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ORIGINAL RESEARCH ARTICLE

Curonian Lagoon drainage basin modelling and assessment of climate change impact☆

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Summary The Curonian Lagoon, which is the largest European coastal lagoon with a surface area of 1578 km^2 and a drainage area of 100,458 km^2, is facing a severe eutrophication problem. With its increasing water management difficulties, the need for a sophisticated hydrological model of the Curonian Lagoon's drainage area arose, in order to assess possible changes resulting from local and global processes. In this study, we developed and calibrated a sophisticated hydrological model with the required accuracy, as an initial step for the future development of a modelling framework that aims to correctly predict the movement of pesticides, sediments or nutrients, and to evaluate water-management practices. The Soil and Water Assessment Tool was used to implement a model of the study area and to assess the impact of climate-change scenarios on the run-off of the Nemunas River and the Minija River, which are located in the Curonian Lagoons drainage basin. The models calibration and validation were performed using monthly streamflow data, and evaluated using the coefficient of determination (R^2) and the Nash-Sutcliffe model efficiency coefficient (*NSE*). The calculated values of the R^2 and *NSE* for the Nemunas and Minija Rivers stations were 0.81 and 0.79 for the calibration, and 0.679 and 0.602 for the validation period. Two potential climate-change scenarios were developed within the general

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patterns of near-term climate projections, as defined by the Intergovernmental Panel on Climate Change Fifth Assessment Report: both pessimistic (substantial changes in precipitation and temperature) and optimistic (insubstantial changes in precipitation and temperature). Both simulations produce similar general patterns in river-discharge change: a strong increase (up to 22%) in the winter months, especially in February, a decrease during the spring (up to 10%) and summer (up to 18%), and a slight increase during the autumn (up to 10%).

1. Introduction

The Curonian Lagoon is located at N 55°30′ latitude and E 21°15′ longitude. It is the largest European coastal lagoon, separated from the Baltic Sea by a narrow 0.5—4 km wide sandy Curonian spit and connected to the Baltic Sea through the Klaipeda Strait. Several small rivers — such as the Bolshaya and Malaya Morianka, Kalinovka, Deima, Rybnaya, Minija, Dane and Dreverna — and one large river (Nemunas) discharge into the Curonian Lagoon. The southern and central parts of the lagoon contain fresh water due to the discharge from those rivers. The run-off of rivers to the lagoon varies from 14 to 33 km^3 per year (444 m^3 s^{-1} to 1046 m^3 s^{-1}) and exhibits a strong seasonal pattern, peaking with snowmelt during the flood season of March to April (Dubra and Červinskas, 1968).

The area of land draining into the Curonian Lagoon covers 100,458 km^2, of which 48% lies in Belarus, 46% in Lithuania, and 6% in the Kaliningrad Oblast and Poland (Gailiušis et al., 1992) (see Fig. 1). The drainage area of the Curonian Lagoon consists of several river basins; however, the most important of them is the Nemunas River drainage basin in terms of flow rates and nutrient inputs, supplying about 98% of its inflows (Jakimavičius, 2012). The annual Nemunas River water inflow into the Curonian Lagoon is more than three times greater than the volume of water in the lagoon (Žilinskas et al., 2012). According to researchers, the average annual run-off during 1812 to 2002 was 22.054 km^3 (699 m^3 s^{-1}) (Gailiušis et al., 1992), and from 1960 to 2007 it was 21.847 km^3 (692 m^3 s^{-1}) (Jakimavičius and Kovalenkovienė, 2010). As a result, the lagoon's water level is usually higher than that of the Baltic Sea; therefore, the dominant currents are from the lagoon to the Baltic Sea.

Figure 1 Curonian Lagoon drainage area.

Over the years, the water discharge to the lagoon changed, and this led to a fluctuation of the water balance. Major changes have been observed in the last decade in the winter—spring period. In the winter months of January and February, due to observed warmer winters, the Nemunas' run-off has increased, while spring floods are decreasing; therefore, run-off levels over the year became more homogeneous (Žilinskas et al., 2012).

Agriculture has a significant impact on the status of water bodies in the Nemunas River basin, especially in the sub-basins of the Sesupe and Nevezis Rivers; this factor has a local, but serious, impact. Chemicals that enter the river from agriculture and fishponds are a major source of pollution. A substantial proportion of point-source pollution comes from industry. According to the Second Assessment of Transboundary Rivers, Lakes and Groundwaters by the United Nations Economic Commission for Europe (2011), there is room for development in the monitoring of the Nemunas River, as the current list of monitored pollutants is limited. There is a lack of biological observation and monitoring of pollutants in river-bottom sediments, and a joint, harmonized monitoring programme for the transboundary watercourses is needed. It is important to develop a model for nutrient and other biogeochemically significant dissolved-substance contributions that are altering and influencing the ecosystems of the Nemunas River and Curonian Lagoon.

The first step is the development of a hydrological model and analysis of changes in the Curonian Lagoon drainage basin due to global processes (climate change, etc.), as well as local anthropogenic activities, and forecasting possible changes in the future. Model hydrology calibration, uncertainty analysis and sensitivity analysis enables a broader understanding of key processes in the catchment area. Recent work conducted in the field of Curonian Lagoon drainage basin modelling is reported in the doctoral dissertation "Changes of water balance elements of the Curonian Lagoon and their forecast due to anthropogenic and natural factors" by Jakimavičius (2012). In this work, the author had created hydrological models for the separate Nemunas catchment areas using HBV (Hydrologiska Byråns Vattenbalansavdelning), before calibrating and validating them. The sensitivity and uncertainty of the Nemunas run-off model parameters were assessed using the SUSA (Software for Uncertainty and Sensitivity Analyses) package. Hydrometeorological information of the period 1961—1990 was used for the model's creation. The period 1961—1975 was selected for the model's calibration, whereas the period 1976—1990 was used for its validation. Prognostic data from 14 measurement stations, data from 1961 to 1990 and the downscaling method were applied to calculate the daily mean data from the mean monthly output data of climate-change scenarios. In this way, obtained prognostic values of precipitation and temperature data were used to simulate the Nemunas' inflow and to compute its water balance (Jakimavičius, 2012).

Projections of the temperature and precipitation of the Nemunas' river basin for the 21st century (according to conclusions of the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change, as well as the results of output data of ECHAM5 and HadCM3 global climate models under A2, A1B and B1 greenhouse gas emission scenarios) were used to create the climate-change scenarios. These data were used to compute the Nemunas' inflow to the lagoon during 2011—2100, the amount of precipitation entering the lagoon and water evaporation from the lagoon's surface (Jakimavičius, 2012).

The study conducted by Jakimavičius (2012) is quite comprehensive; however, it lacks some key points. The research mainly focuses on the changes of water-balance elements of the Curonian Lagoon, such as the Nemunas River's inflow to the lagoon, and the water exchange between the Baltic Sea and the Curonian Lagoon, with no focus on the smaller rivers', such as the Minija, run-off change. The precipitation amount used covered only the territory of Lithuania. The selected baseline period is outdated and does not fully represent the current conditions of the catchment area. The climate change scenarios covered the precipitation amount and temperature change, with no change to the relative humidity.

The SWAT (Soil and Water Assessment Tool) model is also used by Lithuania's Ministry of Environment in development of a method and modelling system for nitrogen and phosphorus load-calculation for the surface waters of Lithuania (ELLE and PAIC, 2012). The model covers only the territory of Lithuania, which is divided into more than 1200 sub-basins. The developed model uses high-resolution DEM (Digital Elevation Model), soil and land-use data layers in order to create Hydrologic Response Units (HRUs) with a resolution of 5 m × 5 m; therefore, the model's accuracy and predictive capability is reduced. Overall, the model's Nash-Sutcliffe efficiency coefficient (*NSE*) performance for the monthly median flow is 0.5. The model is primarily used for the development of methods and tools for multi-objective spatial optimization, and structural agriculture-change scenario assessments. With additional model set-up corrections and a more thorough calibration, this model can become state-of-the-art for Lithuania's territory; however, it is not open access, is unavailable for usage outside of the Lithuanian Environmental Protection Agency and results have not yet been published in peer-reviewed journals. These facts led to the necessity of producing a more flexible tool for analysing and predicting hydrological and biogeochemical cycles of the Curonian Lagoon's drainage basin. In addition, the created model could allow the exchange of modelling results and benefit development of large-scale modelling systems.

2. Material and methods

The Curonian Lagoon drainage basin model was set up using the SWAT: a physically based, continuous-time catchment model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged drainage areas (Arnold et al., 1993).

The drainage basin area was divided into multiple subbasins, which were then further subdivided into Hydrological Response Units that consist of homogeneous land-use, management and soil characteristics (Arnold et al., 1993). Using the SWAT, run-off was predicted for each HRU separately and routed to obtain the total run-off of a catchment area. This solution improves the model's accuracy and provides a much better physical description of the water balance (Neitsch et al., 2011).

A stable version of the SWAT from 2009 was used due to the fact that additional extensions and extra tools are available for this version, and also because this version has undergone much testing and correction.

For the calibration of the Curonian Lagoon drainage basin model, the SWAT-CUP (Soil and Water Assessment Tool Calibration and Uncertainty Programs) semi-automated SUFI-2 method (Sequential Uncertainty Fitting, version 2) was applied, as it is most commonly used, well-documented method, and is reported to produce satisfactory results (Arnold et al., 2012). Model calibration and validation were performed using monthly streamflow data.

Several publications (Arnold et al., 2012; Balascio et al., 1998; Moriasi et al., 2007) have examined the usage of different model-evaluation statistics; however, not many of them provide directions or advice on using acceptable ranges of values for these performance indicators. Some of the guidelines suggest using the *NSE* and the coefficient of determination (R^2), in addition to graphical techniques (Moriasi et al., 2007). Suggested guidelines were followed, and the Curonian Lagoon's drainage basin model was evaluated according to them.

2.1. SWAT model description and features

The development of the SWAT is a continuation of the United States Department of Agriculture Agricultural Research Service (USDA-ARS), a modelling experience that spans a period of roughly 30 years. The current SWAT model is a direct descendant of the Simulator for Water Resources in Rural Basins (SWRRB) model, which was designed to simulate management impacts on water and sediment movement for ungauged rural basins across the U.S. (Arnold et al., 2010). The SWAT has experienced constant reviews and an extension of its functionality since it was created in the early 1990s. The most significant improvements are listed in the official SWAT theoretical documentation (Neitsch et al., 2011) and include the following: incorporation of multiple HRUs, auto-fertilization and auto-irrigation management options, incorporation of the canopy storage of water, the Penman-Monteith potential evapotranspiration equation, instream water quality equations, improvement of snow melt routines, nutrient cycling routines, rice and wetland routines, bacteria transport routines, Green and Ampt infiltration, weather generator improvements and many other factors. The incorporation of the Curve Number (CN) method and non-spatial HRUs allow adaptation of the model to virtually any drainage basin with a wide variety of hydrological conditions (Gassman et al., 2007). Simulation of the hydrology of a catchment area can be separated into two major points:

1. Land phase of the hydrological cycle: the amount of water, nutrient, sediment and pesticide loadings in the main channel in each sub-basin.
2. Water or routing phase of the hydrological cycle: the movement of water, sediments, etc., through the channel network of the drainage area to the outlet (Neitsch et al., 2011).

The hydrologic cycle simulated by SWAT is based on the water balance equation:

$$SW_{t+1t} = SW_{t0} + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}), \quad (1)$$

where SW_{t+1t} is the final soil water content at day t [mm H_2O], SW_{t0} the initial soil water content, R_{day} the amount of precipitation on day t [mm H_2O], Q_{surf} the amount of surface runoff on day t [mm H_2O], E_a the amount of evapotranspiration on day t [mm H_2O], w_{seep} the amount of water entering vadose zone from the soil profile on day t [mm H_2O], and Q_{gw} is the amount of return flow on day t [mm H_2O].

2.2. Model set-up and data

There are four main data sets that were used in the SWAT set-up:

1. Digital Elevation Model (DEM) data;
2. Land-use data;
3. Soil data;
4. Weather data.

There are many more optional datasets that can be used as inputs for the SWAT.

2.2.1. DEM

DEM data were obtained from the Consortium for Spatial Information (CGIAR-CSI) database (CGIAR — Consortium for Spatial Information, accessed: February 2014) based on the SRTM (Space Radar Topographic Mission) survey data provided by NASA (National Aeronautics and Space Administration) dating back to 2001. The resolution of the DEM is 51 m × 51 m. To use this DEM in the SWAT, the grid size had to be changed to a coarser resolution. This decision is based on studies of the DEM's resolution effects on the SWAT's output. Studies showed that run-off had little or no sensitivity to the resampled resolution, and the minimum DEM resolution should range from 100 m to 200 m in order to achieve a less than 10% error rate in the SWAT's output for flow, NO_3-N and total P predictions (Chaubey et al., 2005; Ghaffari, 2011; Lin et al., 2010). A coarser resolution results in a decrease of the computational needs by up to three times during model's set-up and run phases. The DEM grids were resampled to a size of 153 m x 153 m, which is within the recommended range (Chaubey et al., 2005).

Table 1 Land use type occurrence in the Curonian Lagoon drainage basin area.

Nr.	Class label	Land use type	Area [% of total]
1	CRWO	Cropland/woodland mosaic	64
2	CRDY	Dryland cropland and pasture	23
3	FOMI	Mixed forest	6
4	CRGR	Cropland/grassland mosaic	3
5	WATB	Water bodies	2
6	FOEN	Evergreen needleleaf forest	2
7	FODB	Deciduous broadleaf forest	1
8	URMD	Residential medium density	<1
9	GRAS	Grassland	<1
10	FODN	Deciduous needleleaf forest	<1
11	CRIR	Irrigated cropland and pasture	<1
12	TUWO	Wooded tundra	<1
13	SHRB	Shrubland	<1

2.2.2. Land-use data

Land-use data were acquired from the WaterBase project database (United Nations University, accessed: November 2014) based on the FAO's (Food and Agriculture Organization of the United Nations) land-use data. There are 13 classes of land-use types in the study area, which correspond to the ones used in the SWAT database (Table 1). The most dominant type of land-use in the area is CRWO (covering 64% of the study area), which is the abbreviation for "cropland, woodland mosaic", followed by CRDY (23%) — "dryland, cropland and pasture" and FOMI (6%) — "mixed forest". The information required to simulate plant growth is stored in the SWAT plant-growth database file according to plant species. The SWAT uses a plant-growing cycle in order to determine how much water is consumed by the canopy, and how much can be stored and released by it. The model takes into account growing seasons, harvesting and other parameters, which can be specified or modified by the user during the model's set-up stage.

2.2.3. Soil data

Soil data were acquired from the WaterBase project database of United Nations University (accessed: November 2014). Twenty-six classes of soil are present in the study area, which correspond to the ones used in the SWAT database (Table 2). Soil-class characteristics can be determined in the same way as for land-use classes, by using a database that is implemented in the tool, which contains the most common soil types and their properties.

Soil data used by the SWAT can be divided into two groups: physical characteristics and chemical characteristics. Physical properties of the soil govern the movement of water and air through the soil's profile, and have a major impact on the cycling of water within the HRU, whereas inputs for chemical characteristics are used to set the initial levels of chemicals that are present in the soil (Neitsch et al., 2011). Physical properties for each soil type are necessary for use of the model, while chemical ones are optional. The most widely presented soil layer in the study area is De18-2a-3049 (33%), which is categorized as "loam", followed by Gm32-2-3a-3074 (10%) and Lg55-1a-31993199 (9%), which are "clay loam" and "sandy loam" respectively.

Table 2 Soil class occurrence in the Curonian Lagoon drainage basin area.

Nr.	Class label	Soil texture	Area [% of total]
1	De18-2a-3049	LOAM	33
2	Gm32-2-3a-3074	CLAY_LOAM	10
3	Lg55-1a-3199	SANDY_LOAM	9
4	De20-2ab-3052	LOAM	8
5	De18-1a-3048	SANDY_LOAM	6
6	De17-1-2a-3047	SANDY_LOAM	4
7	Pl5-1ab-3236	LOAMY_SAND	4
8	Lo78-1-2a-3204	SANDY_LOAM	3
9	Be144-2-3-3019	CLAY_LOAM	3
10	Dg5-1ab-3055	SANDY_LOAM	3
11	Dd8-1ab-3045	SANDY_LOAM	2
12	De13-1ab-3046	SANDY_LOAM	2
13	De19-1a-3050	SANDY_LOAM	2
14	De19-2a-3051	SANDY_LOAM	1
15	Je87-2-3a-3149	CLAY_LOAM	1
16	Lg41-2-3a-3194	LOAM	1
17	Lg43-2ab-3196	SANDY_LOAM	1
18	Lo69-2ab-3201	LOAM	1
19	Od22-a-3217	LOAM	1
20	Oe14-a-3223	LOAM	1
21	Pl5-1ab-3236	LOAMY_SAND	<1
22	Po30-1ab-3239	SANDY_LOAM	<1
23	Be126-2-3-6436	LOAM	<1
24	Lo79-2a-6572	LOAM	<1
25	Lo81-1a-6574	SANDY_LOAM	<1
26	Qc62-1a-6623	SAND	<1

2.2.4. Weather data

Historical weather data are usually gathered and archived by the countries' meteorological services. In Lithuania, such data are available from the Lithuanian Hydrometeorological Service, under the Ministry of Environment of the Republic of Lithuania (LHMS). However, the study area covers not only the territory of Lithuania, but also Kaliningrad Oblast and Belarus, meaning that data had to be acquired from global public resources. The weather data were acquired through Global Weather Data for the SWAT service (National Centers for Environmental Prediction, Accessed: November 2014). It provides data for the 35-year period between 1979 and 2014. The service allows the downloading of daily data for precipitation, wind, relative humidity and solar radiation in the SWAT's file format for a given location and time period. Weather data used for the Curonian Lagoon drainage basin model covered a period of 16 years, from 1995 to 2010; the first five years' data (1995—1999) were used for the model's warm-up stage, whereas the remaining data were used for the model's set-up, calibration and validation.

2.2.5. Observed data

The observed run-off data files had to be prepared for the model's output analysis and calibration. The available observed data were for two river discharges: Nemunas, near Smalininkai, and Minija, near Lankupiai (Fig. 2). The data files present the daily time series over 11 years (2000—2010) for measured discharges in $m^3\ s^{-1}$. These data were provided by the Klaipeda University Coastal Research and Planning Institute (KU CORPI).

2.2.6. Sub-basin set-up

The study area was delineated using the MapWindow Terrain Analysis Using Digital Elevation Models (TauDEM) tool, following the specification of the threshold drainage area, which is the minimum drainage area required to form the origin of the stream, and identification of the drainage basin outlets. The accuracy of the delineation process was influenced by the DEM's resolution. Several iterations were performed with different delineation threshold-values, thus creating models with different numbers of sub-basins. Each model's initial output performance was tested in order to analyse the delineation threshold-value's influence on its predictive flow capabilities. As a result, a total of 117 sub-basins were produced, which proved to be the best performing number of sub-basins for this study. Multiple HRUs were then created automatically with the MapWindow SWAT plug-in within each sub-basin, as a function of the dominant land-use and soil types.

2.3. Calibration procedure

The available period of observation data (2000—2010) was divided into the two groups of 2000—2007 for calibration and 2008—2010 for validation; this supplies a period of 8 years for calibration and 3 years for validation.

Various studies have reported different input parameters used in the SWAT model's calibration. Table 3 summarizes the most frequently used parameters in various studies (Abbaspour, 2011; Arnold et al., 2012). As the SWAT is a comprehensive model that simulates process interactions, many parameters will impact multiple processes. For instance, CN (Curve Number) directly impacts surface run-off; however, as surface run-off changes, all components of the hydrological balance change. The described feature is the primary reason for calibrating the model starting with the hydrological balance and streamflow, then moving to sediment and, finally, calibrating nutrients and pesticides (Arnold et al., 2012). All suggested parameters described in Table 3 were subjected to calibration and sensitivity analysis in order to regionalize the most sensitive parameters and make the necessary adjustments to their values. These steps were performed iteratively, as recommended in the SUFI-2 calibration procedure documentation (Abbaspour, 2011). The maximization of *NSE* for river discharge was used as an objective function:

$$NSE = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \overline{Q}_m)^2}, \tag{2}$$

where Q_m is the measured parameter value (e.g. river discharge), Q_s the simulated parameter value, and $\overline{Q}_m$ is the average value of measured parameter. *NSE* values ranges between $-\infty$ and 1.0, with 1.0 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values below 0.0 indicate unacceptable performance of the model (in this case the mean observed value is a better predictor than the simulated one) (Krause et al., 2005).

SWAT-CUP calibration iteration presumes the existence of a set of simulations with predefined parameters, uncertainty ranges for these parameter values, statistics of every

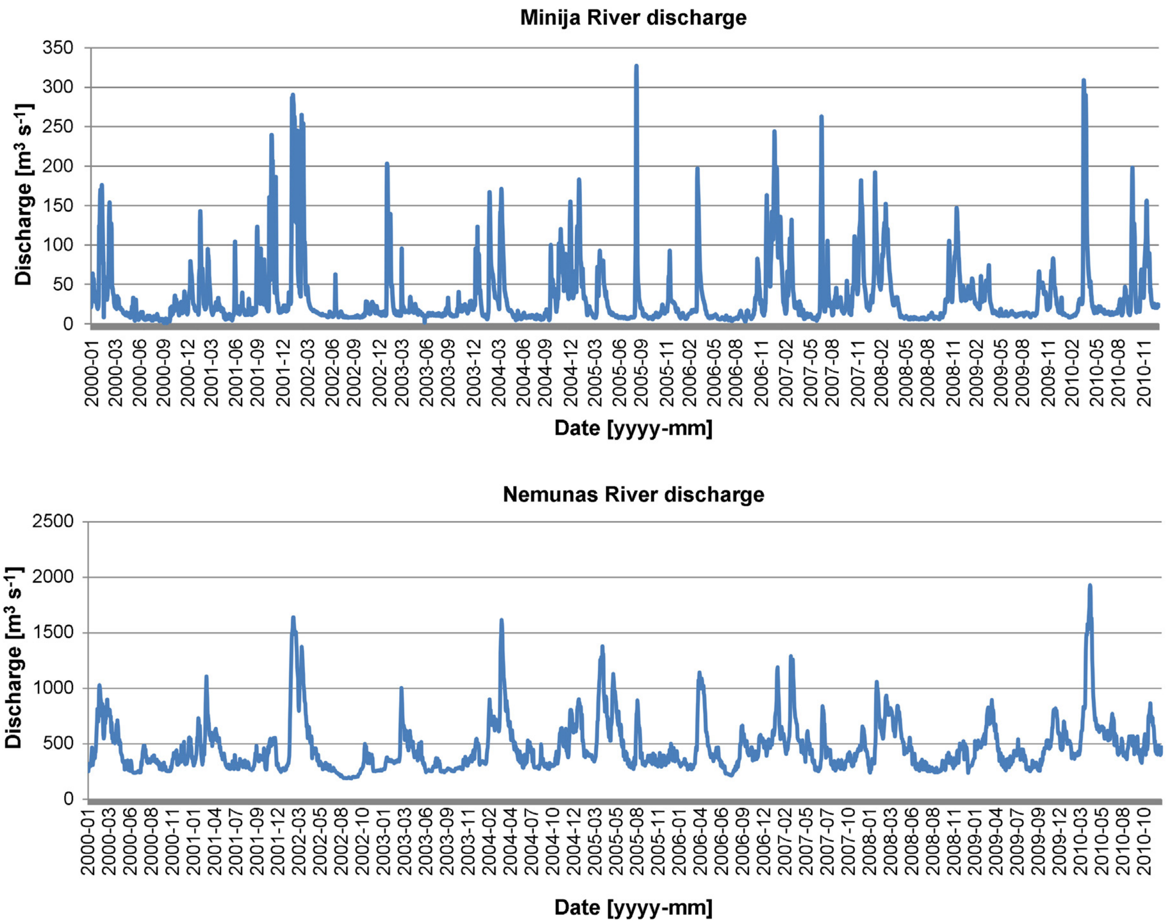

Figure 2 Minija and Nemunas river historical discharge.

simulation output and overall statistics of the calibration process. A simulation is a single execution of the SWAT model, with certain parameter values within a boundary of the uncertainty ranges, as defined in the iteration set-up process. The initial calibration run was carried out with 2000 model simulations. As the number of parameters and simulations was high, the time consumption of such a calibration iteration was demanding. To complete one iteration cycle on a standard laptop computer (with an Intel Core i7 2.4 GHz processor) with 2000 simulations, the calibration tool had to run for 36 h (for a model with 117 sub-basins). The speed performance of the calibration tool is strongly dependent on the complexity of the model (the number of sub-basins, HRUs, calibration parameters and simulated period), the processor's clock speed and some other factors, such as the speed of the hard drive and the architecture of the machine. Studies have shown that the calibration procedure's run time could be enhanced by enabling the parallel processing of the calibration tool (Rouholahnejad et al., 2012).

Calibration was carried out, accounting for spatial parameter variations in different basins (of the Minija and Nemunas Rivers) (see Fig. 3). Global model performance for the monthly run-off values of $NSE = 0.79$ and $R^2 = 0.81$ were achieved, which correspond to very good ratings (see Table 4). This model was subjected to further validation and used in the scenario assessment. SWAT-CUP produces a fitted parameter value table for the best simulation. Corresponding values are given in Table 5.

Some parameter values are similar for every sub-basin, whereas others differ substantially. This can be explained by the spatial distribution of sub-basins and their differences in soil, land-use and the topographic properties of the area. Since sub-basins and HRUs are spatial averaging over some area, the parameter values for the same catchment area will change as the sizes of sub-basins and HRUs change.

Defining proper parameter boundaries for parameters used in the calibration stage can be a challenging process. These ranges have a strong impact on the autocalibration outcome. In some SWAT model autocalibration studies (Arnold et al., 2012; Balascio et al., 1998; Moriasi et al., 2007), different parameter ranges are used for the same parameters that are subjected to calibration, but the explanation for such boundary usage is not always provided.

The high number of parameters complicates and prolongs the model's parameterization and calibration procedure, and can therefore be considered as a weakness of the model, especially if the soil and geological differences of the catchment area are not well known. This was the drawback for Curonian Lagoon basin model, as the soil and land-use data were acquired from public sources and not from local ones, which would be of better quality and backed-up by more recent observations. Different competences in various fields of study are required in order to fully assess the influence of each parameter and its value to the basin. A more detailed analysis of each parameter, not only those that are used in

Table 3 Most frequently used calibration parameters in various SWAT model calibration studies.

Parameter	Definition	Process
CN2	Initial Soil Conservation Service runoff curve number	Surface runoff
CH_K1	Effective hydraulic conductivity in tributary channel alluvium [mm h^{-1}]	
CH_K2	Effective hydraulic conductivity in main channel alluvium [mm h^{-1}]	
CH_N2	Manning's "*n*" value for the main channel	
ESCO	Soil evaporation compensation factor	
EPCO	Plant uptake compensation factor	
SURLAG	Surface runoff lag coefficient	
CANMX	Maximum canopy storage [mm H_2O]	
ALPHA_BF	Baseflow alpha factor [days]	Baseflow
GW_REVAP	Groundwater "revap" coefficient	
GW_DELAY	Groundwater delay time [days]	
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur [mm H_2O]	
GWHT	Initial groundwater height [m]	
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur [mm H_2O]	
SFTMP	Snowfall temperature [°C]	Snow
SMFMN	Melt factor for snow on December 21 [mm H_2O °C-day^{-1}]	
SMFMX	Melt factor for snow on June 21 [mm H_2O °C-day^{-1}]	
SMTMP	Snowmelt base temperature [°C]	
TLAPS	Temperature laps rate [°C]	
SOL_Z	Depth from soil surface to bottom layer [mm]	Soil
SOL_AWC	Available water capacity of the soil layer	
SOL_ZMX	Maximum rooting depth of soil profile [mm]	
SOL_BD	Moist bulk density [Mg m^{-3}] or [g cm^{-3}]	
SOL_K	Saturated hydraulic conductivity [mm h^{-1}]	
SOL_ALB	Moist soil albedo for top layer	

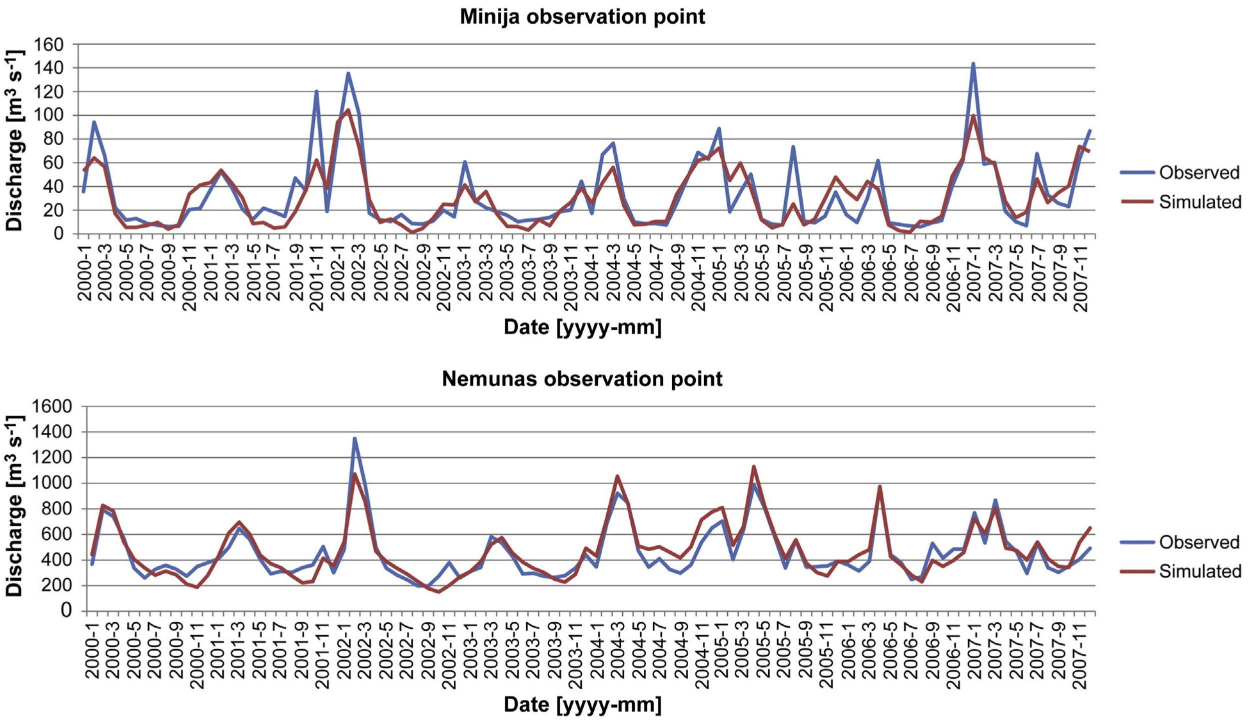

Figure 3 Calibration results for Minija and Nemunas river discharge.

Table 4 Statistics report for the calibration period (2000—2007) of the Curonian Lagoon drainage basin model.

Variable	*P*-factor	R^2	*NSE*	Mean (simulated) [$m^3 s^{-1}$]	StdDev (simulated) [$m^3 s^{-1}$]
FLOW_OUT (Minija)	0.28	0.77	0.76	32.61 (30.59)	29.99 (23.91)
FLOW_OUT (Nemunas)	0.38	0.85	0.84	455.91 (470.84)	204.85 (208.56)

this study, would benefit future developments of a Curonian Lagoon drainage-basin model.

2.4. Validation procedure

Validation results show whether the parameters were calibrated in such a way as to represent the modelled system adequately, in this case, the Curonian Lagoon's drainage area. The model's validation output can be analysed in the same way as the model calibration: a value for R^2 and *NSE* can be computed and the plot of the simulated flow, as compared to the observed flow, produced. After the successful validation of the model, it can be used for various purposes: monitoring seasonal and long-term trends, predicting any of the model's output elements under different conditions and scenarios and using outputs as inputs for other models.

Table 5 Fitted parameter values for the Curonian Lagoon drainage basin model.

Parameter[a]	Fitted parameter values	
	Nemunas sub-basin	Minija sub-basin
R[b]_CANMX.hru[c]	24.810646	−39.028244
R_CH_N2.rte	27.378458	37.603989
R_CN2.mgt	248.030533	−43.943916
R_SOL_ALB.sol	−0.964783	−19.724804
R_SOL_AWC.sol	−44.375572	−71.344315
R_SOL_BD.sol	−0.63497	−1.009578
R_SOL_K.sol	10.870995	−0.729487
R_SOL_Z.sol	1.501782	30.346178
R_SOL_ZMX.sol	36.707863	−35.845459
V_ALPHA_BF.gw	0.116285	1.178193
V_CH_K1.sub	199.661301	63.989532
V_CH_K2.rte	−11.417052	−53.535545
V_EPCO.bsn	0.651629	0.598089
V_ESCO.bsn	0.484453	0.799542
V_GW_DELAY.gw	279.003998	−72.274193
V_GW_REVAP.gw	0.143441	0.11155
V_GWHT.gw	14.892682	4.632501
V_GWQMN.gw	381.135162	803.918335
V_REVAPMN.gw	331.778961	18.785471
V_SMFMN.bsn	3.019845	9.110275
V_SMFMX.bsn	12.965604	9.025815
V_SMTMP.bsn	0.340758	0.831538
V_SURLAG.bsn	27.429886	8.502431
V_TLAPS.sub	2.980006	−8.614986

[a] Parameter definitions are given in Table 3.

[b] The qualifier (V_) refers to the substitution of a parameter by a value from the given range, while (R_) refers to a relative change in the parameter where the current value is multiplied by 1 plus a factor in the given range.

[c] The extension (.hru,.rte,.mgt,.sol,.gw,.sub,.bsn) refer to the SWAT file type where the parameter occurs.

The global Curonian Lagoon drainage area model validation results are $R^2 = 0.679$ and $NSE = 0.602$, which correspond to satisfactory values for the model at a monthly time-step. The validation result confirms that this area-specific hydrological model can produce sufficiently accurate predictions.

Although the required model performance objectives were met, validation results give an insight into possible errors in the output. The SWAT model was unable to predict the high amounts of run-off occurring in the spring months (for both observation points), and some peak flows were underestimated. The model failed to simulate the high amount of run-off that occurred in the late autumn and winter months (November—January) of 2008—2009 and 2009—2010 for both Minija and Nemunas (see Fig. 4). For improving the model's predictive accuracy, snowmelt and ice-formation parameter temperatures might be adjusted to account for early melting or late ice/snow formation.

2.5. Scenario formulation

Air temperature and the precipitation amount are the main climate elements directly affecting the total run-off of rivers. Prognostic air temperature, precipitation amount and humidity-change data, derived from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5), were used with the SWAT for modelling river inflow changes.

Near-term projections from the General Circulation Model-Regional Climate Model (GCM-RCM) model chains for Europe were used for modelling precipitation and temperature changes. The analysis includes the following 10 GCM-RCM simulation chains for the Special Report on Emissions Scenarios' (SRES) A1B scenario (which includes the RCM group and GCM simulation): HadRM3Q0-HadCM3Q0, ETHZ-HadCM3Q0, HadRM3Q3-HadCM3Q3, SMHI-HadCM3Q3, HadRM3Q16- HadCM3Q16, SMHIBCM, DMI-ARPEGE, KNMI-ECHAM5, MPI-ECHAM5, DMI-ECHAM5 (Kirtman et al., 2013). The CMIP5 (Coupled Model Intercomparison Project, Phase 5) multi-model ensemble was used for the relative humidity change.

The current-condition scenario was carried out before implementation of the climate-change scenario simulations; the produced average monthly run-off values were considered as the baseline. In order to analyse the impacts of potential future climate change on the hydrology of the Curonian Lagoon drainage area, every scenario was implemented with downscaled, spatially variable climate inputs (air temperature precipitation, relative humidity) using the matching simulation period, which delivers a consistent foundation for comparison of the scenario outputs. The near-term change and projected changes described are for the period 2016—2035.

According to the summary of IPCC AR5, air temperature is going to increase by up to 1°C in winter, 0.5°C in spring and

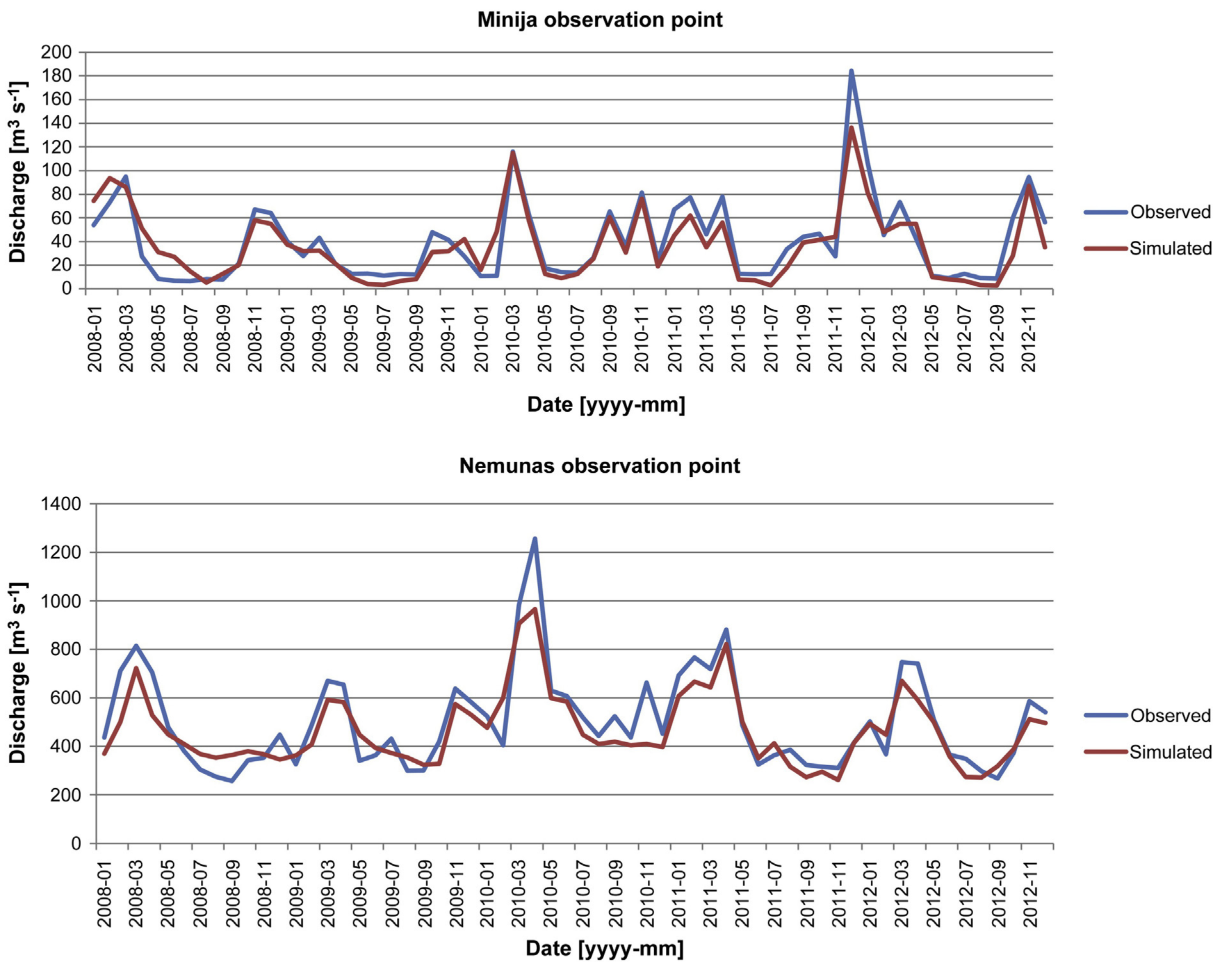

Figure 4 Validation result with the best fitted parameter value set for Minija and Nemunas river discharge.

autumn and 0.7°C in summer in the near-term; precipitation is expected to increase by 7.5% in winter, 5.0% in autumn and spring, and 2.5% in summer and humidity is likely to decrease slightly, by about 1% over most land areas (Kirtman et al., 2013). Two climate change scenarios, one pessimistic and one optimistic, were formulated (Table 6), and the effects of these scenarios on river run-off were explored. The pessimistic scenario includes high values for temperature and precipitation change, whereas the optimistic scenario's corresponding values were lower. Such scenarios were formulated for assessing the response of the study area to various conditions of climate change, and in order to determine the sensitivity of the modelled system.

3. Results

3.1. The pessimistic scenario's results

For the pessimistic scenario, high values of precipitation and temperature change were used to assess their effects on the Nemunas and Minija Rivers' run-off. For the Nemunas River, the projected changes in precipitation, temperature and

Table 6 Climate variable change in pessimistic and optimistic scenarios.

Scenario	Simulated changes in:						
	Temperature [°C]			Precipitation [%]			Relative humidity [%]
	DJF[a]	MAM, SON[b]	JJA[c]	DJF	MAM, SON	JJA	All seasons
Pessimistic	+2	+0.5	+0.7	7.5	5	2.5	−1
Optimistic	+0.6	+0.4	+0.3	3	1.5	0	−1

[a] "DJF" refers to winter months: December, January, February.
[b] "MAM" refers to spring months: March, April, May; "SON" refers to autumn months: September, October, November.
[c] "JJA" refers to summer months: June, July, August.

Table 7 Simulated inter-seasonal Nemunas and Minija river average (av), minimal (min), and maximal (max) discharge change for the pessimistic (^{P}) and optimistic (^{O}) scenario.

River	River discharge change [±%]											
	Winter			Spring			Summer			Autumn		
	av	min	max	av	min	max	av	min	max	av	min	max
^{P}Minija	22	21	23	−7	−28	−2	−18	−64	44	10	−10	23
^{P}Nemunas	17	20	1	−10	−24	−19	−8	−16	14	9	0.5	12
^{O}Minija	18	16	17	−5	−25	−8	−10	−65	−25	5	−18	20
^{O}Nemunas	10	8	1	−9	−32	−20	−2	−20	2	3	−3	2

humidity will result in a stronger inter-seasonal fluctuation of run-off. During the winter months, it is expected that the Nemunas River run-off will increase by 17% in the short term. The probable reason for this is the increased winter temperatures, which will result in earlier snowmelt. An increase in precipitation is also having a strong effect on run-off during the winter months. The peak run-off for the winter will experience no significant change, whereas the minimal run-off will increase by approximately 20% (see Table 7, Fig. 5), although the SWAT overestimated minimal run-off for the Nemunas River in some cases, so this percentage could be less.

For the Minija River, the effect of early snow melting is more prominent; the increase in discharge will be approximately 22%. Minimum and maximum discharges for the winter months will also increase by 21–23%. The strongest

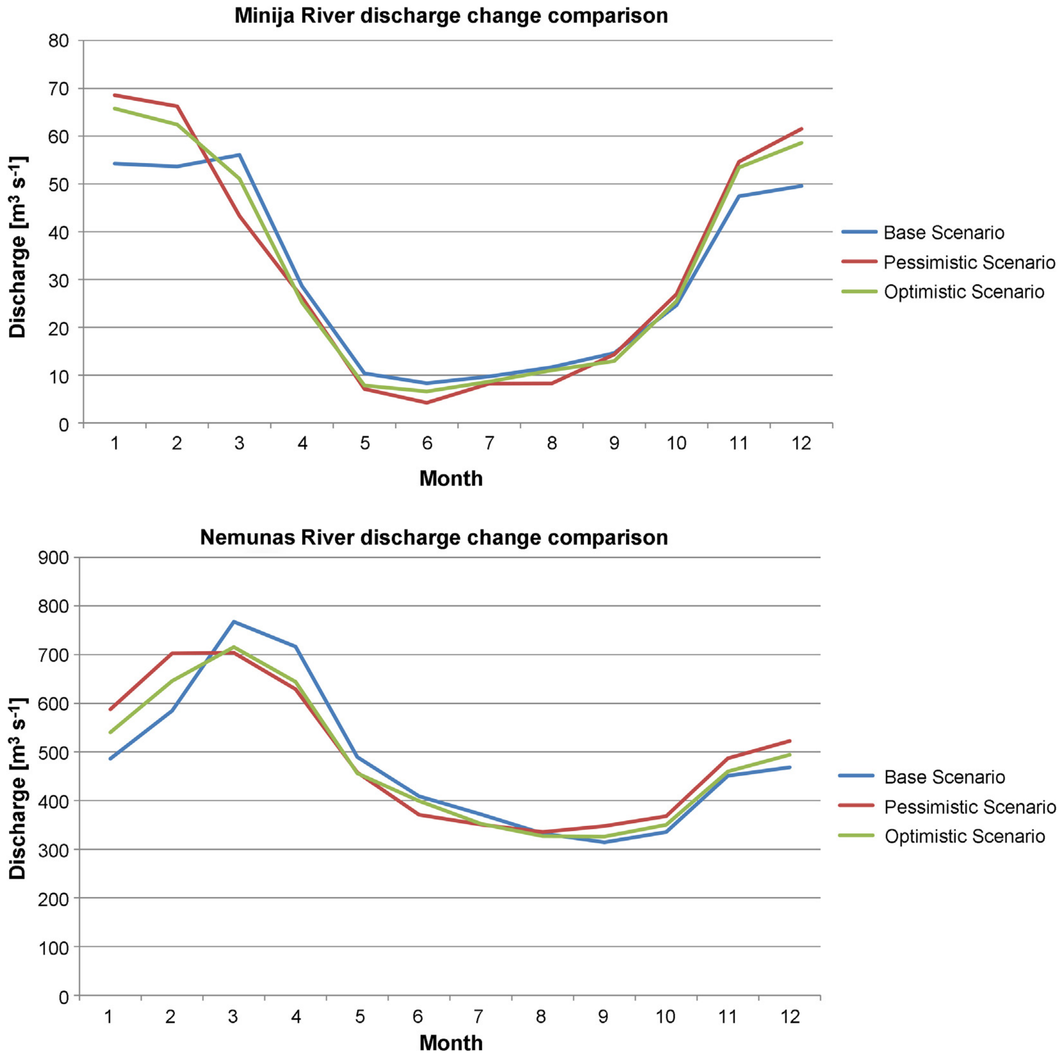

Figure 5 Monthly simulated discharges of base, optimistic, and pessimistic scenarios for Minija and Nemunas rivers.

increase of discharges for both rivers is observed in February, where the peak flow values are simulated to increase by more than 60%.

During spring months, a 10% decrease in run-off is expected for the Nemunas River and a 7% decrease is expected for the Minija River (Table 7, Fig. 5). This is caused by the ice-melting season moving to the winter months. The maximum spring discharges in Lithuanian rivers generally take place during March to April, but in the light of current climate change, these events will happen earlier. The strongest decrease in discharge during spring months is observed in May for Minija, whereas for Nemunas, it is observed in April.

The summer months are expected to be warmer; this has a significant negative impact on the discharge of rivers during this period. For Nemunas, it results in an 8% decrease in run-off, whereas for Minija, it results in an 18% decrease. The minimal and maximal discharge values vary: for Nemunas, peak flows during summer months will increase by 14%, but the minimal flow will decrease by 16%. For Minija, peak flows will increase by 44% and minimal flows will decrease by 64%. The highest discharge change is expected during June to July for Nemunas, and in July for Minija (see Fig. 5). Even if in some cases the model overestimated the values of peak flows and underestimated the minimal flows, the inter-seasonal differences between climate change and baseline scenarios are significant.

Discharge changes in the autumn months are less affected by climate change. During this period, the average discharge will increase by 10% for Minija and 9% for Nemunas. Maximal run-off will increase by 23% for Minija and by 12% for Nemunas. Minimal run-off will decrease by 10% for Minija and will not change significantly for Nemunas (Table 7). In the autumn months, the average discharge will increase for Nemunas during the whole season, with no distinct patterns. The Minija River's discharge, however, displays a decrease in the run-off during September, and a steady increase in the following months, reaching the highest increase during November (Fig. 5).

The annual discharge in the short term for the Nemunas River will increase by around 7%, and Minija's will increase slightly, by around 2—3%. These results confirm those of similar studies (Kriaučiunienė et al., 2008; Meilutytė-Barauskienė and Kovalenkovienė, 2007; Rogozova, 2006), which indicate a slight increase in annual river run-off in the near-term and a change in flood behaviour during the spring.

3.2. The optimistic scenario's results

For the optimistic scenario, low values of precipitation and temperature change were used to assess their effects on river run-off. As expected, results of the optimistic scenario show smaller changes than those of the pessimistic one, although their tendencies remain the same (see Table 7).

For both Nemunas and Minija, the expected river discharge will change mostly in the winter season: 18% for Minija and 10% for Nemunas. Minimal and maximal discharges during this season will increase by 16% and 17%, respectively, for the Minija River, while for Nemunas an increase of 8% in minimal discharge is expected, where the peak flows will remain at almost the same level. The increase in discharge is simulated during the entire season, with no distinct patterns for Minija. The strongest increase is observed during February for the Nemunas River.

During the spring months, a reduction in river flow is expected: 5% and 9% for Minija and Nemunas, respectively (Table 7). The maximal discharge will decrease by 8% and 20%, respectively, and the rivers' minimal discharges will decrease by even more: 25% and 32%. The strongest decrease in discharge is observed in April for Nemunas, and in May for Minija (Fig. 5).

During the summer months, a small increase in precipitation and a decrease in humidity were used in the optimistic scenario, with no change in the temperature. However, a decrease in the rivers' run-off was simulated: 10% for Minija and 2% for Nemunas (Fig. 5). This may be caused by the increased ET (evapotranspiration) and a higher water uptake by plants. The highest reduction in discharge is observed in the period of June to July for both rivers.

The autumn months will experience a small increase in river discharge: 5% for Minija and 3% for Nemunas. The peak and minimal flows will experience small fluctuations in both cases. A general decrease in run-off during September, compared to the baseline scenario, is simulated for Minija, with a gradual increase of flow in the following months. The Nemunas River's discharge displays a steady increase during September and October, with the highest values occurring in November. With this optimistic scenario, the annual discharge in the near-term for the Nemunas River will increase by around 5%, and by 2—3% for the Minija River.

4. Discussion

The SWAT is a very useful tool for investigating climate change's effects on the drainage basin, assessing management strategies on a catchment area's hydrological and water-quality response and other different scientific and practical uses. However, calibration and validation of the model is a key factor in reducing uncertainty and increasing confidence in its predicative abilities, thus making application of the model effective.

The Curonian Lagoon drainage basin model was successfully calibrated and validated, although some improvements to the results could be achieved in the future. During calibration, the model simulations generally underestimated high seasonal amounts of run-off for Minija, especially during the spring flood months of March to April. For both rivers, the model underestimated the amount of discharge during the months of June to August. This could be caused by some fitted parameters of groundwater or base-flow; an overestimation of plants' water uptake could also be the reason for these occurrences. Further improvements to the model could assess the influence of each parameter on the run-off separately, for acquiring a better understanding of the river-discharge governing processes for each sub-basin.

During the climate scenario evaluation, both optimistic and pessimistic scenario simulations produced similar general patterns in changes to river discharge: a strong increase in the winter months, especially in February, a decrease during spring and summer and a slight increase during autumn. It is noteworthy that even in the optimistic scenario, river discharges show a relatively high reduction during the spring months, meaning that the temperature threshold for snowmelt can be reached even with a small increase in temperature (see Fig. 5).

Different climate-change factors have influenced the simulated changes in different ways. The relative humidity change has an impact on river discharges through an increase in water uptake by plants and ET. The share of the forested area in the Minija River's basin is approximately 21% (Kontautas and Matiukas, 2010), and about 35% for the Nemunas River's basin (Rimkus et al., 2013). Relative humidity can affect the flow of water through the plant: the higher the relative humidity, the more slowly transpiration occurs and vice versa. In the Curonian Lagoon drainage basin model, a reduction in relative humidity led to a reduction in river run-off during the summer months. This was the case even in the optimistic scenario, where higher precipitation values were used and the temperature values were not altered for this period. Relatively high absolute changes in minimal and maximal flows were simulated for the Minija River during the summer months, especially in the pessimistic scenario. Minija is a river dominated by rain floods in the run-off balance. This factor becomes even more distinct in the light of climate change, where heavy rain results in high local increases of generated discharge. Approximately half of the total run-off comes from rainwater; snow and groundwater comprise 22% and 25%, respectively, of the run-off. As a result of the earlier melting of snow, these values are projected to change accordingly.

A general tendency for potential hydrological droughts during the summer season is observed in both rivers. The Nemunas and Minija Rivers' basins lie under humid temperate climate conditions and cannot experience such water shortages as appear in the tropical and mid-latitudinal arid regions. Therefore, simulated dry periods and periods of low streamflow are interpreted here as droughts, because of the impact on wildlife and socio-economic factors (Rimkus et al., 2013) — a decrease in crop yields, a reduction in overall agricultural productivity, a massive increase in wildfires, an intensification of tree defoliation, etc.

The Minija River's sub-basin response to different climate-change factors was more significant than that of the Nemunas River, which displayed some robustness to projected changes. As smaller rivers in the Curonian Lagoon basin's western boundaries display a high correlation (0.76—0.97) in run-off and synchronicity in flood seasons (Meilutytė-Barauskienė and Kovalenkovienė, 2007), it is assumed that the changes in other, smaller rivers' sub-basins, such as the Deima River's sub-basin, will be similar to those simulated for the Minija River's sub-basin.

Possible future research directions may include improvement of the model's performance, a more thorough calibration and more detailed sensitivity and uncertainty analysis. In addition, the completed Curonian Lagoon drainage-basin model could be used to assess different climate-change, water-management and agricultural-management scenarios. The SWAT can be coupled with other models that require a hydrological input, in order to assess different management problems and scenarios.

As the SWAT model contains biogeochemical sub-models for nutrient transformation in its terrestrial and aquatic components, as well as plant growth and agricultural management operations, the model developed in this study can be upgraded to a full-featured drainage-basin model that can fill in the time-based gaps of monthly monitoring of the Nemunas River's outlet, giving an idea of what kind of variations occurred in the period of a month between two monitoring expeditions. With further research and additional calibration, this model can be used to simulate sediment, pesticide and nutrient transport in the basin. The model developed in this study can be linked to ecological-, biogeochemical- and sediment-transport models for the Curonian Lagoon. It can also support water-quality management studies of the Curonian Lagoon as well as scientific projects such as the ecological response of the Curonian Lagoon to different load conditions through the Nemunas River, or detailed studies of carbon, nitrogen and phosphorus budgets.

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