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Abstract: Eutrophication of stream water due to nutrient inputs has become a worldwide aquatic problem. Understanding nutrient transport processes and the relationship with hydrologic processes is important for water resource management and prediction of stream water quality under climate and land use change. In this study we used the integrated process-based hydrologic and water quality model HYPE (Hydrological Predictions for the Environment) to simulate water flow and stream water nutrient concentrations (nitrogen and phosphorus) at a meso scale nested catchment (Selke) in Germany. The hydrograph was represented well with NSCE of 0.84 and was characterized by high flow during winter due to snow melting and low flow in summer. The nitrogen seasonal dynamics was caught by the model which presented a proportional relationship to water flow. The simulated phosphorus concentrations were at the similar level as the measured values which were more constant compared to nitrogen across the year. The calculated nutrient loads were 8.92 kg IN/yr/ha and 0.162 kg TP/yr/ha at the Silberhuette subbasin, which are consistent with former findings at catchments with similar hydrological pattern and land use type. However, it has to be pointed out that sparse nutrient measurements are not sufficient to fully identify the model due to inability to evaluate model performance on representation of more detailed internal variability. In future work, available high resolution multiple hydrochemical data sets will be integrated for further model identification.

Keywords: HYPE model, stream flow, nutrient transport

1   Introduction

Eutrophication of stream water by point source (e.g. wastewater treatment plant) and diffuse source (mainly from fertilizer inputs on agricultural lands) have become a main aquatic problem in many countries. It has a negative effect on economy development and also deteriorates survival environment of human being and fresh water species. Current surveys conducted in the course of the implementation of the EU-WFD suggest that 76% of the river system is unlikely or unsure to reach a good ecological status, because of high nutrient load and heavily modified river morphology (49% unlikely, 27% unsure) (Landesbericht, März 2005). Nutrient fluxes from landscapes to stream reach are complex processes involving water flow and chemical processes (Thompson et al., 2011). Different water flow pathways are main driving forces for nutrient transport. As a result, catchment characteristics, such as topography, soil type and underlying geology have great influences on runoff generation processes and affect nutrient leaching in turn. For example, more nutrients are found to be transported into streams in highly permeable soil covered land due to short residence time and low nutrient retention (Rode et al., 2009). Through altering hydrological behaviors, climate change in

terms of temperature and precipitation also affects nutrient transport and transformation processes (Bouraoui et al., 2004). Diffuse sources (e.g. fertilizer inputs in agricultural land) are main nutrient inputs, many studies have been undertaken to investigate land use impacts on river nutrient loads by running different land use scenarios (Rode et al., 2009). Soil has a storage effect on nutrient and it may take from days to years for the nutrient transporting from landscapes to the stream reaches depending on catchment hydrogeological properties. Therefore nutrient concentrations of stream water may reflect previous nutrient inputs (Howden et al., 2011). Proportional relationships between annual discharge and nutrient outputs was noticed in managed catchments and it was argued that nutrient leaching at catchments of this type is transport-limited rather than supply-limited (Basu et al., 2010).

Water quality modeling is increasingly used for investigating nutrient transport processes and prediction of river nutrient loads under change of climate and land use. Over recent years, several integrated hydrological and water quality models have been developed and applied in many catchments of different scale and characteristics, such as HBV-N (Hydrologiska Byråns Vattenbalansavdelning) (Arheimer and Brandt, 1998), SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998), SWIM (Soil and Water Integrated Model) (Krysanova et al., 2005). The large-scale project TERENO (Terrestrial Environmental Observatories) spans an Earth observation network across Germany that extends from the North German lowlands to the Bavarian Alps. It aims to catalogue the long-term ecological, social and economic impact of global change at regional level. In this project, the Bode river catchment (approx. 3300 km^2) which consists of the Harz mountainous region and lowland loess areas was chosen to study impacts of global change on hydrological regime. The Bode River is one of the best hydrological and meteorologically equipped meso-scale catchments in eastern Germany. It has 29 long term discharge gauge stations (some of them have records over 50 years) and dense precipitation and climate gauges network especially in the mountainous region (2 rain gauge stations/100km^2). Long-term river water quality data are available from regular monitoring (bi-weekly/monthly grab sampling) at 6 discharge gauge stations. Within the frame of the implementation of the Global Change Hydrological Observatory (GCO), a measurement program of high resolution water quality data is conducted at the Bode River and the data are available from 2010. The Selke catchment is an important tributary of the Bode River which is located at southeast of Bode catchment and ranges from Harz mountainous region to lowland area (Figure 1(a)). In this study we modeled water flow and nutrient concentrations of stream water at the nested Selke catchment to investigate hydrologic and nutrient processes. The objectives are to (i) evaluate the performances of a newly developed integrated processes-based water flow and water quality model HYPE (HYdrological Predictions for the Environment) on simulation of water flow and stream water nutrient concentrations (nitrogen and phosphorus); (ii) investigate nitrogen and phosphorus transport processes and their relationship with water flow.

2   Material and methods

2.1   Site Description and available data

The Selke catchment is a meso-scale, lower mountain range catchment covering an area of 463 km^2. It is a main tributary of the Bode river which is located in southwest of the state Saxony-Anhalt, Germany (see Figure 1(a)). The Selke river originates from southwest of Harz mountain and discharges into the Bode river in the northeastern lowland area. The elevation ranges from 605 to 53 m (see Figure 1(b)) and the channel slope varies from mild (<1%) in the downstream to steep (>10%) in the upstream. Land cover is dominated by forest in the mountain area and arable land in the lowland area. The shares of different land use for contributing area of each discharge gauge station are shown in Table 1. Soil type is characterized as Dystric/spodic cambisols and Stagnic gleysols in the mountain area and Haplic chernozems in the lowland area. The underlying geology of the

catchment consists of schist and claystone in the mountain area and tertiary sediments with loess soils in the lowland area. Annual precipitation varies from 450 to 1600 mm and presents substantial decrease from upstream mountain area to downstream lowland area. It is characterized by higher precipitation in summer with a ratio between summer and winter of 1.35. Mean annual temperature is 6.8ºC, with an average monthly low of -1.8 ºC in January and a high of 15.5 ºC in July.

Spatial data obtained for the catchment included a digital terrain model, digital land use data and digital soil type data. The digital terrain model was extracted from a 90×90 m digital terrain model of Germany. The digital land cover data was extracted from a 25×25 m land cover map of Germany for 2006. The digital soil type data was extracted from a 50×50 m soil map of the Bode catchment. The driving data including daily precipitation and air temperature were derived from 16 precipitation monitoring stations and 1 climate station located inside the Selke catchment. Daily discharges were derived from three gauge stations (Silberhütte, Meisdorf, and Hausneindorf, seeing Figure 1(b)). Near the discharge gauge stations Silberhütte and Meisdorf, water samples are taken bi-weekly/monthly to analyze multiple hydrochemical constitutes, such as different forms' nitrogen and phosphorus, DOC, chloride, calcium, magnesium, and sulfate etc. (see Figure 1(b)).
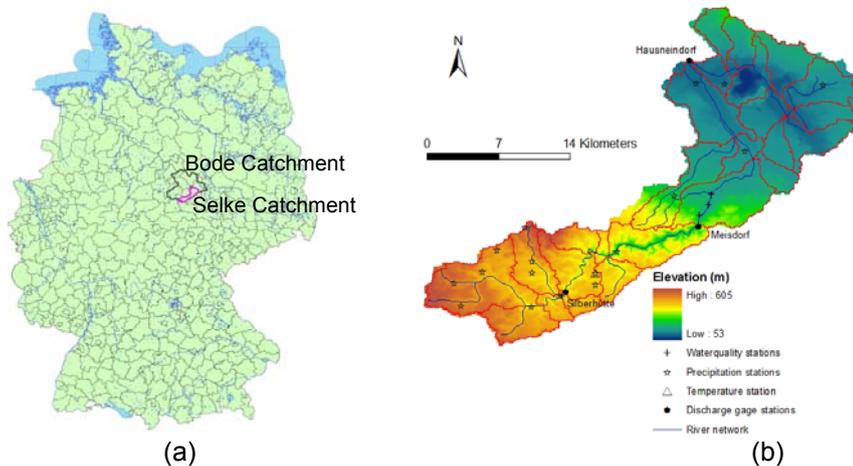

(a)   (b)

Figure 1. (a) Location of Selke catchment; (b) Map showing catchment elevation, stream network, precipitation monitoring stations, climate station, discharge gauge stations, and water quality sampling locations

Table 1. Land use shares for contributing area of each discharge gauge station

Land use	Unit	Silberhuette	Meisdorf	Hausneindorf
Arable land	%	25.3	16.9	52.3
Grassland	%	10.3	7.4	3.2
Forest	%	60.4	71.9	35.4
Settlement	%	2.4	2.4	6.0

2.2   Model description

The HYPE model (Hydrological Predictions for the Environment) was developed by Swedish Meteorological and Hydrological Institute (SMHI) during 2005-2007 (Lindström et al., 2010). It is an integrated process-oriented hydrological and water quality model which simulates stream flow, transport of nutrient (nitrogen and phosphorous), DOC, and conservative substances (e.g. $\delta^{18}O$ and chloride) on daily time step and at catchment scale. Both soil processes and in-stream processes of nutrient transport and transformations are simulated. The HYPE model was developed based on the well known hydrological model (HBV) (Lindström et al., 1997) and HBV-NP (Lindström et al., 2005). The hydrological part of HYPE has

similar model structures and process descriptions as HBV-96 precipitation-runoff model. HYPE model is similar to HBV-NP in terms of nitrogen and phosphorus simulation, which is based on HBV-96. Routines for flux and retention calculations of nitrogen (N) and phosphorus (P) were added. SWAT is widely used for water flow and water quality simulation at catchments with different characteristics. But it requires more forcing data for hydrological simulation compared to the HYPE model; groundwater entering deep aquifer is not considered in the water balance calculation. In the application of the HYPE model, the catchment is divided into subbasins based on topography and stream network. Each subbasin is divided into a number of SLC classes (Soil and Land use Combination). The model simulates hydrological and nutrient/hydrochemical processes on each SLC. The total water flow and nutrient/hydrochemical loads of each subbasin are calculated as accumulations of corresponding variables. The simulated variables at each subbasin are routed directly to the catchment outlet (Lindström et al., 2010).

As for hydrological simulation, it includes processes of snow accumulation and melt, evaporation, surface runoff (including infiltration excess runoff and saturation excess runoff), infiltration, macropore flow, percolation, runoff at each soil layer, flow from drainage pipes, and regional groundwater flow. The forcing data for hydrological simulation includes daily precipitation and air temperature for each subbasin. For nutrient simulation (nitrogen and phosphorus), various processes of nutrient flux and retention are included, comprising nutrient transport through different flow paths, crop uptake, denitrification (nitrogen), transformations between different nutrient pools, primary production, soil erosion, sedimentation/resuspention. For nutrient simulation, point source (including wastewater treatment plant and rural household) and diffuse sources, including inorganic fertilizer and manure inputs from agricultural management, plant residues, and atmospheric deposition need to be defined. The initial nutrient storages in the soil which are land use dependent, such as humus nitrogen and humus phosphorus etc. need to be defined. The detailed model concepts for hydrological and nutrient simulations and corresponding equations will not be described in detail here. For more information, please see Lindström et.al. (2010).

2.3   Model set up

For the application of HYPE at Selke catchment, the whole catchment was divided into 29 subbasins based on digital data of terrain and stream network (see Figure 1(b)). Three gauge stations (Silbehuette, Meisdorf, and Hausneindorf) were set as outlets for subbasins 28, 29, and 2 respectively. According to land use and soil type map, the Selke catchment covers 10 types of land use and 19 types of soil. 117 SLCs were defined through overlaying land use and soil type map. For hydrological simulation, daily precipitation for each subbasin was prepared using the data from the precipitation monitoring station located inside the subbasin/the most adjacent station if there is no station available inside the subbasin. It was adjusted subsequently with parameters "pcadd" and "pcelev" depending on subbasin mean elevation. Daily temperature was derived from the only available climate station and was calculated as arithmetic mean values of maximum and minimum daily values. It was adjusted subsequently with a parameter "tcalt" depending on subbasin mean elevation. For nutrient simulation, point sources consisting of outflows from wastewater treatment plant and rural households were prepared through consulting corresponding authority. The information includes measurement of daily discharge (m^3/d) and corresponding grab sampling of nutrient concentrations (IN and TP) (mg/l) of outflow. In the model, point sources are added to the main river as a volume of water and concentrations of IN and TP. They were incorporated into the relevant subbasins according to their locations. Information on diffuse sources such as agricultural practices and atmospheric deposition etc. were derived from long-term statistical data. Initial values of various parameters for hydrological and nutrient simulations were defined based on literature review and previous model applications, which were optimized in subsequent calibration steps.

Parameter sensitivity analysis helps to determine the key processes and parameters, through which we can speed up the calibration process. Local sensitivity analysis method OAT (one-at-a-time) was used in this study considering its simple application and non-linearity in the system equations and parameter interaction are not significant within the ranges of the calibrated parameters (Rode et al., 2007). According to parameter sensitivity analysis results, 3 hydrological parameters (cevp, wcfc, and lp), 4 nitrate parameters (uptsoil1, denitr, humusN, and degradhn), and 4 phosphorus parameters (humusP, degradhP, hPhalf, and freund3) were chosen for calibration. For physical meaning of each parameter, please see Lindström et.al. (2010).

As a good hydrological simulation is a prerequisite for sensible nutrient modeling, parameter calibration was carried out in a stepwise way which means first calibrating hydrological parameters and then moving to nutrient parameters. Regional calibration was applied calibrating the hydrological/nutrient parameters using measurements from all three gauge stations. Manual calibration combining with automatic optimization tool which use Brent routine optimization approach developed in the HYPE were used to calibrate the parameters. Several parameters can be calibrated at one time. The model was calibrated for the period 01.01.1994-01.01.1997 and validated for the period 01.01.1997-01.01.2000. Year 1993 was used for model warming up during the calibration process. Measured daily discharge from three gauge stations and bi-weekly/monthly sampling of nutrient concentrations (IN and TP) near discharge gauge stations Silberhuette and Meisdorf were used to calibrate hydrological and nutrient parameters.

3 Results and Discussion

3.1 Hydrological modeling

Because the HYPE model had similar performances on water flow and nutrient simulation at corresponding gauged subbasins, we present in this paper only the simulation results at subbasin Silberhuette. The modeled and observed discharge in response to precipitation for calibration period (1994-1997) and validation period (1997-2000) are shown in Figure 2. Observed hydrograph is represented very well with NSCE (Nash-Sutcliffe Coefficient) of 0.84. The modeled stream flow presented good response to the measured precipitation. Most of high flows occurred in winter due to snowmelt. Some peak flows were underestimated, of which the greatest underestimation at 13.04.1994 was noted. The high discharge was probably generated by a high rainfall event at 12.04.1994 (87.15 mm). As HYPE model calculates discharge on daily step using daily mean precipitation intensity, it can not calculate high flow precisely which is caused by intensive precipitation. The same phenomenon was found in water flow simulation at Weida catchment, Germany (Hesser et al., 2010). Other mismatches can also be due to input data uncertainties such as precipitation and temperature.
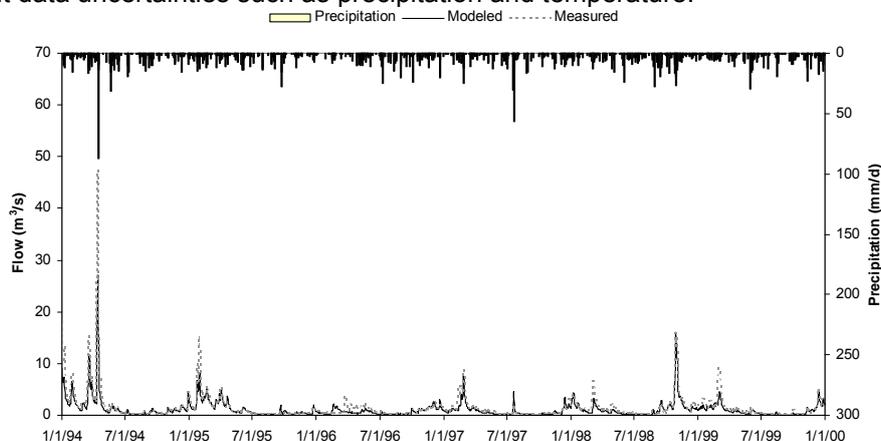

Figure 2. Observed and modeled stream flow for the calibration (1994-1997) and validation (1997-2000) periods at Silberhuette discharge gauge station

3.2 Water quality modeling

3.2.1 Nitrogen

The simulation results of IN (inorganic nitrogen) concentration for the calibration (1994-1997) and validation period (1997-2000) at subbasin Silberhuette are shown in Figure 3. The nitrogen dynamic is caught by the model during both calibration and validation periods. It shows clear seasonal dynamics which were characterized by high nitrogen concentration in winter and low concentration in summer. The reasons can be (i) high water flow in winter due to snowmelt transports more nitrogen to the stream; (ii) longer water residence time under base flow conditions and higher temperature in summer cause more denitrification to nitrogen. The large overestimation of nitrogen concentration during the period of 12.1998-05.1999 may be caused by the underestimation of discharge during this low flow period, which weakened water dilution effect. As there are no corresponding nitrogen and phosphorus measurements, discharge underestimation effects on nitrogen and phosphorus at 13.04.1994 can not be estimated properly. However, it is estimated that both nitrogen and phosphorus concentrations will be under-estimated because high discharge can transport more nutrients (especially phosphorus) to the stream during high flow event. Through calculating daily IN load, we found the HYPE model represented daily IN load dynamics very well with NSCE of 0.67 and 0.76 during calibration and validation periods respectively. The calculated mean annual IN load in the catchment (area above discharge gauge station Silberhuette) were 9.08 kg IN/ha/yr and 8.76 kg IN/ha/yr during calibration and validation periods respectively. They are in the same order as the IN load calculated in the catchment with similar catchment characteristics (Rode et al., 2009). However, it has to be pointed out that it is difficult to fully identify the water quality module with only regular sparse sampling of modeled variables as the model performances on simulation of detailed internal dynamics can not be evaluated.
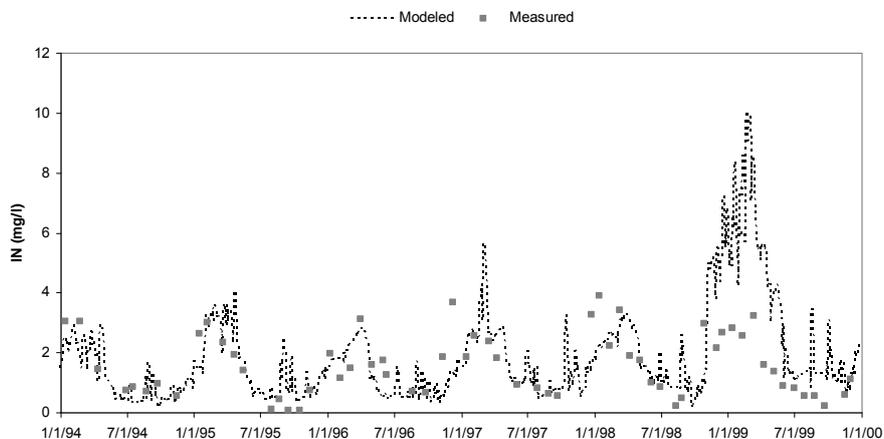

Figure 3. Observed and modeled IN for the calibration (1994-1997) and validation periods (1997-2000) at Silberhuette water quality gauge station

3.2.2 Phosphorus

The modeled total phosphorus (TP) concentrations during calibration (1994-1997) and validation (1997-2000) periods at subbasin Silberhuette were shown in Figure 4. Compared to nitrogen, phosphorus presented lower seasonal dynamics. The HYPE simulated TP concentration fairly. Overall TP was underestimated, which is due to the fact that (i) the underestimation of peak flow causes less phosphorus leaching to the stream as phosphorus was found to be mainly transported by overland flow during storm events; (ii) the underestimation of point sources from wastewater treatment plants in terms of outflow volume and nutrient

concentrations. The NSCE for daily TP load simulation is 0.50 and 0.27 during calibration (1994-1997) and validation (1997-2000) period respectively. The calculated mean annual TP load is 0.148 kg TP/ha/yr and 0.122 kg TP/ha/yr. Similar to nitrogen simulation, the sparse sampling and measurements of TP are not sufficient to fully identify the model due to inability to reveal detailed internal variability.
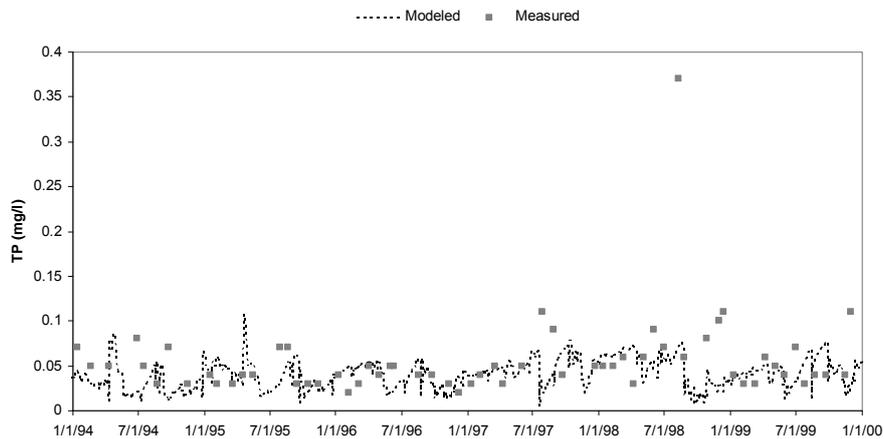

Figure 4. Observed and modeled TP for the calibration (1994-1997) and validation periods (1997-2000) at Silberhuette water quality gauge station

According to the guidelines for hydrological and water quality modeling evaluation suggested by Moriasi et.al, 2007, HYPE model simulated discharge and nutrient loads (IN and TP) of stream flow satisfactorily in terms of dynamics and water/mass balance. The calculated mean nutrient loads for subbasin Silberhuette are 8.92 kg IN/ha/yr and 0.162 kg TP/ha/yr, which are consistent with the findings of former studies for catchments with similar hydrological behavior and land use (Kronvang et al., 1995; Rode et al., 2009).

4   Conclusion

In this study, we implemented the newly developed processes-based integrated hydrological and water quality model HYPE in a meso-scale catchment. Through parameter calibration and independent model validation, we found that it simulated stream water flow, IN and TP concentrations in terms of dynamics and water/mass balances satisfactorily. IN presented proportional relationship with discharge, which both show clear seasonal dynamics characterised by high values during winter and low values during summer. TP was more constant across the year. Easily available forcing data for discharge simulation and straightforward model structures and processes descriptions make it appealing for application. Therefore HYPE is suitable to simulate water flow and water quality at both large and small catchments for process understanding and prediction purpose. A large number of input variables containing inherent uncertainties for water quality simulation and complex parameter set increase difficulties for model identification. In future work, we will use newly available high resolution water quality data for model identification and multi-objective methods for parameter calibration.

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