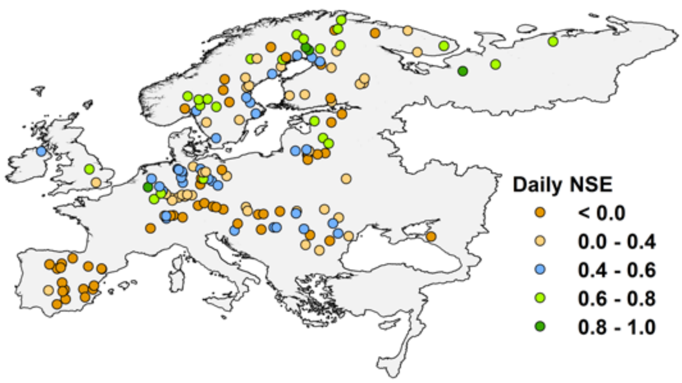


Figure 10. Variation in daily Nash-Sutcliffe Error (NSE) across Europe for 157 stations

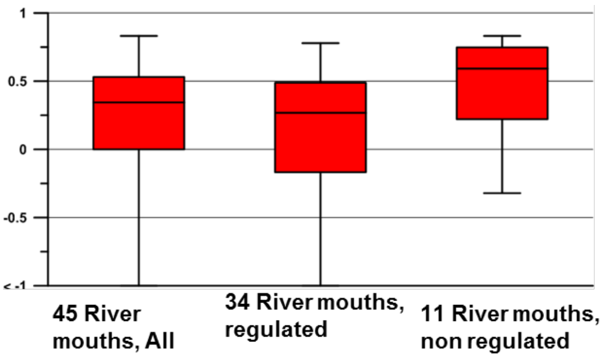


Figure 11. Variation in Nash-Sutcliffe Error (NSE) for (a) 45 river mouth stations (b) 34 regulated river mouth stations and (c) 11 negligibly regulated river mouth stations

Comparison of simulated discharge with Climatological Mean

Because climatological means have traditionally been used to represent discharge fluxes to seas in oceanographic models, an attempt was made to quantify whether or not the model is better than a climatological mean estimation of discharge from rivers to the sea. The NSE calculated at each river mouth observation station for the error between the climatological mean and the observations. This was then compared to the NSE for the E-HYPE model. Fig. 12 shows the comparison between the climatological mean and the E-HYPE simulated discharge. As can be seen, the majority of stations are better than a climatological mean; however, about a third of the stations cannot outperform the climatological mean. The poorer results reflect regions stations where the relative error was poorest as the Nash-Sutcliffe takes into account both temporal variation as well as the overall level of discharge.

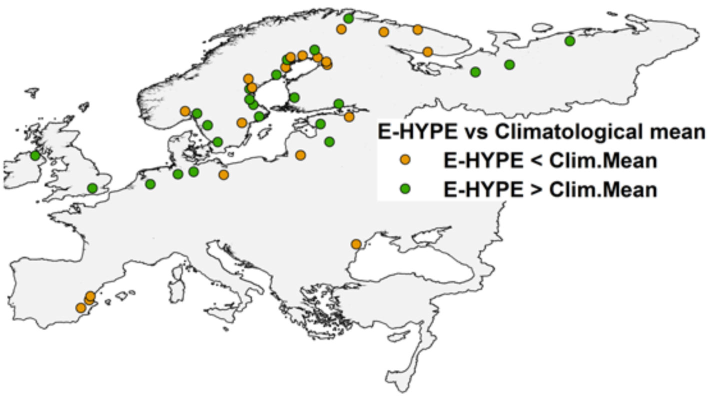


Figure 12. Comparison of NSE for climatological mean discharge vs E-HYPE simulated discharge for the 45 river mouth stations. Green dots show stations where E-HYPE outperforms the climatological mean as based on the NSE.

Representation of Extremes

Finally, the model was assessed for its ability to reproduce less frequent, extreme events, i.e. floods and droughts. Figure 13 shows the spread across all stations of the model's ability to represent different flow percentiles. It can be seen that the spread increases significantly for flows below the 30th and above the 80th percentile. There is also a trend in the models' ability to simulate different flow percentiles with the lowest flows at each station more often underestimated, while the highest flows are more often overestimated. There are many factors that could cause this. The model parameter set may underestimate storage of soil moisture, in regulated rivers and rivers with natural lakes retention may be underestimated. Low flows are difficult to simulate in Europe due to losses to groundwater and the level of anthropogenic influence including extractions for irrigation, town water and power station cooling, regulation of rivers for irrigation, flood control and hydropower and diversion via canals. Although the model has simple routines for simulation irrigation regulation and extractions and hydropower regulation, these routines can only simulate an assumed pattern of human behaviour. There is significant scope for improving the model's ability to simulate extreme events.

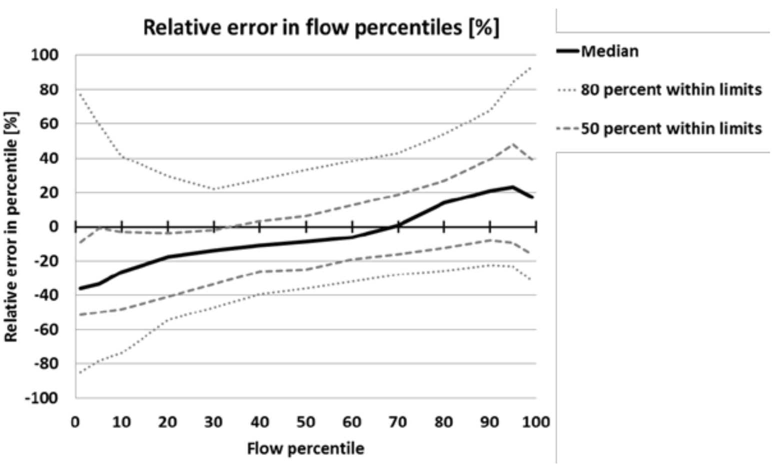


Figure 13. Spread across all stations of the model's ability to represent different flow percentiles

Summary of Discharge validation

The E-HYPE model shows mixed results for reproduction of discharge across the 181 observation stations for which validation was made. Given the wide variety of climatological, physiographic, anthropogenic and catchment scale conditions to which the model is verified and given the limitations of continental and global scale input databases, it is positive that the model manages to simulate 75 % of the catchments to within 25 % of the correct volume, and 66 % of catchments could simulate daily variation in discharge better than the mean of the observations (as indicated by NSE > 0). It is also useful to note that the E-HYPE model can in most cases reproduce the seasonal variation of discharge as well as the inter-annual variation. In general, it seems that the models' poor ability to reproduce mean discharge or discharge volumes in Northern Europe and in Southern Europe affects the models' ability to produce good NSE results or outperform the NSE for a climatology. There is large scope to improve the variation of mean annual discharge across Europe, by improving the forcing precipitation (using newly available high-resolution reanalysis data sets for example) and in southern and eastern Europe, by improving the model's ability to simulate losses to groundwater and the extraction of water for irrigation, town water supply and other purposes. It is also believed that improving the simulation of regulation of reservoirs for different purposes could help improve the overall simulations.

4.5. Validation of E-HYPE nutrients

The E-HYPE water quality model

The HYPE model was used to compute in-stream concentrations of the two major nutrients/riverine pollutants nitrogen (N) and phosphorus (P) along with the water balance. The limited data availability at the European scale constrains the validation of E-HYPE modelled nutrient levels; here, we used averaged data reported in the European Environmental Agency Water Information System for Europe (EAA WISE) database as well as observations obtained from the Global Environment Monitoring System (GEMS) and select Swedish routine observations from the Swedish Agency for Marine and Freshwater Management (HaV). Data from catchments > 500 km^2 were used for the validation, each with at least 90% unique upstream area. An evaluation period from 1999 to 2008 was chosen, since most data was available for this period. Overall, 352 catchments were evaluated, 310 with annual average data, and 45 with daily to monthly data frequencies.

Long-term concentration means and inter-annual variability

E-HYPE-modelled long-term average loads of total nitrogen (TN) and total phosphorus (TP) illustrate the main passageways for nutrient transport to the European sea basins (Figures 14 and 15). Both TN and TP loads are high in the large river systems of Central and Eastern Europe with long accumulation lengths but also with multiple upstream pollution sources through e.g. intensive agriculture and industrial point sources. These model predictions were evaluated using EEA WISE Water Framework Directive Database observations for the decade from 1999 to 2008. The annual averages of TP and TN cover a North-South gradient of the European continent, even though data are sparser in the South. A validation of the modelled inter-annual dynamics of TN and TP concentrations using Pearson correlation coefficients (R^2) indicates no clear regional performance pattern throughout Europe (Figure 16). Performance analysis using R^2, however, masks constant concentration biases as observed in the rainfall-runoff model (see Fig. 5), but the focus for water quality was put on the concentration dynamics (a) because these indicate if the internal model processes represent the measured signals, and (b) because the EEA WISE annual averages were based on episodic samples and not flow-weighted, in contrast to the modelled values, and the resulting average levels thus not entirely representative for the annual balance. The overall results are promising, even though there still is considerable variation in the model's ability to capture the inter-annual dynamic locally, where the model estimates regarding agricultural practices, population density, or other factors may be deficient in the current model.

Figure 14: Modelled average annual TN loads (tons per year), evaluation period 1999 to 2008.

Figure 15: Modelled average annual TP loads (tons per year), evaluation period 1999 to 2008.

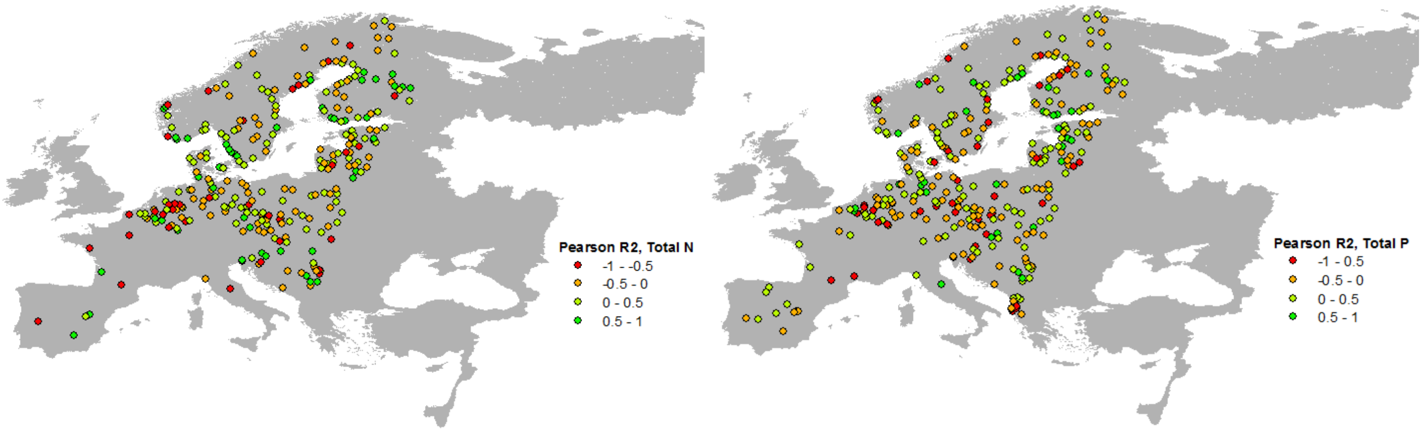


Figure 16: Variation in Pearson correlation coefficients across Europe, annual concentration averages for TN and TP.

A decomposition of R^2 performances according to upstream catchment area using the EEA WISE data shows a slightly better correlation for large catchments (>20000 km^2) compared to smaller catchments, while small catchments (>2000 km^2) show the largest spread in correlation (Figure 17). Using the non-averaged validation data set with Swedish HaV and GEMS data, the validation can be further differentiated (Figure 18). The data include four additional N and P species which are also simulated in E-HYPE. Overall, the R^2 performances increase compared to the annual summary data, which confirms the model's ability to simulate nutrient dynamics, also at inner-annual scales. There is no consistent performance difference in catchment of different area, and the computed nutrient species correlate similarly well to measured values as the totals. Note, however, that the spatial extent of these detailed data is limited and mainly covers Sweden and outlets to the North Sea.

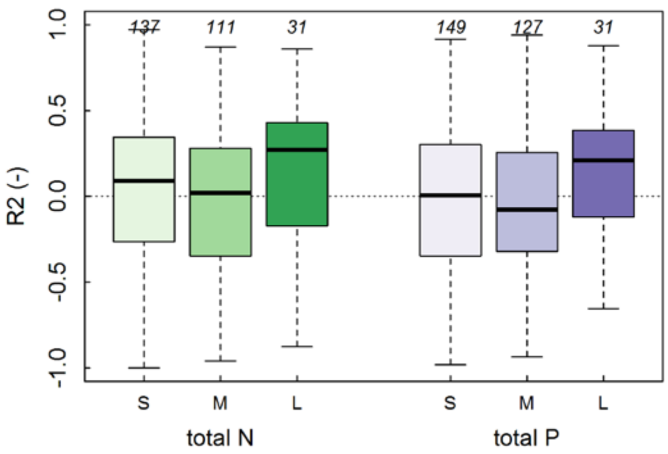


Figure 17: Water quality model performance, annual average concentrations of total N and P (EEA WISE database) for the evaluation period 1999 to 2008. Pearson correlation coefficient between modelled and observed values, data grouped by catchment size (S: <2000 km^2, M: 2000 – 20000 km^2, L: >20000 km^2). Observation data coverage between 3 and 10 years. Number of catchments in each group in italic.

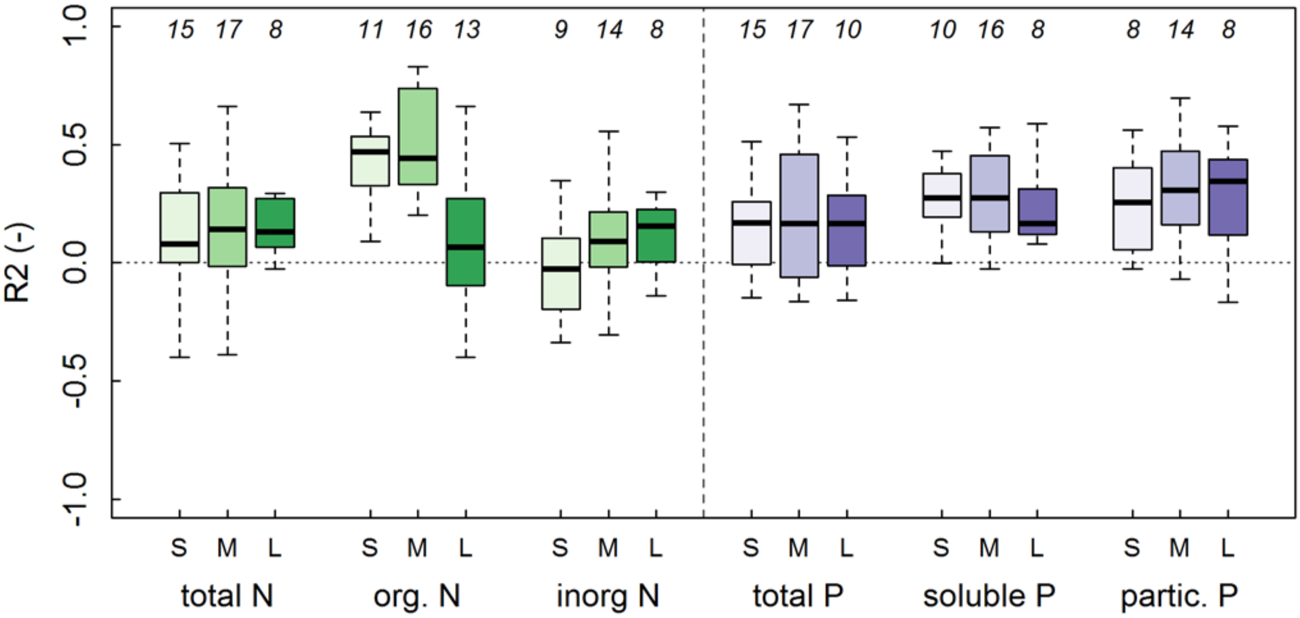


Figure 18: Water quality model performance, based on single sample observations (GEMS and HaV databases) for the evaluation period 1999 to 2008. Pearson correlation coefficient between modelled and observed values, data grouped by catchment size (S: <2000 km^2, M: 2000 – 20000 km^2, L: >20000 km^2). Note that the spatial coverage is focused on Swedish basins and select large river mouths in Western Europe. Number of catchments in each group in italic.

Seasonal variability of nutrients

The seasonal variability of nutrient concentration was exemplarily assed using GEMS (river Elbe) and HaV (river Göta Älv) data, for both TN and TP. From measured and simulated time series during the evaluation period (1999 to 2008), monthly long-term averages were computed to investigate the observed seasonal variability and the modelled counterparts (Figures 19 and 20). In the Elbe, TN concentrations are overestimated in the model, and the seasonal signal with higher concentrations in winter and lower concentrations in summer lags in the modelled concentrations. The lag is also present in the TP signal, concentration levels, however, are matched more closely. The lags could be caused by insufficient crop

In the Göta Älv, the seasonal signal is much weaker for TN, and also here, the model overestimates in-stream nitrogen concentrations throughout the year, while TP is matched more closely. The overestimation of TN concentrations could be addressed to errors in atmospheric deposition or deficiencies in crop growth parameterisation. Nevertheless, the overall performance of the E-HYPE nutrient model

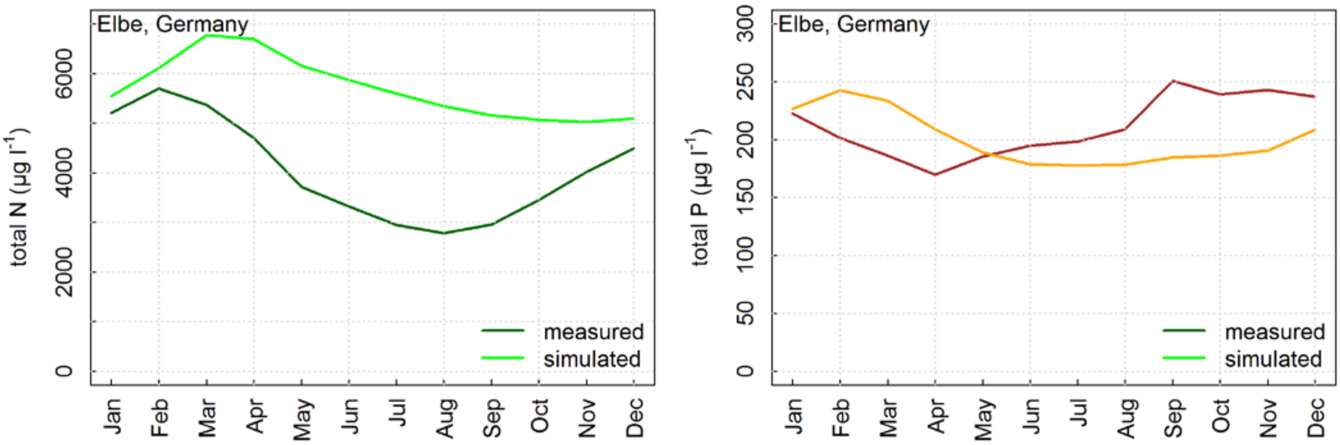


Figure 19: Seasonal variability of TN and TP in the river Elbe.

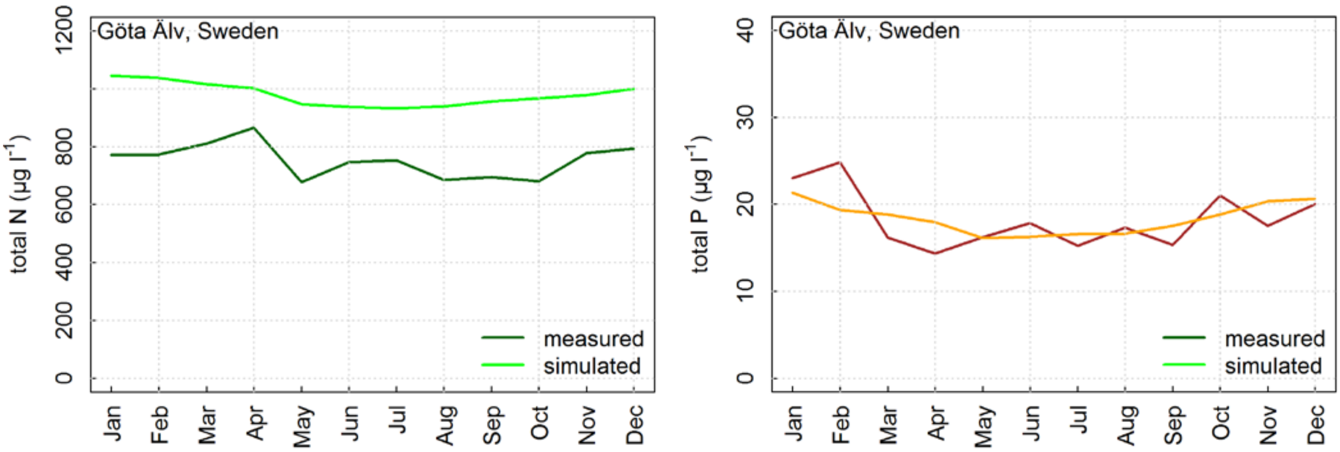


Figure 20: Seasonal variability of TN and TP in the river Göta Älv.

Summary of Nutrients validation

The E-HYPE model validation of nutrient concentrations of nitrogen and phosphorous shows a variable performance with no clear regional signal in terms of inter-annual dynamics. Promisingly, the majority of 310 evaluated sites show positive correlations between modelled and observed values. Considering the large uncertainties and limitations in availability for input data at the continental scale, the results are certainly promising. The nutrient fluxes and transformations are strongly coupled to the modelled hydrological states and processes, and model performance of the water balance is therefore directly influencing the performance of modelled water quality. Nonetheless, the water quality predictions of the E-HYPE model have the potential to deliver a wealth of spatially distributed model estimations of N and P concentration levels and dynamics as well as derived figures, e.g. annual loads to coastal zones and sea basins. This is especially important as routine monitoring of water quality is still much more cost-intensive and subsequently sparse compared to runoff volume measurements.

4.6. Preliminary validation of E-HYPE discharge forecasts

A rerun of the analysis system was made from 2012-03-02 to 2013-04-09 and compared to observation data in 25 coastal points : 19 in Sweden (due to easy availability of real-time data from SMHI), 2 in Norway (from NOOS), 3 in Germany (NOOS) and 2 in Spain (Spanish hydrological agency). Because the forecast system is run for 10 days from an initial start condition, this allows the initial condition (day 0) and each of the 10 day forecasts to be compared wtih the time-series of observations from the previous year, i.e. there are 11 x 1 year time-series of forecasts for each station.

Table 1 shows Nash-Sutcliffe Efficiency's (NSE), Relative volume Errors (RE) and correlation coefficients (CC) for the 25 stations for day 0 (initialisation) and day 10. Half of the stations have correlations coefficients greater than 0.5, indicating a reasonable reproduction of the daily variability in discharge, but only 7 stations had NSE > 0, inidicating poor performance for bias (or relative error) in many stations. Although none of the stations coincide with hindcast evaluation stations, the regions where the model performs poorly, reflect regions where the model performs poorly in hindcast (e.g. Spain). Some of the evaluation stations in Sweden are located at hydropower dams (e.g. those with suffix 'KRV' in the station name) which makes it difficult to reproduce daily variations in discharge, even if the monthly and annual variability can be reproduced.

The results indicate that there is only a small deterioration in median performance across all evaluated stations from model initialisation (day 0) to day 10. This is mainly because the change in performance compared with the spread in performance across all stations was small. For the best stations (7 stations with NSE > 0), change in performance from day 0 to 10 ranged from -0.09 % to + 0.15 %.

There is a need for further evaluation of the forecast model over several years, including a long-term evaluation of the forecast forcing data for systematic bias which could potentially be adjusted for.

					Day 0			Day 10		
SUBID	RIVER	STATION	COUNTRY	AREA	RE	CC	NSE	RE	CC	NSE
115223	JONDALSELV	FASSEROED	se	142	-5%	0.43	-1.71929	-6%	0.39	-1.8544
300416	INDALSÄLVEN	BERGEFORSENS KRV	se	25746	-11%	0.11	-11.1472	-12%	0.13	-10.7821
300785	DALÄLVEN	ÄLVKARLEBY KRV	se	28429	-16%	0.50	-3.00108	-15%	0.49	-2.85865
300859	LJUSNAN	LJUSNE STRÖMMAR KRV	se	20110	-37%	0.38	-17.5771	-39%	0.35	-19.5102
300868	UNDEFINED RIVER	RAKTFORS	SE	17148	21%	0.75	0.512686	20%	0.71	0.429159
301276	TORNEÄLVEN	PELLO	SE	32812	-8%	0.48	-0.73214	-10%	0.47	-0.85447
301914	MOTALA STRÖM	GLAN	SE	14259	5%	0.23	-0.15823	5%	0.24	-0.1387
302291	GÖTA ÄLV	VÄNERN	SE	48918	-6%	0.53	0.246535	-7%	0.51	0.217924
302852	MAELAREN	OEVRE STOCKHOLM	SE	24961	1%	0.47	0.217601	3%	0.46	0.208788
303950	SKELLEFTEÄLVEN	KVISTFORSENS KRV	SE	11365	-16%	0.51	-0.53972	-16%	0.48	-0.62487
304353	PITEÄLVEN	SIKFORS KRV	SE	10760	-5%	0.81	0.492446	-7%	0.80	0.399849
304803	LULEÄLVEN	BODEN	se	24795	6%	-0.32	-4.09483	5%	-0.35	-4.54801
307181	OEREAELVEN	TORRBOELE	SE	2767	0%	0.53	-0.07626	1%	0.47	-0.37828
307235	UMEÄLVEN	UMEÅ	se	28623	-22%	0.26	-2.97825	-23%	0.27	-3.0081
308111	GLOMMA	OSLOFJORD	no	41593	-168%	0.84	-149.471	-170%	0.83	-148.094
315430	ÅNGERMANÄLVEN	NÄMFORSENS KRV	se	20410	-22%	-0.15	-10.7907	-26%	-0.13	-11.0531
408008	MÖRRUMSÅN	MÖRRUM	SE	3431	-19%	0.89	0.52402	-20%	0.84	0.467397
440334	LAGAN	ÄNGABÄCK	SE	5758	-48%	0.76	-0.09885	-46%	0.68	-0.14085
446285	EMÅN	EMSFORS	SE	4176	13%	0.60	0.301342	17%	0.48	0.150839
446814	ALSTERAN	GETEBRO	SE	1450	41%	0.05	-0.37296	40%	0.04	-0.34835
511321	EMS	VERSEN WEHRDURCHSTICH	de	5000	-41%	0.86	-2.77278	-44%	0.77	-2.97308
511538	WESER	INTSCHEDE	de	38362	-28%	0.90	-0.7754	-22%	0.80	-0.60079
535094	MINHO	ORENSE	es	13103	-34%	0.64	-0.12798	-29%	0.54	-0.24572
570778	ELBE RIVER	NEU-DARCHAU	DE	130744	-18%	0.82	0.344904	-15%	0.81	0.436101
764025	Ebro	EBRO EN TORTOSA	es	na	-236%	0.35	-5.81431	-223%	0.30	-5.39819

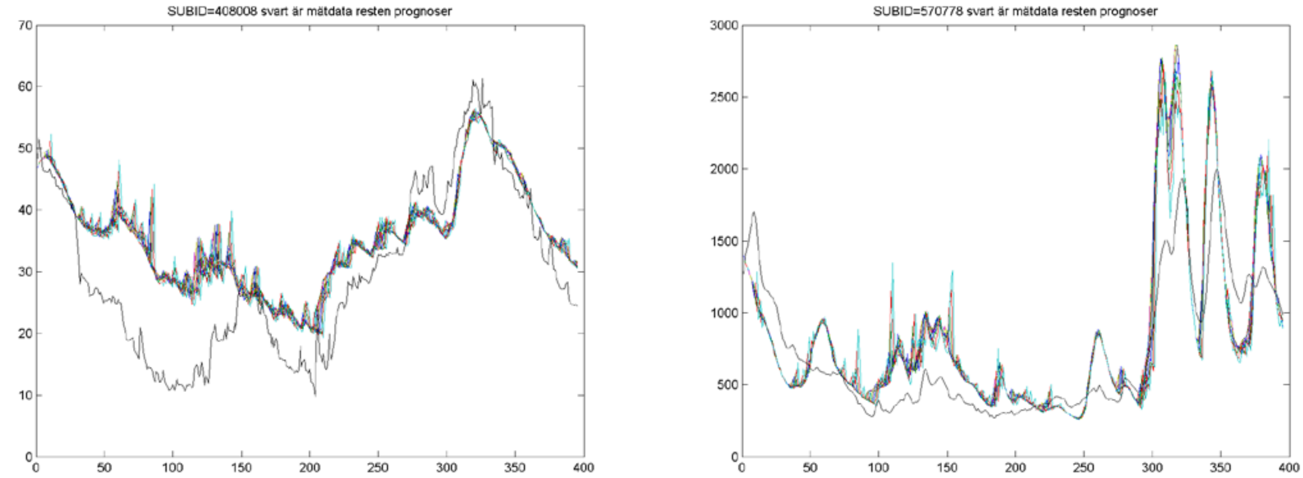


Figure 21. Example of better forecast performance : (a)Mörrums Stations on Mörrums Ck SE, (b) Neu Darchau station, Elbe River, DE (x-axis are days during 2012, y axis is discharge)

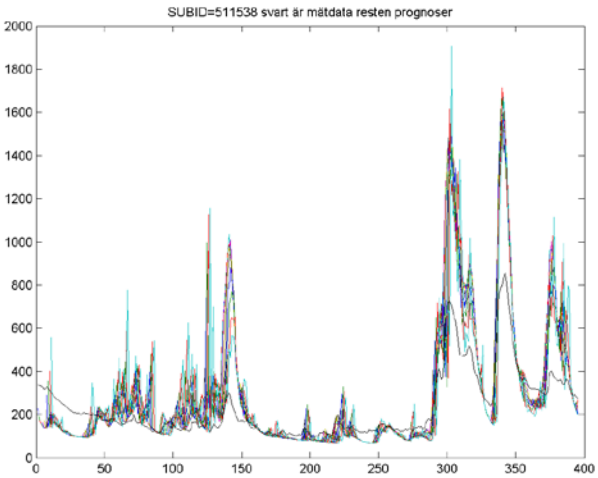


Figure 22. Example of forecast performance where CC is high (0.9), RE is -28 % and NSE is poor (-0.77) : Intscheder Station on the Weser River (x-axis are days during 2012, y axis is discharge)

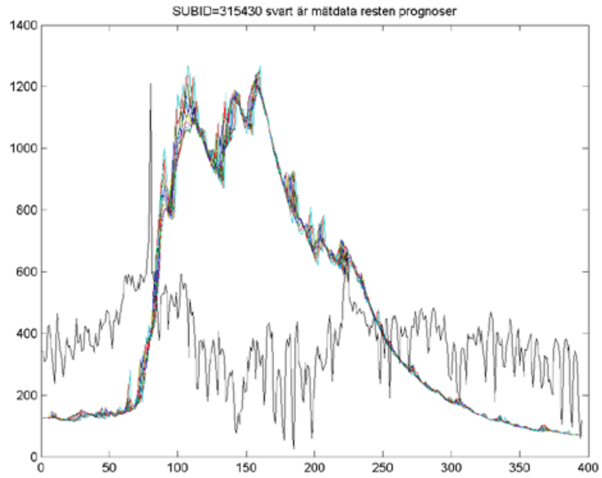


Figure 23 : Example of poor forecast performance : Nämforsens KRV Ängerman River. In this case the model does not reproduce regulation and underestimates total volume by 22 % (x-axis are days during 2012, y axis is discharge)

5. Demonstration of a pan-European transport product – using HIROMB

To demonstrate how a pan-European transport product may be realised, the aim here is to estimate transport of water between different domains in the Baltic and Skagerrak sea area. This means a system to produce results similar to the "BOOS transect" transport calculations as shown in figure 1. The estimates will be based on model currents from the current operational HIROMB model with 3 nm resolution. The model area is covering the North Sea, Swedish west coast and the Baltic Sea as is shown in figure 24.

5.

5.1. HIROMB in brief

HIROMB is an abbreviation for High Resolution Operational Model for the Baltic. As the name suggests, it is a circulation model with high resolution intended to be used for the Baltic Sea, but it is used for other regions as well; see below. Output variables from HIROMB include:

- sea level
- currents
- salinity
- temperature
- ice concentration
- level ice thickness
- deformed ice thickness
- total ice thickness
- number of ridges per kilometer
- mean height of ice ridges
- ice drift velocity
- ice convergence or divergence
- Turbulent Kinetic Energy (TKE)
- dissipation rate of TKE
- turbulent diffusivity

5.2. HIROMB Applications

HIROMB has been used for operational forecasting at SMHI since 1995, with increasingly higher resolution vertically as well as horizontally. It is a so-called "nested" model, which means it can have higher resolution in a smaller region of interest. These two model grids are two-way coupled, which means they exchange information with each other along the boundary of the smaller grid.

The forecasting area extends out to the English Channel in the west and to the northern North Sea in the northwest, where the horizontal resolution is 3 nm (nautical miles). This grid is nested to a higher-resolution grid (1 nm resolution) which covers the whole Baltic Sea, the Danish Straits, Kattegat and Skagerrak. Thus, its western boundary is along latitude near Skagen in Denmark. As was mentioned previously for this study the 3 NM setup was used. The model was forced with HIRLAM C11, i.e. the operational configuration and state of the art.

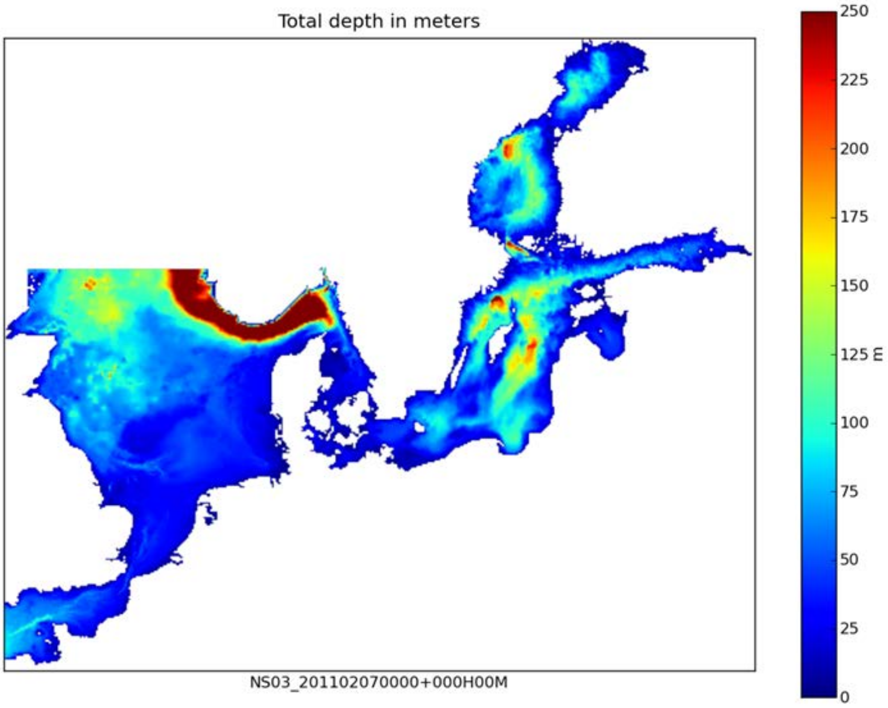


Figure 34 - HIROMB model area

Water transport transects were selected to be more or less same as what is shown on the BOOS webpage[1], to enable comparisons.

5.2. Transport calculation method

Water transport, Q (in units, Sv, Sverdrup; $10^6 m^3 s^{-1}$), over the specific (3D) transects estimated. This was done by first estimating the area of each gridbox side at each depth then multiplying with the current (u or v component). The transects where chosen as straight; they were either from $latitude_1$ to $latitude_2$ at constant longitude or $longitude_1$ to $longitude_2$ at constant latitude. Then the north-south-, U, or the east-west-component, V, of the modelled current was used to estimate the water flow though the transect. The method may be described by

[1] http://www.boos.org/index.php?id=24

$$Q=\sum_0^{Zi} v_i A_i \quad [m^3s^{-1}]$$

where the water transport Q, is estimated as the sum of the transports in all model gridboxes, i, from the surface, Z=0, to maximum model depth Z_i. For each i the transport was estimated by multiplying the current velocity, v_i by the area, A_i;

$$A_i=\delta x_i*\delta h_i \quad [m^2]$$

where the horizontal size of the gridbox, δx is multiplied by the vertical size of the gridbox δh (model depth).

The calculations were done using FORTRAN (code available in appendix).

The hourly model current values where used and Q estimated for each hour. This data were stored as ascii files and an Python program was written to sum the hourly data to estimate the 24 hour net transports. This program also created the plots and webpages.

5.3. Alternative transport calculation method - in Öresund

SMHI has developed an empirical model that estimates the transport of water through Öresund. It was parameterised with measurements of current and relates the sea level difference at station Viken (N 56° 8.3', E 12° 34.5') and Klagshamn (N 55° 31.6', E 12° 53.1') with the inflow of water. Essentially, e.g. if the sea level is lower at Viken than Klagshamn, then there is an outflow (“downhill”). For a detailed description of this method, including Python code, please see in the appendix. In order to compare the transport calculations described in this study with this empirical model, the estimated flow over the north transect in Öresund was summarised and converted to the same units as was presented by the empirical model (km^3).

5.4. Result

The results of the transport estimates were presented on a demonstration website at http://www.smhi.se/hfa_coord/BOOS/Transports.html

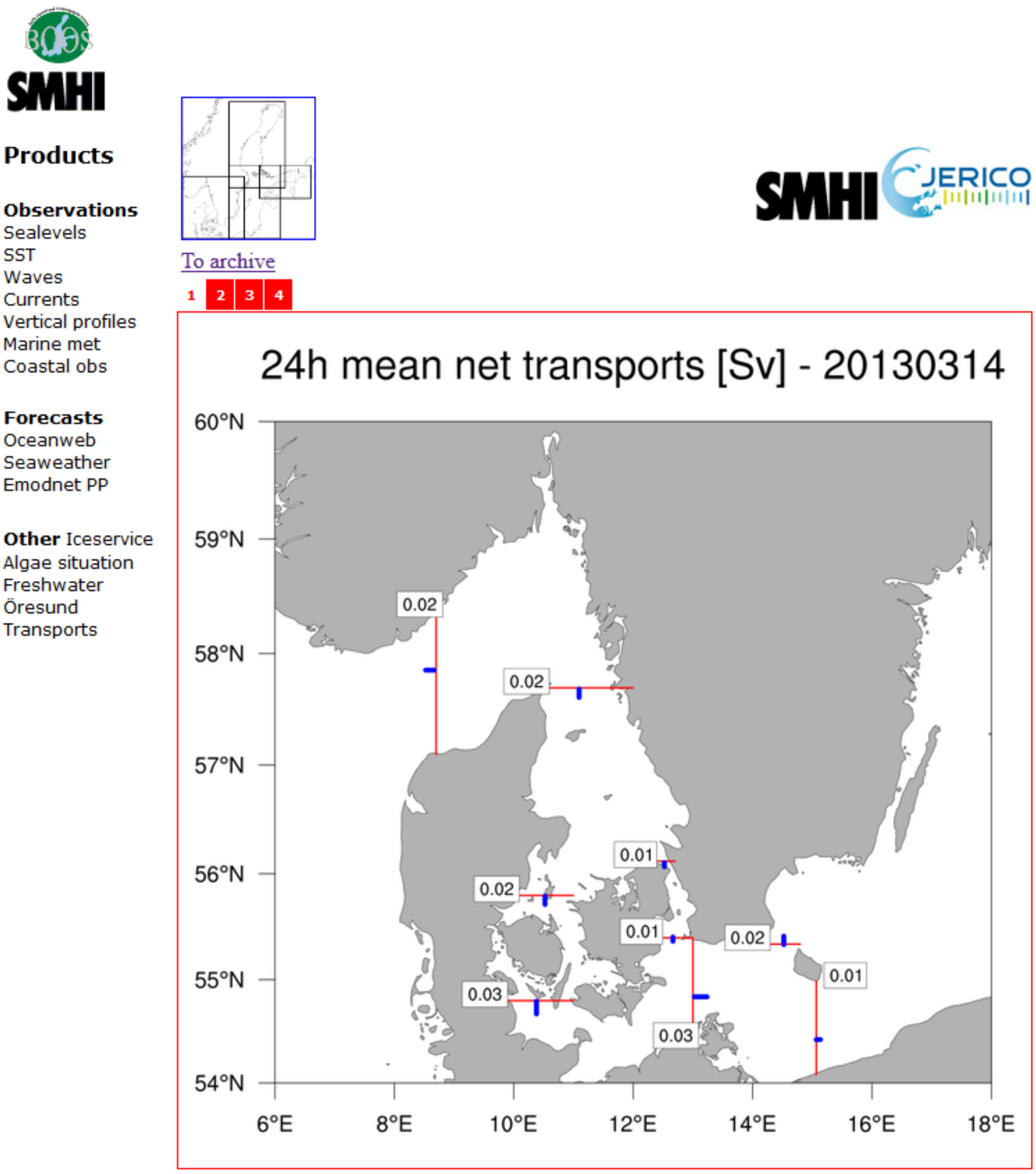


Figure 25 demo web. Figures available for the entire Baltic sea region. Plots older than 5 days are kept in an archive

5.5. Comparison with alternative methods

Results compared with the “empirical model” showing similar pattern, when the North Öresund transect values where used and summed. The results indicate that the flow of water though the Öresund may potentially be underestimated by a factor of about two (26). The empirical model was tested with modelled sea level from HIROMB and then the results are more similar (27). It may potentially indicate a systematic negative bias in the HIROMB modelled currents in the Öresund, but it is stressed here that no observations of current where available to test this. The empirical model was specifically parameterised for the Öresund and hence not possible to use for any other area or transect.

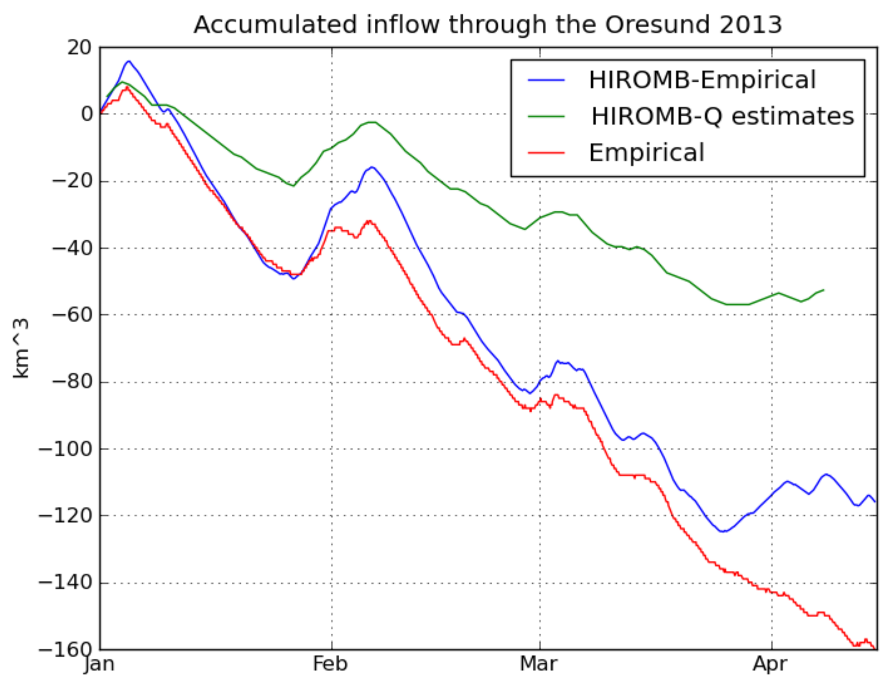


Figure 26 – Comparisons of three methods. "HIROMB-empirical" is the "empirical model" run with HIROMB sea level, "HIROMB-Q estimates" is the transect transport calculations and "empirical" is estimated from measured sea level.

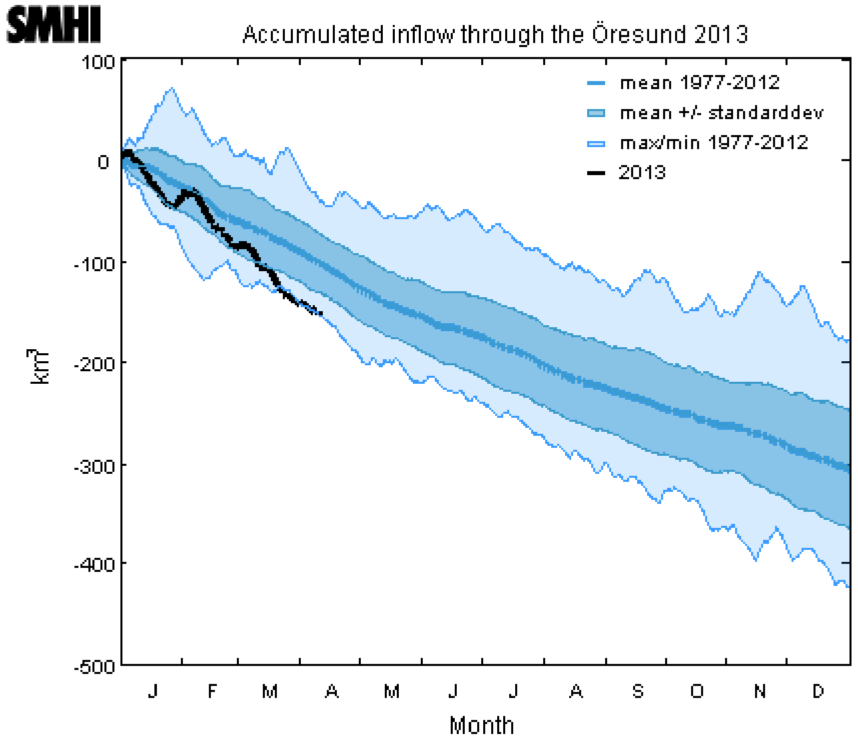


Figure 27- Empirical model long time series

6. Conclusions

The availability of prognostic and hindcast runoff and nutrient fluxes from land to sea is an important consideration for oceanography. The E-HYPE model makes available daily simulated runoff, Nitrogen and Phosphorous fractions from land to sea at high-resolution along the European coastline both for hindcasts (from 1979) and operational forecasts (0 to 10 day deterministic). This simulated data has the potential to replace the insufficient observational data available around Europe's coastline as input to oceanographic models. Although there are some biases in the simulated runoff, particularly for Northern and Southern Europe, interannual variability of runoff is well reproduced, indicating that the simulated data can give a better representation of runoff variation than a monthly climatology. Similarly correlations between observed nutrient and simulated nutrient averages are generally positive, indicating the model's ability to reproduce interannual variation of nutrient concentrations. The operational production of forecasts from the model has been demonstrated and tested against discharge observations for a number of sites around the European coastline.

We have demonstrated the feasibility and usefulness of presenting sea water transport estimates from HIROMB. The method of calculating the flux was compared to an alternative method in the sound. The mechanistic model, HIROMB, showed values of about a factor two lower than the empirical model. The reason for this has to be further investigated, but may be related to a. the bathymetry in the area and/or b. the drag coefficient (bottom roughness) of the mechanistic model. To enable a truly pan-European transport product the transport calculations should be expanded to other European seas. Perhaps this could be the Mediterranean where we are currently not aware of the existence of such a product.

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FORTRAN code for the transport calculation

```
! vertical cross section dA
if (dir == 'N') then
  dArea = dx*cos(lat(i)*grad2rad)*dz(k) ! m**2
elseif (dir == 'E') then
  dArea = dy*dz(k)                ! m**2
else
  stop 'Undefined direction! Stopping.'
end if

! horizontal volume transport through dArea
qsum = qsum + uvel(i,j)*dArea ! m**3/s
! for each grid point
qsec(k,p) = uvel(i,j)
```

Empirical method of estimating sea water transport through Öresund

Essentially the algorithm relates the sea level difference, of a station at the very northern part of Öresund, Viken, with a station at the very southern part of Öresund, Klagshamn, with the flux of sea water though the sound. It may be expressed as:

$$Q(\Delta Z) = K * \sqrt{abs(\Delta Z)} * \frac{\Delta Z}{abs(\Delta Z)}$$

where the flow of water Q is related to the sea level difference Δ Z. K was empirically determined to K=73083. Estimation of Δ Z:

$$Z_k = Z_k^{'} - \alpha\left(Z_v^{'} - Z_k^{'}\right) \qquad \alpha = 0.21 \text{ if } Z_v^{'} - Z_k^{'} \rangle 0 \text{ else } \alpha = 0$$

$$\Delta Z = Z_v^{'} - Z_k = Z_v^{'} - \left[Z_k^{'} - \alpha\left(Z_v^{'} - Z_k^{'}\right)\right]$$

$$Z_k^{'} - Z_k = Z_v^{'} - Z_k^{'} + \alpha\left(Z_v^{'} - Z_k^{'}\right)$$

$$\therefore Z_v^{'} - Z_k = \left(Z_v^{'} - Z_k^{'}\right)(1 + \alpha)$$

where $Z_v^{'}$ = sea level at Viken in RH70, $Z_k^{'}$ sea level at Klagshamn in RH70,l Z_k corrected sea level at Klagshamn RH70.

Python code for estimating sea water transport through Öresund

(part of code)

```
'''
 - Read sea level time series from HIROMB at
 Viken & Klagshamn
 - Read or calculate offset
 - Save data
 - Use in the alternative water flow model
   for comparison
 - (Main calculation “translated” matlab
    code from T.Hammarklint)
 - SMHI Patrik Stromberg 2013-04-23
'''
def sign(val):
   '''
    function equivalent
    from matlab
   '''
   x=0.0 # val = 0 sign in 0
   if val > 0.0:
      x=1.0
   if val < 0.0:
      x=-1.0
   return x


outf.write('datum viken klagsh Q_sum\n')
for i, vst in enumerate(vst_klagshamn):
   datum_wl=vst.split()[0]
   tmp=getbias('viken',datum_wl[0:8],biases)

   if tmp != 0.0:
      b_viken=tmp
   del(tmp)
   wlviken=float(vst_viken[i].split()[1])+b_viken+((845.5+0.10*(yyyy-1986))*10)/10-848.6

   tmp=getbias('klagshamn',datum_wl[0:8],biases)
   if tmp != 0.0:
      b_klaga=tmp
   del(tmp)

   wlklags=float(vst.split()[1])+b_klaga+((800.4+0.06*(yyyy-1986))*10)/10-796.7
   #print wlviken, wlklags
    #Q
   if wlviken > wlklags: #            %Inflow
     print 'out'
     Dw=1.12*(wlviken-wlklags)
   else: #    outflow
     print 'in'
     Dw=wlviken-wlklags
   Q=74774.0*sqrt(abs(Dw*0.01))*sign(Dw)  #sign(Dw))
   Q_sum+=Q*3600.0  # Unit out = m^3s^-1 (kubik m. / s)

   print Q_sum
   outf.write(datum_wl+' '+str(wlviken)+' '+str(wlklags)+' '+str(Q_sum)+'\n')

outf.close()
```

Acknowledgements:

Co-operation with EU-FP7 projects MYOCEAN1 and OPERR is acknowledged.