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Discharge and Nitrogen Transfer Modelling in the Berze River: A HYPE Setup and Calibration

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Abstract **– This study is focused on water quality and quantity modelling in the Berze River basin located in the Zemgale region of Latvia. The contributing basin area of 872 km^2 is furthermore divided into 15 sub-basins designated according to the characteristics of hydrological network and water sampling programme. The river basin of interest is a spatially complex system with agricultural land and forests as two predominant land use types. Complexity of the system reflects in the discharge intensity and diffuse pollution of nitrogen compounds into the water bodies of the river basin. The presence of urban area has an impact as the load from the existing wastewater treatment plants consist up to 76 % of the total nitrogen load in the Berze River basin. Representative data sets of land cover, agricultural field data base for crop distribution analysis, estimation of crop management, soil type map, digital elevation model, drainage conditions, network of water bodies and point sources were used for the modelling procedures. The semi-distributed hydro chemical model HYPE has a setup to simulate discharge and nitrogen transfer. In order to make the model more robust and appropriate for the current study the data sets previously stated were classified by unifying similar spatially located polygons. The data layers were overlaid and 53 hydrological response units (SLCs) were created. Agricultural land consists of 48 SLCs with the details of soils, drainage conditions, crop types, and land management practices. Manual calibration procedure was applied to improve the performance of discharge simulation. Simulated discharge values showed good agreement with the observed values with the Nash-Sutcliffe efficiency of 0.82 and bias of –6.6 %. Manual calibration of parameters related to nitrogen leakage simulation was applied to test the most sensitive parameters.**

Keywords **– Hydrological response units; HYPE model; calibration; discharge; nitrogen**

1. INTRODUCTION

Issues related to eutrophication process in inland water bodies and the Baltic Sea has become increasingly important in the last decades in national as well as in international level. Excessive leaching of plant nutrient compounds was determined as the main cause for water quality degradation [1]. It has been estimated that agriculture and forestry are the main sources of nutrient inputs (70 % to 90 %) from total diffuse source pollution [2], [3]. Overall, 74 % of total nitrogen inputs as a diffuse source pollution were caused by anthropogenic activity in Latvian conditions [4]. The objectives according to HELCOM PLC-5 [5] and the EU Nitrates directive (91/676/EEC) [6] political agenda regarding nutrient inputs into local water bodies and the Baltic Sea are to reduce or prevent eutrophication caused by nutrients from agricultural sources. In order to identify water pollution or risk of pollution from agricultural sources the threshold value for nitrate-nitrogen concentration is strictly defined by the EU Nitrates directive, hereby it is a concentration of 11.2 mg L^{-1} for nitrate-nitrogen (NO_3-N) or 50 mg L^{-1} nitrates (NO_3), respectively. The

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objectives of the present study are to build up a platform to simulate discharge and nitrogen transfer in the Berze River basin and to make it adjustable for the future studies to evaluate the impacts of changed land management practices and implementation of different agro-environmental measures.

Diffuse pollution from different types of land use, agricultural land management practices and background conditions including crop distribution, fertilization treatments, soil textures, drainage conditions as well as contribution from point sources makes the study area as a complex system [7]. Furthermore, it is challenging to evaluate the dynamics in water quality in an accurate manner by using manual grab sampling approach at the river basin scale study. Moreover, the impact of changing meteorological conditions should be taken in consideration as precipitation and evapotranspiration might have a significant effect on water balance and nutrient leaching patterns [8]. The dynamic model HYPE was chosen as a reasonable tool for the purposes of this study as it has been previously successfully applied for mesoscale river basin modelling [9]–[11].

2. MATERIALS AND METHODS

Modelling was pursued for the Berze River basin by using the dynamic model HYPE. Spatial hydro-chemical response units (SLC) were determined for modelling purposes [12]. In current setup, 53 SLC classes were designated. Those consist of a combination of the type of land use, agricultural crop, presence of tile drainage systems, and soil characteristics such as soil texture and number of soil layers. To simulate water and nutrient movement within the study basin available geospatial information was collected and analyzed including data sets of Corine Land Cover 2012 [13], agricultural field database of the Rural Support Service of Latvia [14], soil type, drainage conditions, river network and lakes, and digital elevation model with a spatial resolution of 30 meters, which was obtained from the Space Shuttle Radar Topography Mission (SRTM) [15]. Data on wastewater discharges and nutrient concentrations at the inlet and outlet was obtained from the publicly available data source of "2-Ūdens" [16] maintained by the State Limited Liability Company "Latvian Environment, Geology and Meteorology Centre" (LVGMC) and covered a time period of 2005–2014. Interviews with local farmers, regulation of the Cabinet of Ministers Nr. 834 [17] developed based on the EU Nitrates directive [6], recommendations of Latvian Rural Advisory and Training Centre [18] were used to determine the most commonly applied practices in agricultural land management. The content of residuals and nitrogen for particular crops was determined with respect to the yields obtained. The representing values were adjusted according to the IPCC 2006 guidelines [19].

Meteorological data for the period of 1961–2014 were used to force the model calculations. Meteorological conditions were determined with a daily time step for average daily temperature (°C) and total precipitation per day (mm) from the weather station located in the city of Dobele [20]. Contribution of point sources from 21 waste water treatment plants (Table 6) and information on crop management (Table 5) were included as constant values.

The total drainage area of the Berze River is 872 km^2 [7]. The Berze River basin has been furthermore divided into 15 sub-basins (Fig. 1) according to conditions of the river network and water sampling programme. Different land uses to characterize nitrogen leaching patterns, transport and source apportionment also were taken into consideration.

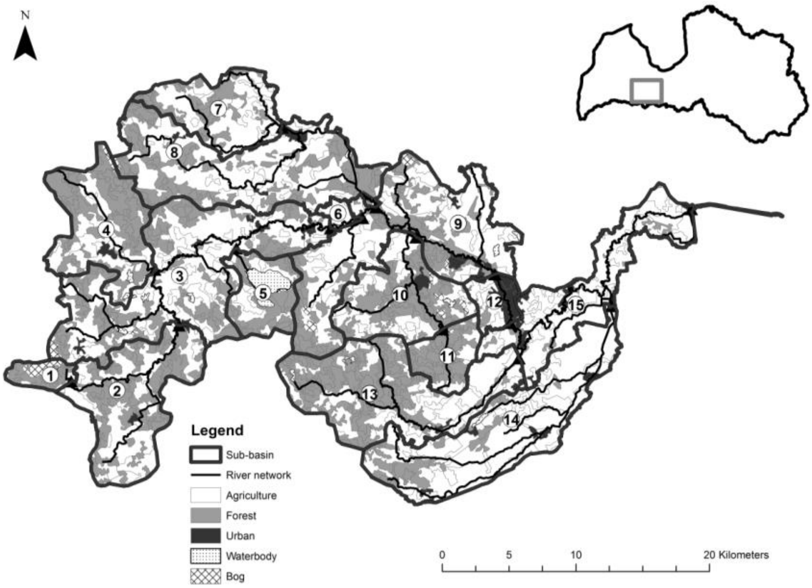

Fig. 1. The geographical location and land use of Berze River basin.

Value on the mean elevation varies from 121 m to 25 m in the uppermost sub-basin and downstream sub-basin, respectively (Table 1). The mean slope varies from 0.9 % to 2.8 % within the sub-basins studied. There are nine lakes and reservoirs in the Berze River basin [7]. For the sub-basin ID 5 two lakes (Zebrus and Svete) and for the sub-basin ID 6 water reservoir of the Annenieku hydropower plant were considered for the current study as those are larger than 5 % of the sub-basin area. Monthly grab sampling is carried out at the outlet of every sub-basin since 2005 by the Department of Environmental Engineering and Water Management of Latvia University of Agriculture. Hydrological measurements are carried out at the gauging station located at the outlet of the Berze River basin.

The HYPE is a process based model and it is applicable for hydrological and nutrient (nitrogen, phosphorus, carbon) simulations. HYPE belongs to open source community. Its code is written in the FORTRAN programming language. There is no interface invented as there can be possibilities to improve calculation methods or adapt the model for specific requirements. HYPE is a semi-distributed type of model whereas the model outputs represent conditions at outlets of sub-basins. Landscape management, soil and other information are incorporated as special response units. Those are defined as a fraction of the sub-basin area whereas there is no more specific location defined instead of grid-based models such as SWAT [21].

To run the HYPE model on a daily time step average daily time series of precipitation and temperatures should be coupled with each sub-basin. The modelling process consisted of a warm-up period (1961–2004), calibration period (2005–2010), and validation period (2011–2014) where outputs were presented on a daily basis. To evaluate the performance of simulations the following observed data sets were used: 1) monthly grab samples taken in 15 sub-basins for inorganic and total nitrogen forms; 2) average daily discharge from the gauging station located at the river outlet [20]. Manual calibration was applied to imitate physically and biochemically based processes related to hydrological and nitrogen transfers. The model performance was evaluated by the Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) and percent bias (PBIAS) in details described in the guidelines for the model evaluation [22].

TABLE 1. CHARACTERISTICS OF LANDSCAPE AND SUB-BASINS ACCORDING TO THE HYPE SETUP FOR THE BERZE RIVER

Sub-basin ID	Area, km^2	Upstream area, km^2	Main River length, km	Mean Elevation, m	Mean Elevation STD, m	Mean Slope, %	Mean Lake depth, m	Lake basin, fraction*
1	9.3	0.0	1.3	121	2.8	0.92	–	–
2	69.3	9.3	26.0	111	7.5	1.76	–	–
3	121.2	163.7	54.6	101	11.0	1.76	–	–
4	57.2	0.0	13.2	112	8.9	1.84	–	–
5	27.9	0.0	2.0	98	9.1	2.78	5	0.83
6	4.2	284.9	3.2	68	7.4	2.56	5	0.30
7	43.2	0.0	21.5	96	10.4	1.35	–	–
8	100.9	43.2	42.0	88	16.5	1.13	–	–
9	105.6	506.8	43.2	68	15.1	2.17	–	–
10	53.0	20.6	19.7	66	9.9	2.00	–	–
11	20.6	0.0	6.2	66	6.0	2.13	–	–
12	12.8	612.4	4.7	57	12.1	2.66	–	–
13	89.5	0.0	32.7	76	15.8	2.80	–	–
14	93.7	0.0	60.6	48	16.3	0.98	–	–
15	63.7	808.4	57.8	25	17.4	1.10	–	–
Basin	872.0	0.0	388.7	80.1	11.1	1.90	5	0.03

*Contributing area for lakes as a fraction of sub-basin area.

3. RESULTS AND DISCUSSION

Conditions of spatially located parameters such as land use, river network, types of soil and others are distributed on a general sub-basin scale. There are no options in the model to allocate the specific characteristics in a detail of geographical coordinates as Hype is semi-distributed model [9]. The model simulations are based on lumped data unified in hydrological response units (SLC). The SLCs are defined as a fraction for each of sub-basin.

3.1. Overview of the SLCs Determined for the Berze River Basin

Overall, 53 SLCs were created during the model setup. Each of SLCs differs based on individual features characterized in the file called GeoClas.txt. Fig. 2 provides a summary of the features included in the model setup. The apportionment of the SLCs area within every sub-basin is stored in the file called GeoData.txt. Majority of the SLCs (1 to 48) describe processes in agricultural land including arable land and grassland. All other five SLCs reflect conditions in forests, urban areas, and water bodies. The most variable feature of the SLCs representing agricultural area is crop. All together eight agricultural crops are distributed among the agricultural SLCs (1 to 48). In order to cover the model requirements for a maximum number of SLCs (99) and make the model more robust several simplifications are applied. Those are characterized in the further description of the HYPE model setup process.

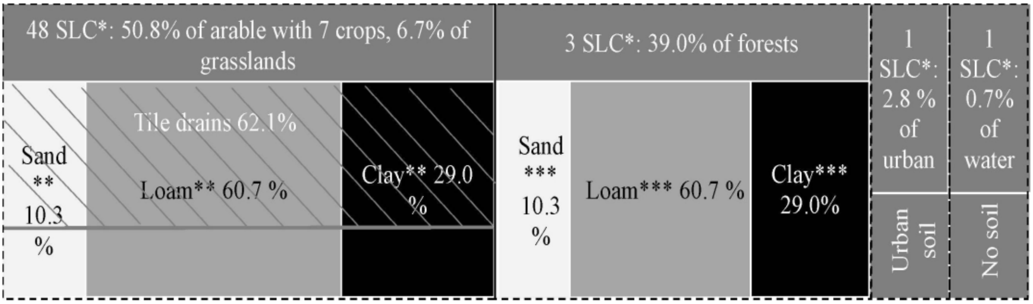

Fig. 2. Soil parameters for agricultural land and forest.

*Area given represents the share in the Berze River basin; ** Area of arable lands and grasslands; ***Area of forests.

3.2. Description of Land Use Conditions

A GIS based spatial analysis is appropriate when land-based characteristics such as land use, soils, crop distribution and other information that could be relevant for an individual case area need to be quantified. Typically geospatial information of soil and land use is processed as basic criteria [9], [12] to determine SLCs. Similar approach was used for setting up the HYPE for the Selke River basin in Germany [10], [11] and the Helge-a River basin in Sweden [23] as a part of the MIRACLE (Mediating integrated actions for sustainable ecosystems services in a changing climate) project implementation under the Bonus programme.

For the Berze River model setup a more specific approach was applied to define types of land use. More detailed geospatial data analysis was performed during the setup of SLCs for arable land and grassland. Spatial distribution of soils and tile drainage systems were overlaid on the basis of the crop distribution data provided by the agricultural field data base. According to the map of crop distribution there are 38 % of arable land and 11 % of grassland in the Berze River basin. It does not cover all the agricultural land as the agricultural field data base consists only of the areas receiving direct agricultural support payments for farmers. The area of each SLC was recalculated proportionally according to Corine Land Cover 2012 (50.8 % of arable lands and 6.7 % of grassland) to avoid any contradiction.

Furthermore, there are other contradictions in the HYPE setup as the actual land use classes and distribution of those in the Berze River basin are slightly different. All land use classes are transformed into 5 classes by unifying similar ones of 15 provided by Corine Land Cover 2012 (Table 2). Moreover, in the HYPE model for the Berze River basin only water bodies with larger contributing area than 5 % of the particular sub-basin. Inland marshes and peat bogs consisting of 1.2 % of the basin area by Corine Land Cover 2012 are not included in the model setup as those are considered as irrelevant for the current study. The area of each of the land use was recalculated proportionally to cover the area of each sub-basin and total area of the Berze River basin. The area of forest in each sub-basin was considered from the Corine Land Cover 2012. There was no analysis of soil distribution for forested areas. Soil type was assigned for forested area by using the same soil proportions as those for agricultural land (Fig. 2).

3.3. Description of Soil and Drainage Conditions

Soil type and presence of tile drainage systems is another feature represented in the individual SLC. Soil types are unified in 3 classes instead of 7 included in an original source map. These three soil classes were assigned to agricultural land and forested area (Table 3). The most wide spread soil type is loam. A unique soil type was assigned for the urban areas as there are hard surfaces covering parts of ground surface. It is likely that this leads to different hydrological conditions with respect to infiltration, overland flow, and other hydro physical conditions for the particular soil type [24]. The depths of certain soil layers are considered constant for all soil types due to lack of precise information for this purpose (Table 4). It is assumed that *tile drainage* systems are installed at an average depth of 1.2 m [25]–[27] as this corresponds to historical and present regulations defining the installation depth of tile drainage in Latvia.

TABLE 2. LAND USE

Land-use*	Code**	CLC meaning**
	112	Discontinuous urban fabric
	121	Industrial or commercial units
	132	Dump sites
	141	Green urban areas
Urban	142	Sport and leisure facilities
	211	Non-irrigated arable land
	222	Fruit trees and berry plantations
	242	Complex cultivation patterns
Arable land	243	Agriculture + natural vegetation
	311	Broad-leaved forest
	312	Coniferous forest
	313	Mixed forest
Forest	324	Transitional woodland/shrub
Grassland	231	Pastures
Water	512	Water bodies
	411	Inland marshes
Not considered	412	Peat bogs

*According to the HYPE setup for the Berze River; **According to Corine Land Cover 2012 (CLC).

TABLE 3. SOIL FOR AGRICULTURAL LANDS AND FORESTS

ID*	Name from map**	Name*	Area, %*
	Clay overlaying by sand		
	Heavy clay without stones		
1	Medium and light clay without stones	Clay	29.0
	Medium and light loam with stones		
2	Sandy loam without stones	Loam	60.7
	Organic soil		
3	Sand	Sand + organic	10.3

*According to the HYPE setup for the Berze River; **According to source map.

TABLE 4. SOIL AND DRAINAGE CONDITIONS ACCORDING TO THE HYPE SETUP FOR THE BERZE RIVER

Tile-depth, m*	Total drain-depth	Number of soil layers	Depth**1st	Depth**2nd	Depth** 3rd
0 or 1.2	2.5	3	0.0 to 0.25	0.25 to 1.0	1.0 to 2.5

*Areas with tile drainage a depth of 1.2 m is applied, zero value represents areas without tile drainage;
**Soil layer depth from the ground surface.

3.4. Description of Land Management Conditions

Land management and growing conditions for different crops are aggregated in the file called CropData.txt. The data of fertilization practice and nutrient uptake as well as nutrients accumulated in the residuals [28] is considered to be an important aspect (Table 5). All factors previously stated can have a significant effect on nitrogen loads initiated by leaching processes [29]. The amounts of nitrogen fertilizer applied were extracted from the regulation of Cabinet of Ministers determined for the nitrate vulnerable zones defined according to the EU Nitrates directive [17]. Maximum nitrogen application rates and corresponding yields were considered. The amount of phosphorus fertilizer applied for the specific crops was adjusted for the corresponding yield with the respect to methodology provided by the Ministry of Agriculture [18]. Initial land management practices, soil physical and nutrient conditions were not taken in consideration due to lack of information. The nitrogen content in residuals was adjusted from the previous studies proportionally to the crop yield in the current study. The phosphorus/nitrogen ratio was considered to be the same as it is in the residuals.

In further studies more detailed data analysis with respect to timing of fertilizer application, sowing, tillage, and harvest activities as well as specifics of organic fertilization practices could be useful. The data from the Agricultural Data Centre of Republic of Latvia could be analyzed to evaluate potential impacts of animal husbandry and manure / slurry management practices.

3.5. Description of Crop Distribution Conditions

Distribution of agricultural crops was determined based on the cropping data collected in 2014 (Table 5). Crop type 'other' unifies the crops represented by less than 4 % from the total crop area. In the current model setup the dominant crop was spring wheat.

TABLE 5. CROP MANAGEMENT AND GROWING SPECIFICS

Crop	Area*, %	Tile drained area, %	Planed yield, t	Fertilizer, kg/ha		Residuals, kg/(ha yr)			Uptake
				N_{tot}	P_{tot}	N_{tot}	P_{tot}	g**, N/(m^2 yr)	P/N ratio
Wheat Spring	21.7	24.0	>7	200	33.1	29.20	3.5	20	0.12
Wheat winter	15.3	46.4	>7	220	33.1	32.10	3.5	20	0.11
Barley spring	9.3	46.8	>7	170	34.2	26.70	3.5	20	0.13
Corn	5.9	38.4	>60	200	27.7	47.00	8.5	20	0.18
Rape spring	4.4	28.9	>4	200	48.2	7.04	4.0	20	0.57
Rape winter	7.3	42.8	>5	230	48.2	7.74	5.0	20	0.65
Gras-slands	23.4	22.6	>8	170	29.4	1.33	0.2	40	0.18
Other	12.6	12.0	...	170	27.7	7.00	1.3	20	0.18

* Percentage of the area occupied by exact crop against the total area occupied by crops;
** Default values described in the Hype manual.

It is of note that a massive damage to winter sown crops was registered during the winter of 2013. Farmers needed to resow damaged areas with alternative spring crops. It means that the data is not accurate enough to analyze a typical crop distribution on the long term basis. Furthermore, part of the spring wheat that was grown on the agricultural land without tile drainage could be the result of reseeding of damaged winter crops. This data set should be improved in further studies. In current data set the most of winter crops were sown on tile drained areas. Winter crops are vulnerable to excess moisture during the autumn and spring periods.

3.6. Description of Point Source Pollution Conditions

Point sources are another factor that might have effect on the hydro-chemical regime in the Berze River. The data are aggregated in the file called PointSourceData.txt. It is prescribed that 23 wastewater treatment plants discharge treated wastewaters in the particular sub-basins. In the model setup a constant load from each wastewater treatment plant are applied [30] including the fraction of inorganic and total nitrogen forms (Table 6). It leads to relatively higher negative impacts during the low flow seasons. Total nitrogen load from all wastewater treatment plants is 52.2 kg a day. It is 0.4 % to 76.4 % of the total nitrogen load calculated for the Berze River outlet. The water volume discharged to the river from the wastewater treatment plants are evaluated from 0.1 % to 4.3 % of the daily average discharge at the outlet of the Berze River.

TABLE 6. NITROGEN LOAD FROM THE WASTEWATER TREATMENT PLANTS IN THE BERZE RIVER, KG/DAY

Sub-basin ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
N_{tot}*	0.0	0.0	2.9	0.8	0.0	0.0	1.3	4.8	13.7	0.0	0.0	19.3	2.7	4.5	2.3	52.2
N_{tot} at the outlet**			68 to 13306													

*Total nitrogen load from the wastewater treatment plant;
**The observed total nitrogen load in the Berze River.

3.7. Calibration Procedure

Information on sub-basin area, topography, and SLCs is required for simulations with the HYPE model. In addition, characteristics of waterways and a fraction of different SLCs within a sub-basin are aggregated in the file called GeoData.txt. Parameters for hydrological and nitrogen transfer processes are separated in the model structure. However, the processes are linked together. There are more than 250 parameters defined for the calibration purposes in the HYPE model. These parameters can be used to calibrate the model performance with respect to discharge, nitrogen, phosphorus, carbon transfers as well as flood processes.

In general, several parameters are very sensitive to have a direct effect on simulated values while some parameters might not have any effect [10], [31]. For this study a manual calibration procedure was applied. A list of parameters considered to be important for simulations in the Berze River basin are presented in Fig. 3.

Hydrological parameters should be calibrated prior other constituents of interest. During the calibration of discharge a set of sensitive parameters were determined. These parameters are classified in three groups including general, land use and soil dependent parameters [9]–[12]. There is a sensitive parameter for the evapotranspiration calculation and it limits processing capabilities for all three groups of parameters, however the original HYPE evapotranspiration model was applied [32]. Similarly the recession coefficients of discharge are included in all three groups. This includes the recession of discharge in the streams, land use dependent parameters drive the overland flow, and soil dependent parameters are linked to the recession coefficients within each of three soil layers as well as tile drains.

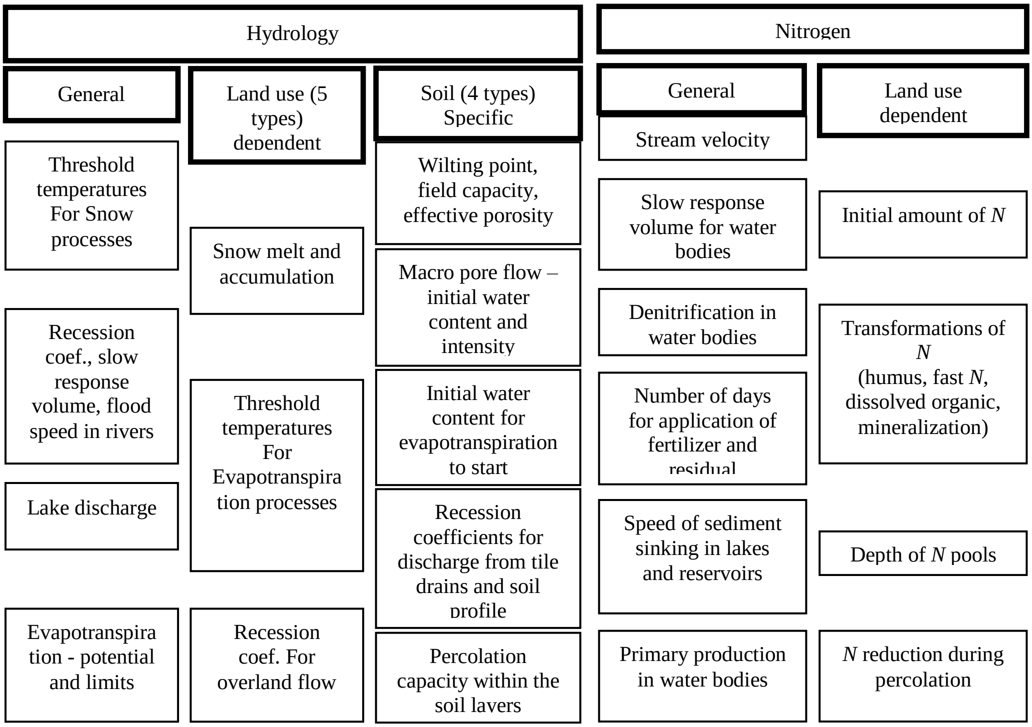

Fig. 3. Calibrated parameters selected for discharge and nitrogen simulation for the Berze River.

In Latvia, discharge is very much linked with weather conditions as snow accumulation occurs during the winter season when the long term average air temperature below 0 °C lasts from December until March for the city of Dobele [33]. In the same time snow melt is a common process during the winter as the absolute temperature maximums varies from 9.5 °C to 20.0 °C. Therefore, parameters related to snow accumulation and melt processes are considered to be important for calibration procedure. Snow melt starts when the average air temperature is above 1.0 °C in an arable lands and above 1.9 °C in forested areas in the current calibration. Sensitive soil dependent parameters should be mentioned such as field capacity and effective porosity. Those are determined as sensitive in the studies for the Selke River in Germany [10].

For nitrogen transfer processes the most sensitive parameters are those related with main water course and tributaries as well as the parameters associated with the most wide spread land uses such as arable land and forested area. Denitrification and related parameters of slow response in water volume and production/decay of nitrogen in water are the most sensitive general parameters. Transformation processes of organic matter are very sensitive land use dependent parameters. Nitrogen uptake by plants should be mentioned as well as it is considered to be a sensitive parameter in the studies for the Selke River in Germany [10].

In the Berze River basin there are seven uppermost sub-basins. These sub-basins are more suitable for calibration of nitrogen processes within land uses and local streams while other sub-basins characterize a combination of different sub-basins and processes in the main water course. Retention processes including denitrification and plant production can be calibrated for main water body and small streams.

The calibration process was finished for the hydrological regime in the Berze River. Estimated average daily discharge values with a PBIAS of –6.6 % showed lower discharge when compared with the observed values (Fig. 4). Simulated discharge results showed underestimation for the high flow periods in the autumn and spring, while discharge was overestimated for the month of February (Fig. 5). The reason for lower estimated discharge could be related with the parameters driven by evapotranspiration. Other reason could be related to occasional character of surface runoff events. The discharge underestimation in February could be associated with the impact of inaccurate snow accumulation and melt processes in different land uses. Extremely dry and wet conditions are challenging for modelling purposes [34]. Another reason for the deviations in the simulated discharge results could be related with the variability in meteorological conditions within the study basin which are not well represented in the model by only one weather station. The model outputs were driven by the precipitation and air temperature data recorded in one weather station located nearby the city of Dobele while the precipitation data from 18 weather stations were used for a similar study in the Selke River (basin area 438 km^2) in central Germany [10].

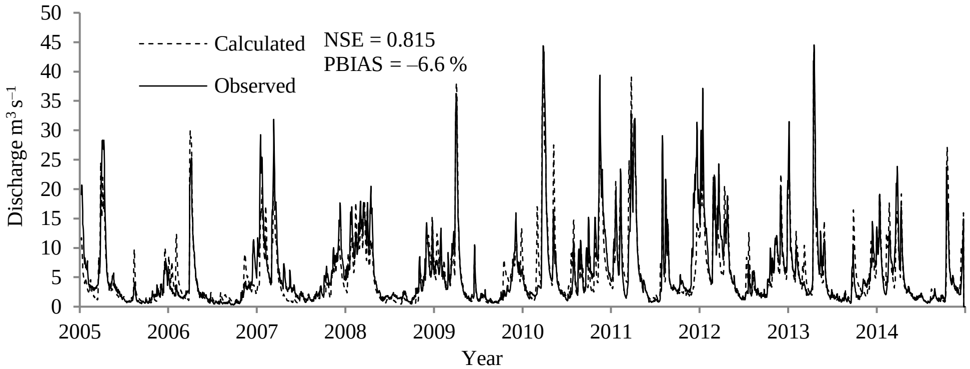

Fig. 4. Observed and calculated average daily discharge in the outlet of the Berze River during the time period of 2005–2014.

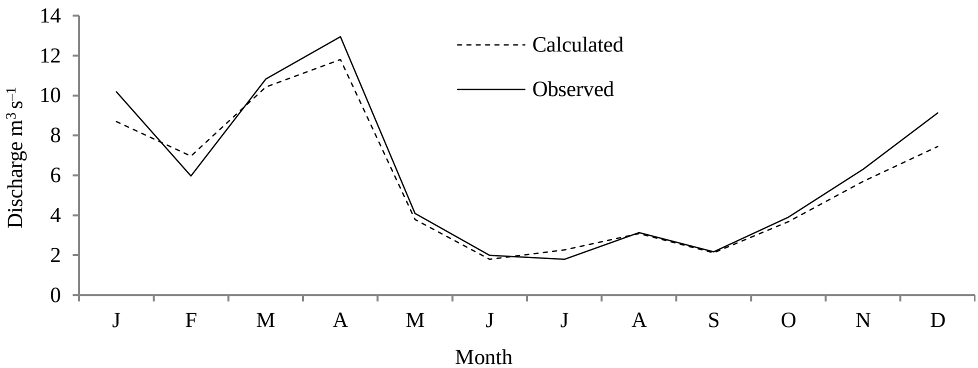

Fig. 5. Observed and calculated average monthly discharge in the outlet of the Berze River during the time period of 2005–2014.

4. Conclusion

This study approves that the Hype model can by successfully applied for the mesoscale rivers in Latvian conditions when water discharge and nutrient losses are simulated. The results of this study might be used in further research as a platform for evaluation of potential impacts of different land management practices and agro-environmental measures. The simplifications are needed to create a generalized representation of the existing environment such as unification of similar land uses and soils.

The calibration procedure showed that the most important parameters having a direct effect on simulated hydrology are related to evapotranspiration, snow accumulation and melting, soil water capacity, and recession in soils and streams. Nitrogen transfer simulation is affected by general and land use dependent parameters such as denitrification and nitrogen transformation in soil and water.

For further improvements long term crop distribution, precise amounts of fertilizers applied, and increased number of meteorological and hydrological stations should be considered.

A further recommendation is suggesting that modelling should be a key component of river basin management systems. This allows the assessment of management actions that are difficult to quantify through environmental monitoring linking the basin-scale evaluation of pollution sources with the effects of implemented management changes.

The Baltic Sea countries according the HELCOM decisions are obligated to reduce nitrogen and phosphorus loads to the sea. Comprehensive models have not been widely applied in Latvia to calculate reduction of nitrogen and phosphorus loads for different scale river basins according to current environmental targets.

Acknowledgement

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