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Development of a hydrology and water quality model for a large transboundary river watershed to investigate the impacts of climate change – A SWAT application

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ABSTRACT

The aim of this study is to assess a different approach of SWAT model setup with enhanced Hydrologic Response Unit (HRU) definition procedure. The method uses a set of customizable MATLAB scripts (hence, SWAT-LAB) to produce HRUs from a combination of topographic, soil, landuse and administrative unit rasterized datasets. We used this approach to setup, run and calibrate a large-scale transboundary Nemunas River model, consisting of eleven sub-models. Nemunas River is the major contributory that discharges into the Curonian Lagoon, which is the largest European coastal lagoon. Belarus, Lithuania, Poland and the Russian Federation Kaliningrad Oblast share Nemunas River basin area. The basin is experiencing nutrient load from different sources in the riparian countries, nevertheless, the burden of improving the water quality of the river falls mainly on Lithuania. This article focuses on assessing the practicability of SWAT-LAB for creating a high-resolution large-scale transboundary hydrological and water quality model, where data availability is limited and fragmented. We demonstrate the model performance on a case study of one of the Nemunas River tributaries: Neris or Vilija River basin, which is situated largely in the Republic of Belarus. Model performance was evaluated graphically, using hydrographs and percent exceedance curves, and quantified using coefficient of determination (R^2) and Nash–Sutcliffe efficiency (NS). We achieved good model performance for monthly (calibration $R^2 = 0.80$, NS = 0.83; validation $R^2 = 0.80$, NS = 0.76) and daily (calibration $R^2 = 0.66$, NS = 0.66; validation $R^2 = 0.67$, NS = 0.66) flow. Satisfactory performance results were achieved in modeling monthly loads of suspended sediments (calibration $R^2 = 0.4$, NS = 0.44; validation $R^2 = 0.58$, NS = 0.34), total phosphorus (calibration $R^2 = 0.71$, NS = 0.61; validation $R^2 = 0.53$, NS = 0.56) and total nitrogen (calibration $R^2 = 0.55$, NS = 0.42; validation $R^2 = 0.48$, NS = 0.4). Furthermore, we use the model to assess possible future nutrient loads that could be transported from Belarus to Lithuania under two climate change scenarios (RCP 4.5 and 8.5) and present the results.

1. Introduction

The Curonian Lagoon, the largest coastal lagoon in the Baltic Sea and Europe as well, is facing severe eutrophication problem. Due to vast land use for agriculture and point source pollution, the amount of nutrients that enter the lagoon thru the rivers is substantial, which in turn is the main cause of the observed plumes. HELCOM Baltic Sea Action Plan (BSAP) is an ambitious program to restore the good ecological status of the Baltic marine environment by 2021 (HELCOM Ministerial Meeting, 2007). The Plan was adopted by all the Baltic coastal states and the EU in 2007. The vision of this plan is a healthy Baltic Sea environment, with diverse biological components functioning in balance, resulting in good environmental/ecological status and supporting a wide range of sustainable human economies and social activities (HELCOM Ministerial Meeting, 2007).

To reduce the eutrophication in the Baltic Sea, a Nutrient Reduction Scheme was adopted by the HELCOM member states (Bartnicki and Benedictow, 2017). HELCOM Nutrient Reduction Scheme is a regional approach of sharing the burden of nutrient reductions to achieve the goal of the Baltic Sea unaffected by eutrophication agreed by the Baltic

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Table 1
Country Allocated Reduction Targets for pollution from both land and air, in tons, agreed in 2013.

	Nitrogen	Phosphorus
Denmark	2890	38
Estonia	1800	320
Finland	2430 + 600*	330 + 26*
Germany	7170 + 500*	110 + 60*
Latvia	1670	220
Lithuania	8970	1470
Poland	43,610	7480
Russia	10,380*	3790*
Sweden	9240	530

Sea countries.

According to the Nutrient Reduction Scheme (Table 1), Lithuania has to achieve a reduction of Nitrogen input of 8970 tons, and Phosphorus – 1470 tons (Bartnicki and Benedictow, 2017). Up to this point, (May-2018) Lithuania has yet to make sufficient progress in land and fertilization management, nutrient recycling and rural water management to achieve substantial reduction for nutrients leeching thru the rivers into the Curonian Lagoon and subsequently – to the Baltic Sea. After the latest HELCOM ministerial meeting in Brussels (6th of March 2018) (Baltic Marine Environment Protection Commission, 2018), it became clear that the set nutrient reduction targets cant' be achieved with the current progress, so strengthening the implementation of the Baltic Sea Action Plan by 2021 was set as a top priority and includes adjusting the BSAP based on new knowledge and future challenges. Our conducted study aims to contribute to this endeavor, and provide more insight about the nutrient loads in one of the Baltic Sea subbasins – the Nemunas River basin.

Nemunas River is one of the biggest river systems in the eastern part of the Baltic Sea and the largest river in Lithuania, which contributes the most in terms of water, sediments and nutrients to the Curonian Lagoon. More than 90% of water and nutrient input to the Lagoon is provided by the Nemunas River (Pilipchuk et al., 2014). The rivers watershed is shared by Lithuania, Belarus, Poland and Russian Federation Kaliningrad oblast.

Several hydrological models (HBV, MIKE, etc.) were applied to the Nemunas River basin in different studies (Kriaučiunienė et al., 2008; Rimkus and Vaikasas, 2012; Stonevičius et al., 2017; Stuopis et al., 2010), assessing impact of different stressors on the system. SWAT (Soil and Water Assessment Tool) is used by Lithuania's Environmental Protection Agency in the development of methodic and modelling system of nitrogen and phosphorus load calculation for surface waters of Lithuania. However, none of the previous studies covered the entire Nemunas River watershed in assessing sediment and nutrient calculations.

To correctly identify the hydrologic regime in the watershed, a basin-scale model with sufficient accuracy was developed in previous studies (Čerkasova et al., 2016). This model was used to assess possible changes in the hydrologic regime of the Nemunas and Minija Rivers in the light of near-term climate projections derived from the IPCC AR5. It was found that the watershed system is sensitive to climate change and can lead to possible shifts in the hydrologic regime. As a continuation of previous studies, the Nemunas watershed model had to be updated to include nutrient transport in the system. A more detail representation of the watershed is needed to be able to simulate land management practices of different countries and different administrative units within the countries' subbasins.

One of the challenges of this study is that the upper river basins (48% of the total watershed area) are situated in Belarus, which is not an EU nor HELCOM member, thus data interchange between Lithuania and Belarus is very poor. On the other hand, National Statistical Committee of the Republic of Belarus releases official statistics of macroeconomic and environment, which is publicly available (National Statistical Committee of the Republic of Belarus, 2017). The National Statistical Committee uses administrative units as a basic cell for data gathering, so the majority of statistical data (like crop-yield, forestry, land management, fertilization, etc.) is available on an administrative unit level. This is an important issue for the hydrological and water quality model development, since usage of standard available modeling tools does not allow direct incorporation of administrative units. Thus, an advanced version of SWAT model setup was developed and used to produce Hydrologic Response Units (HRUs) which incorporate data from not only slope, landuse and soil data, but also the administrative unit grid, providing the flexibility to derive common fertilization practices, land management and crop yields with sufficient precision based on publicly available statistical data.

2. Data and methods

2.1. Model setup method

Some limitations and drawbacks of the standard model setup tools like ArcSWAT, MWSWAT, QSWAT ("ArcSWAT|Soil and Water Assessment Tool," 2012, "MWSWAT|Soil and Water Assessment Tool," 2012; Dile et al., 2017) were the main motivators for creating a different method for SWAT setup. As stated previously, SWAT is a comprehensive model requiring hundreds of model inputs for hydrological parametrization and watershed description some of which also vary according to land use and soil attributes. SWAT operates on text-based inputs only, the preparation of which manually would be an unproductive and cumbersome task. The details of SWAT input files are given by Arnold et al. (2012).

To ease the difficult task, numerous software tools (Danile, 2013; Dile et al., 2016; George and Leon, 2008; Olivera et al., 2006; Rathjens and Oppelt, 2012; Trotochaud, 2014; Wu and Liu, 2014, 2012) were developed for complete or partial SWAT input data set generation. Some of these software tools are GIS based and supported by form-based graphical user interfaces ("ArcSWAT|Soil and Water Assessment Tool," 2012; Dile et al., 2017; George and Leon, 2008), whereas others are based on scripting languages (such as Python or R).

The GIS/GUI based SWAT model input set generators are easier to use, however they are preprogrammed to specific datasets to generate a default SWAT parametrization. Some allow the usage of a lookup table for different and non-standard pixel values in user-supplied grids; however, the SWAT database table integrated into those user interfaces cause some limitations and are not always easy to extend.

Script based SWAT input set generators are relatively difficult to use and even more difficult to learn, but are more flexible in terms of automatic data generation (the user is not obliged to sit in front of a computer and do a mouse-click intensive input editing job) and even programmable to some extend (for example it may be possible to use "if" clauses when a specific condition related to data-layer combination is encountered) either directly or by modifying the underlying scripts.

In this study we chose to develop a script based SWAT input generator coded in MATLAB (hence, SWAT-LAB). The reasons for choosing a script-based approach for this study are listed below:

- European community based field database (such as CORINE, etc.) are not available for the entire case study area;
- Field data such as land-use and soil had to be compiled from many different sources and standard GIS preprocessing techniques were not sufficient in a practical manner;
- Nutrient emission based data were available based on administrative boundaries rather than sub-watersheds so in order to distribute the emissions on SWAT-HRUS, HRUs needed to be based on administrative units as well.

We chose MATLAB as the main development platform because: