KLAIPĖDA UNIVERSITY

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NEMUNAS RIVER WATERSHED INPUT TO THE CURONIAN LAGOON: DISCHARGE, MICROBIOLOGICAL POLLUTION, NUTRIENT AND SEDIMENT LOADS UNDER CHANGING CLIMATE

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Abstract

This study provides an in-depth analysis of the Nemunas River watershed and possible future changes to the stream flow, hydrologic regime, and suspended sediment (SS), Total Nitrogen (TN) and Total Phosphorus (TP) loads from the river to the Curonian Lagoon under different climate change scenarios using high-resolution modelling. The sub-regions of the watershed, represented by sub-basins of the Nemunas River tributaries and the main river branch, were modelled using the Soil and Water Assessment Tool (SWAT). The model setup was performed using the developed customizable Matlab scripts for an advance Hydrologic Response Unit (HRU) configuration and a hillslope delineation procedure. The multi-site manual model calibration and validation were performed using the observed discharge, Suspended Sediments, Total Nitrogen and Total Phosphorus. The calibrated and validated model was used to assess the changes in the watershed under two Representative Concentration Pathways (RCP): RCP4.5 and RCP8.5, using the projected changes to precipitation, temperature and carbon dioxide (CO_2) concentrations for the near-term (up to 2050) and long-term period (up to 2100) compared to the baseline period (1995-2010). Additionally, a coupling possibility with the Shallow water Hydrodynamic Finite Element Model (SHYFEM) of the Curonian Lagoon was explored. The study highlights the possible changes to the inter-seasonal nutrient load change to the Curonian Lagoon and emphasises the threats associated with such changes. The findings of the study suggest that most changes for the near-term and long-term periods are likely to occur in the winter season, especially in January and February. A decrease in snow cover across the watershed, together with the greater frequency of soil freeze-thaw cycles related to it can weaken the nutrient retention of soils and increase nitrogen and phosphorus losses. Coupled with the increased flows in winter, the projected nutrient load changes during winter season indicate an up to two-fold increase in sediment, up to 42% and 62% in TN and TP load to the Nemunas and, subsequently, to the Curonian Lagoon. The combination of hydrologic changes in the watershed and inter-seasonal variation of nutrient loads to the lagoon might result in various system behaviour responses, ranging from increased cyanobacteria blooms, to an increase of net nutrient export to the Baltic Sea.

Key words

Nemunas River watershed, nutrient loads, sediment loads, SWAT model, climate change, Curonian Lagoon, numerical modelling

Reziumė

Šiame tyrime pateikiama išsami Nemuno upės baseino analizė ir galimi debito, hidrologinio režimo, nuosėdų, bendrojo azoto (TN) ir bendrojo fosforo (TP) krūvio pokyčiai iš upės į Kuršių marias skirtingų klimato kaitos scenarijų kontekste taikant didelės skiriamosios gebos modeliavimą. Nemuno upės pagrindiniai intakai ir pati upė buvo modeliuojami kaip pabaseiniai naudojant dirvožemio ir vandens vertinimo įrankį (angl. Soil and Water Assessment Tool – SWAT). Modeliui sudaryti buvo panaudotos šiame tyrime sukurtos Matlab įrankių programos. Modelis buvo sukalibruotas ir validuotas naudojant kelių stočių debitų, TN, TP ir suspenduotos medžiagos matavimus. Sėkmingai sukalibruotas ir validuotas modelis buvo panaudotas įvertinti prognozuojamus pokyčius Nemuno upės baseine pagal scenarijus, sudarytus naudojant du reprezentatyvius koncentracijos kitimo profilius (angl. Representative Concentration Pathways – RCP): RCP4.5 ir RCP8.5. Pakeisti kritulių, temperatūros ir anglies dvideginio pokyčiai buvo panaudoti siekiant įvertinti pokyčius trumpalaikiam (amžiaus vidurio – iki 2050 metų) ir ilgalaikiam (amžiaus pabaigos – iki 2100 metų) laikotarpiams, palyginus su baziniu periodu (1995–2010). Be to, buvo ištirtos Nemuno upės baseino ir Kuršių marių sekliu vandenų hidrodinaminio baigtinių elementų modelių (SHYFEM) sujungimo galimybės. Tyrimo rezultatai rodo, kad dauguma pokyčių trumpalaikiu ir ilgalaikiu laikotarpiu vyks žiemos sezonu, ypač sausio ir vasario mėnesiais. Prognozuojama sumažėjusi sniego danga visame Nemuno upės baseine kartu su dažnesniais dirvožemio užšalimo ir atšalimo ciklais gali susilpninti dirvožemio maistinių medžiagų sulaikymo galimybes, dėl to didės azoto bei fosforo išplovimas . Kartu su prognozuojamais padidėjusiais debitais žiemą numatomas beveik dvigubas nuosėdų apkrovų padidėjimas, iki 42 % bendrojo azoto ir iki 62 % bendrojo fosforo apkrovų į Nemuną padidėjimas. Dėl Nemuno upės baseine numatomų hidrologinių ir maistinių medžiagų išnešimo į Kuršių marias pokyčių galimos įvairios sistemos elgesio reakcijos, pradedant nuo padažnėjusių melsvadumblio žydėjimų mariuose iki padidėjusio maistinių medžiagų eksporto į Baltijos jūrą.

Reikšmingi žodžiai

Nemuno upės baseinas, maistinių medžiagų apkrovos, nuosėdų apkrovos, SWAT modelis, klimato kaita, skaitmeninis modeliavimas.

Contents

List of original publications

The material of this study was presented in 4 original publications, published in peer-reviewed scientific journals, and references to them are provided using Roman numbers in the text.

I. Natalja Čerkasova, Ali Ertürk, Petras Zemlys, Vitalij Denisov, Georg Umgiesser. Curonian Lagoon drainage basin modelling and assessment of climate change impact. Oceanologia. Volume 58, Issue 2, April–June 2016, Pages 90-102, doi: 10.1016/j.oceano.2016.01.003

II. Georg Umgiesser, Natalja Čerkasova, Ali Ertürk, Jovita Mėžinė, Marija Kataržytė. New beach in a shallow estuarine lagoon: a model-based E. coli pollution risk assessment. Journal of Coastal Conservation. June 2018. Vol. 22 (3), Pages 573–586, doi: 10.1007/s11852-018-0596-y

III. Natalja Čerkasova, Georg Umgiesser, Ali Ertürk. Development of a hydrology and water quality model for a large transboundary river watershed to investigate the impacts of climate change – A SWAT application. Ecological Engineering. 1 December 2018, Vol. 124, Pages 99-115, doi: 10.1016/j.ecoleng.2018.09.025

IV. Natalja Čerkasova, Georg Umgiesser, Ali Ertürk. Assessing Climate Change Impacts on Streamflow, Sediment and Nutrient Loadings of the Minija River (Lithuania): A Hillslope Watershed Discretization Application with High-Resolution Spatial Inputs. Water. 1 April 2019, 11, 676; doi:10.3390/w11040676

Author’s contribution

I. N. Čerkasova designed the model setup, performed the data collection, realized the modelling experiments, performed the analytical and practical work and data analysis and wrote the manuscript draft.

II. N. Čerkasova took part in the study design and the analytical work, performed the literature overview; she also contributed to the writing.

III. N. Čerkasova performed the data collection, analytical work, she carried out the model development and experiments, contributed to the model design; she wrote the manuscript draft.

IV. N. Čerkasova performed the data collection, pre-processing and post-processing, analytical work, she carried out the model development and experiments, contributed to the model design; she wrote the manuscript draft.

Abbreviations

Abbreviation	Explanation
AR5	Fifth Aassessment Report
BMP	Best Management Practices
BSAP	Baltic Sea Action Plan
BY	Republic of Belarus
EPA	Environmental Protection Agency
EU	European Union
GCM	General Circulation Models
HELCOM	Baltic Marine Environment Protection Commission, also known as Helsinki Commission
HRU	Hydrologic Response Unit
IPCC	Intergovernmental Panel on Climate Change
LT	Republic of Lithuania
LV	Republic of Latvia
MAI	Maximum Allowable Input
NS	Nash–Sutcliffe model efficiency coefficient
PBIAS	Percent bias
PL	Republic of Poland
PP	Particulate Phosphorus
R^2	Coefficient of determination
RBMP	River Basin Management Plan
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RU	Russian Federation
SHYFEM	Shallow water Hydrodynamic Finite Element Model
SS	Suspended sediment
SWAT	Soil and Water Assessment Tool
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total suspended solids
WFD	Water Framework Directive

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Introduction

Current state of discharge, microbiological pollution, nutrient and sediment load inputs from watersheds to coastal regions. Research on estimation of global water resources can be traced back to as early as 1973 (Lvovitch, 1973), and continues henceforth (Korzoun and Sokolov, 1978; McIntosh and Pontius, 2017; Yates, 1997). Discharge estimations are now performed globally using existing hydrological models with various spatial scale: from macro-scale hydrological models (Abbaspour et al., 2015; Arnold et al., 2000; Nijssen et al., 2001; Rouholahnejad et al., 2014; Yates, 1997) to field-scale models (Bär et al., 2015; Momm et al., 2019; Ndomba et al., 2008; Williams et al., 2008). There have been considerable gains in knowledge of amounts and sources of nutrients entering the terrestrial biosphere, and biogeophysical factors that control the amount of nutrients, sediments and microbiological pollution ultimately exported by rivers to coastal systems, with all studies concurring on the increasing trend of nutrient delivery from the watersheds to the coastal regions (Carpenter et al., 1998; Pätsch and Radach, 1997; Seitzinger et al., 2010). More studies are now focused on addressing how various socioeconomic factors, climate change and approaches to land management impacts river nutrient export and microbiological pollution in river watersheds (Magdoff et al., 1997; Mallin et al., 2000).

Anthropogenic activities impact a watershed, transitional area and sea ecosystems at a global scale and all levels of complexity of life. The pressure on water resources, deteriorating water quality, and uncertainties associated with the climate change create an environment of conflict in large and complex river systems (Rouholahnejad et al., 2014). There is growing evidence that Europe's coastal systems (including marine and terrestrial) are suffering widespread and significant degradation that poses a major challenge to policymakers and coastal managers; land-based sources of nutrients, but also other indirect sources, play important roles in the formation of coastal pressures, and therefore linking the coastal zone and its water bodies with river basins is a priority (Caddy and Bakun, 1995; Cozzi et al., 2018; Grizzetti et al., 2017; Iglesias-Campos et al., 2015; Pätsch and Radach, 1997). The identification, quantification and prioritization of pollution sources are essential tasks. This endeavour is complicated when a variety of pollution sources are found and due to limited data availability, which can result in an inconclusive assessment and differing public perceptions, ultimately hindering the progress of management actions (Tosic et al., 2018).

The incredible complexity and large size of many ecosystems often require the use of computer models to gain this critical knowledge. An example is the case for the Chesapeake Bay and its vast watershed (the largest estuary in the United States and the third largest in the world), for which the suite of computer models (watershed, estuary, airshed and land change models) are used to project the flow, loads of pollution and simulate how changes to pollution controls, land use, atmospheric deposition and precipitation could impact the ecosystem, particularly water quality and living resources (Batiuk, 2010).

Integrated hydrological models and tools have been built for various studies, ranging from climate change impact on freshwater availability assessments to the analysis of components of water resources, crop yields and water quality issues for regional and continental-scale areas (Abbaspour et al., 2015; Arnold et al., 2000; Bär et al., 2015). The current modelling philosophy requires that models are transparently described; and that calibration, validation, sensitivity and uncertainty analysis are routinely performed as a part of the modelling (Abbaspour et al., 2015), therefore it can be stated that modelling is an "alive" process. The Chesapeake Bay Watershed Model is a good example for this statement. As reported by Linker et al., 2012, the modelling efforts began in 1982 and were continued as multiple phases, the first phase being initiated in 1985 and reaching Phase 5.3 in 2010 (Shenk et al., 2012). Recently, modelling phase 6 was initiated (Chesapeake Bay Program, 2017), which incorporates more detailed and revised input data and more advanced modelling tool and infrastructure.

Current nutrients load management in the Baltic Sea area. The recent State of the Baltic Sea report shows that more than 97% of the Baltic Sea area suffers from eutrophication due to past and present excessive inputs of nitrogen and phosphorus (HELCOM, 2018a). Owing to the implementation of the Baltic Sea Action Plan (BSAP) by the Baltic Marine Environment Protection Commission (also known as Helsinki Commission, HELCOM) member states, the inputs from land have decreased considerably, but the effects of these measures are generally not yet reflected in the status. According to the assessment of the progress towards the national targets for input of nutrients achieved by 2014, Lithuania, as a HELCOM member, has yet to reduce the inputs to the Maximum Allowable Input (MAI) levels, although the country has made some progress; for example, Lithuania was the only country that reduced Total Phosphorus inputs to all sub-basins to which it contributes (Svendsen et al., 2018).

Adaptation to climate change is a central issue for the planning and implementation of measures to reduce nutrient inputs, as well as for adjusting the level of nutrient input reductions to ensure protection of the Baltic Sea marine environment in a changing climate. Currently, the MAI are calculated under the assumption that the Baltic Sea environmental conditions are in a biogeochemical and physical steady-state (HELCOM, 2018a), which is not likely to last with a changing climate. Several studies conducted in the Baltic Sea region have addressed the effects of climate change on the river discharge at large scale (c/o International Baltic Earth Secretariat, n.d.; Donnelly et al., 2014; Graham, 2004) and medium to small scale (Rimkus et al., 2011; Stonevičius et al., 2017), and studies focused on nutrient load change (Cousino et al., 2015; Pilipchuk et al., 2014; Povilaitis et al., 2018) from various catchments in the Baltic Sea area. Some studies indicate that the current climate change trends for the region might result in an additional increase in the nutrient reduction targets (Meier et al., 2012).

Most of the land-based nutrient contribution from Lithuania to the Baltic Sea comes through the Nemunas River, which is the fourth largest river draining into the Baltic (HELCOM, 2018b). The Nemunas watershed is shared by Belarus (48%), Lithuania (46%), Poland (2.57%), Russian Federation Kaliningrad oblast (3.34%) and Latvia (0.09%)(for more details on the Nemunas River watershed characteristics refer to Paper I), however the responsibility for reducing the land-based nutrient loads to the river falls mainly on Lithuania, as Belarus is neither a HELCOM nor an European Union (EU) member, thus is not bound by related international agreements. 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 cannot be achieved with the current progress, so strengthening the implementation of the BSAP by 2021 was set as a top priority, and includes adjusting the BSAP based on new knowledge and future challenges.

With nutrient reduction targets to be reached and increasing water management difficulties, a need for a sophisticated hydrological model of the Nemunas River watershed arose, in order to assess hydrologic, microbiological, sediment and nutrient dynamics with regards to climate change, agricultural practices and other factors. The created model should be flexible to be used for large-scale (entire watershed-wide) and medium (sub-basin) to small-scale scenario calculations, as well as it shall be applied in a coupled watershed-coastal area modelling framework. The coupled hydrologic and water quality (watershed-scale) and hydrodynamic (lagoon and transitional zones) modelling framework can be further used to assess the possible consequences of management or policy decisions and the following climate change on the entire region.

The created modelling framework allows us to quantify the possible changes in the flow, nutrient and sediment delivery from all sources, including the transboundary ones, in the light of climate change. In turn, this will enable policy makers to make evidence-based decisions, when adapting the Maximum Allowable Inputs and establishing nutrient reduction measures, provide information support to the European Water Framework Directive and lay the basis for further assessment of the impact of climate change on water resources and quality. Possible effects of the projected hydrological, nutrient and sediment load changes on the Curonian Lagoon and the environment can be determined as well, which consequently will serve for better understanding of the watershed-transitional area systems and their sensitivity to changing conditions.

Discharge, nutrient and sediment load estimations and predictions in the Nemunas River watershed. Several hydrological models (HBV, MIKE, etc.) were applied to the Nemunas River watershed in different studies (Kriaučiuniené et al., 2008; Rimkus and Vaikasas, 2012; Stonevičius et al., 2017; Stuopis et al., 2010), assessing the impact of different stressors on the system. SWAT (Soil and Water Assessment Tool) is used by Lithuanian Environmental Protection Agency (EPA) in the development of a methodical and modelling system of nitrogen and phosphorus load calculation for surface waters of Lithuania (Environmental Protection Agency, 2015).

The Strategic Framework for Adaptation to Climate Change in the Neman River Basin watershed has been developed under the international project "River Basin Management and Climate Change Adaptation in the Neman River Basin" under the Program of the United Nations Economic Commission for Europe (UNECE) and with support from the international Environment and Security Initiative (ENVSEC) and the United Nations Development Program (UNDP) in the Republic of Belarus (Korneev et al., 2015), where the possible future changes on the water resources in the entire watershed are assessed. The Strategic Framework is an excellent example of tackling problems related to water resources at the watershed level, but the study focuses on the hydrological issues and is not sufficiently detailed to provide an in-depth assessment of possible interseasonal changes, with no mention of sediment or nutrient loads.

Some recent studies within the framework of national projects financed by the Lithuanian Research Council analysed the potential nutrient loads in four Lithuanian Rivers (Minija, Šventoji, Nevėžis and Žeimena) that are situated in the Nemunas River watershed, with findings suggesting the decrease in stream-flow and nutrient loads (Povilaitis et al., 2018). However, none of the previous studies covered the entire the Nemunas River watershed assessing discharge and nutrient calculations. Moreover, there are no climate change projection studies related to the Nemunas River watershed microbiological and sediment load analysis and quantification.

1.1 Aim and objectives

The aim of this study is to assess Nemunas River watershed hydrologic, sediment and nutrient dynamics with regards to climate change, agricultural practices and other human-induced factors and analyse possible consequences of nutrient and sediment loads and microbiological pollution by means of applying high resolution modelling techniques.

The following objectives were raised:

1. To apply hydrological modelling techniques and tools to construct a hydrological model that can describe the water, sediment and nutrient dynamics of the Nemunas River watershed;
2. To apply the developed model to forecast trends related to climate change and analyse possible consequences on discharge, nutrient and sediment loads and microbiological pollution by introducing different forcing scenarios in accordance with IPCC AR5 RCP4.5 and RCP8.5 for near-term (mid-century) and long-term (end of century) periods;
3. To analyse the effects of the possible future Nemunas River discharge, nutrient and sediment loads to the Curonian Lagoon; assess the hydrologic and water quality (watershed) and hydrodynamic (coastal lagoon) model coupling possibility.

1.2 Novelty

The study explores new approaches to the hydrologic and water quality model setup for large-scale fine-grid data-scarce transboundary regions in Europe. This research, to this day, is the first of its kind which integrates the hillslope model discretization scheme, the advanced HRU (Hydrologic Response Unit) classification (integrates the topographic, soil, slope, land use and administrative unit information) for a physically realistic representation of the modelled area, the transboundary data homogenisation and high-resolution large-scale modelling within one study. Furthermore, this study provides an insight of the river stream composition, groundwater influence and the quantification of nutrient loads to the Nemunas River.

The novel aspects of this thesis deal with 1) advanced hydrologic and water quality model setup schemes; 2) possibility of hydrologic and hydrodynamic (from the watershed to the transitional coastal zone) model coupling assessment; 3) long term estimations of Sediments, TN and TP loads in the entire Nemunas River watershed, including transboundary loads; 4) streamflow composition of the Nemunas River and tributaries. This study is the first that analysed and quantified the sediment loads to the rivers of the Nemunas watershed and the Curonian Lagoon.

1.3 Scientific and applied significance of the results

An understanding of nutrient and pollutant loads in the watershed to the river stream, their transportation and retention effectiveness is a vital part for the management efforts aimed at reducing anthropogenic impacts on inland and coastal waters. Apart from direct measurements, it is crucial to be able to predict the possible future loads and changes to the river systems under different forcing, such as climate change. The results of this study can be used to adapt the HELCOM Nutrient Reduction Scheme (HELCOM Ministerial Meeting, 2007) and calculate the Maximum Allowable Inputs for Lithuania under the changing environmental conditions. Further, the results and the model can be used by the local Environmental Protection Agencies to identify the "hot-spots" of high nutrient and/or pollutant loads in the Nemunas River watershed and the best nutrient retention areas. This knowledge can provide the decision support to derive an optimal strategy for land and fertilization management, nutrient recycling and rural water management to achieve a substantial reduction in the amount of nutrients transported through the rivers to the Curonian Lagoon, which in turn will be beneficial to the management of algae blooms in the lagoon.

The evaluation of nutrient loads generated in the watershed and transported to the large estuarine system is critical to understand the amounts of sediments, N and P that are delivered to the transitional areas and the open sea. This study provides valuable insights on the large-scale hydrologic and sediment/nutrient load estimations where data is scarce, inconsistent and scattered. Moreover, the study demonstrates the need to conduct flexible frameworks, where the model can be easily adapted to meet the task at hand best, without going through the time and resource-consuming process of developing a model from scratch for each new study.

The created model setup scripts have been licenced under the GNU General Public License. The developed models and tools have a long life-cycle and will be further improved and used to 1) assess the different nutrient and pollutant loads to the Curonian Lagoon, including bacteria transport modelling, 2) quantify anthropogenic influence on the nutrient loads; 3) assess the influence of landuse change dynamics, trends and projections on the hydrologic regime and land-based loads; 4) conduct socio-economic evaluations and assess related ecosystem services; 5) assess the effectiveness of nutrient retention measures and best management practices.

1.4 Scientific approval

The results of this study were presented in 10 international and 3 regional conferences and seminars:

1. Natalja Čerkasova, Vitalijus Denisovas, Ali Ertürk, Petras Zemlys, Georg Umgiesser. Impact of climate change on the hydrology of drainage basin of the Curonian lagoon. Abstract book of 12th international conference Littoral 2014, Klaipeda, Lithuania.
2. Natalja Čerkasova, Vitalijus Denisovas, Ligita Venckuvienė. Modeling the Effects of Potential Climate Change on The Hydrology of The Curonian Lagoon Watershed Using Soil And Water Assessment Tool (SWAT). Proceedings of the youth scientific and practical conference in the framework of Science Week XLIII SPbPU Section «Environmental Engineering». The editorial section of «Environmental Engineering». Board: Arefiev N.V. (Chief. Editor), Badenko V.L., Volkova Y.V., Gorbovskaya A.D., Zotov K.V. Kuchurina T.N.
3. Natalja Čerkasova, Ali Ertürk, Petras Zemlys, Vitalij Denisov, Georg Umgiesser. Curonian Lagoon watershed modelling and assessment of climate change impact. Abstract book of 10th Baltic Sea Science Congress, 2015 Riga, Latvia.
4. Georg Umgiesser, Ali Ertürk, Jovita Mežinė, Natalja Čerkasova, Marija Kataržytė, Gerlad Schernewski. The influence of Nemunas water on the bathing water quality in the Curonian lagoon. Abstract book of 10th Baltic Sea Science Congress, 2015 Riga, Latvia.
5. Georg Umgiesser, Ali Ertürk, Jovita Mežinė, Natalja Čerkasova, Marija Kataržytė. Bacterial pollution and its impact on the bathing water quality in the Curonian Lagoon. Abstract book of 7th European Coastal Lagoons Symposium, EUROLAG, 2016, Murcia, Spain.
6. Natalja Čerkasova, Georg Umgiesser, Ali Ertürk. Minijos baseino hidrologinio modelio sudarymo ypatumai. 9-oji Nacionalinė Jūros Mokslų ir Technologijų Konferencija Jūros ir Krantų Tyrimai. 2016. Klaipėda, Lithuania
7. Natalja Čerkasova, Marija Kataržytė, Georg Umgiesser, Eglė Baltranaitė. Curonian Lagoon bathing water quality assessment trough microbial pollution modelling. 1st Baltic Earth Conference. Conference Proceedings, 2016, Nida, Curonian Spit, Lithuania.
8. Natalja Čerkasova, Georg Umgiesser, Ali Ertürk, Jovita Mėžinė, Marija Kataržytė. Modelling microbial pollution transport in the Curonian Lagoon. Littoral 2016 «The changing littoral. Anticipation and adaptation to climate change». Biarritz. France
9. Natalja Čerkasova, Georg Umgiesser, Ali Ertürk. Development of the Nemunas River watershed model for hydrology, sediment and nutrient calculations. 2017 International SWAT Conference. 2017. Warsaw. Poland.
10. Natalja Čerkasova, Georg Umgiesser, Ali Ertürk. Nemuno upės baseino hidrologinis ir vandens kokybės modeliavimas. 9-oji jaunųjų mokslininkų konferencija „Fizinių ir technologijos mokslų tarpdalykiniai tyrimai“. 2018. Vilnius, Lithuania.

11. Marija Kataržytė, Gerald Schernewski, Georg Umgiesser, Eglė Baltranaitė, Arūnas Balčiūnas, Natalja Čerkasova and Jovita Mėžinė. New bathing sites at the Curonian Lagoon coast: Application of the Systems Approach Framework. 8th European Coastal Lagoons Symposium. 2018. Athens, Greece.
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2

Materials and methods

2.1 Study area

The Nemunas River watershed lies at 56°15‘ – 52°45‘ N and 22°40‘– 28°10‘ E; the total length of the river is 937 km, and the watershed area constitutes 97 928 km^2 (The Environmental Protection Agency, 2015). The 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 the Russian Federation Kaliningrad oblast (Fig. 1). Moreover, the mouth of the river and a significant part of the downstream is shared between Lithuania and Russian Federation Kaliningrad oblast, making it at the same time a transboundary and border river, which is a unique combination in the Baltic Sea drainage basin.

The mean annual precipitation over the Nemunas River watershed in the period from 1995 to 2015 was 698 mm, with the average long-term daily runoff of 473 m^3/s (at Smalininkai station). The total watershed area is large and the landuse is very diverse, ranging from urban areas to vast mixed forests, pine forests, agricultural plains, pastures, swamps and sandy coastal zones (see Table 1 and Table 1A in the annexes, where all the landuse types present in the watershed are compiled by N. Čerkasova).

Fig. 1. Nemunas River watershed area

***Table 1.* Most common landuse types and their percentages in the entire Nemunas River watershed area**

Nr.	Landuse type	Percentage of the total watershed area
1	Cropland/woodland mosaic	38.65
2	Dryland cropland and pasture	9.67
3	Winter Pasture	9.64
4	Pine	6.13
5	Agricultural – General	4.45
6	Forest – Deciduous	3.56
7	Forest – Evergreen	3.09
8	Winter Wheat	2.73
9	Poplar	2.68
10	Range-Brush	1.68

Many of the river sections are heavily modified and managed; dams and reservoirs are situated in the river's tributaries built for various purposes, i.e., flood control, water supply and hydroelectricity production. Crop variation and production and livestock management also differ substantially, as the watershed area covers different countries. Land management in Lithuania and Poland are similar due to same EU (European Union) regulations that are in force, however they are quite different in Belarus and Kaliningrad Oblast of the Russian Federation. However, the land management in the past (until the 1991) was the same all over the watershed, because the entire Nemunas River watershed belonged to the Soviet Union.

The soil types in the case study area, according to FAO classification (Land and Water Development Division FAO, 1995), are provided in Table 2 (for a full list, refer to the Annexes Table 2A).

***Table 2.* Most common Soil types and their percentages in the entire Nemunas River watershed area**

Nr.	Soil type	Percentage of the total watershed area
1	Eutric Podzoluvisols	43.65
2	Terric Histosols	8.63
3	Haplic Arenosols	8.45
4	Gleyic Luvisols	5.79
5	Haplic Luvisols	4.21
6	Gleyic Cambisols	3.88
7	Eutric Leptosol	2.39
8	Gleyic Podzols	2.36
9	Cambic Arenosols	2.28
10	Gleyic Arenosols	2.01

Sod-podzolic soils (FAO – Eutric Podzoluvisols) predominate in the territory of the Nemunas watershed (43.65%). They develop under the conditions of automorphic moistening and have a weakly cloddy structure. Peat bog soils (FAO – Terric Histosols) occupy 8.63% of the territory. Histosols have low bulk density and are poorly drained because the organic matter holds water very well.

2.2 Watershed modelling method and tools

SWAT is a comprehensive tool that requires hundreds of model inputs for hydrological parametrization and watershed description, some of which vary according to land use and soil attributes. In this study, a script-based SWAT input generator coded in Matlab (The MathWorks, Inc., Natick, Massachusetts, United States), was developed, hence SWAT-LAB was used to create all the input files from a set of homogenised datasets (described in Section 2.4). A script-based approach provides the flexibility to overcome the difficulties related to inconsistent data structure and availability through the region (EU and non-

EU datasets differ in data structure, accuracy and resolution), nutrient emission based data availability on administrative-level boundaries rather than sub-watersheds, inflexible and unpractical standard GIS tool functionality (for more details about the created tools and applied methods the reader is referred to Paper III). The Matlab was further used to post-process the model output data and to perform the statistical analysis.

2.3 Discretization scheme and the model setup

Drawing upon the experiences published by Hoang et al., 2017; Jencso et al., 2010; Kraft et al., 2012; Vigiak et al., 2017, 2015; Zhao and Beighley, 2016, and using the suggested model setup in the SWAT Documentation (Arnold et al., 2012), the optimum discretization method considering the realistic link of the cascade of flow and related impacts of it on the hydrographs and pollutographs and the computational burden of more advanced discretization methods, hillslope/catena-based discretion can be considered as the optimum.

There are no standard tools for SWAT that automatically generate hillslope based hydrological model domain. This is the reason why a SWAT hillslope delineation procedure and customized tools were developed in this study. The pre-processing was conducted using a series of tools developed by ArcGIS 10.4 (ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute) model builder (for further details, the reader is referred to Paper IV, Supplementary Material B).

As the modelled area is very large and the intent of the study is to provide opportunity to model landscape processes with sufficient accuracy, it was decided to split the modelled area into sub-models, each representing a sub-watershed of the main Nemunas River branch. Furthermore, to achieve better parametrisation, a separate sub-model represents the Nemunas and all smaller tributaries situated in the Belarus and Poland territories. The result of the sub-model division yielded the following configuration (see Fig. 3):

- 1 sub-model in the Belarus territory of river Neris, which is called Vilija in Belarus;
- 2 trans-boundary watersheds: Šešupė (PL, RU, LT) and Nemunas upstream (PL, BY);
- 7 sub-models with more than 95% of territory in the territory of Lithuania or entirely situated in Lithuania;
- 1 sub-model, - the Nemunas main branch - discharging into the Curonian Lagoon.

Total of eleven sub-models were setup, configured, connected and parametrized.

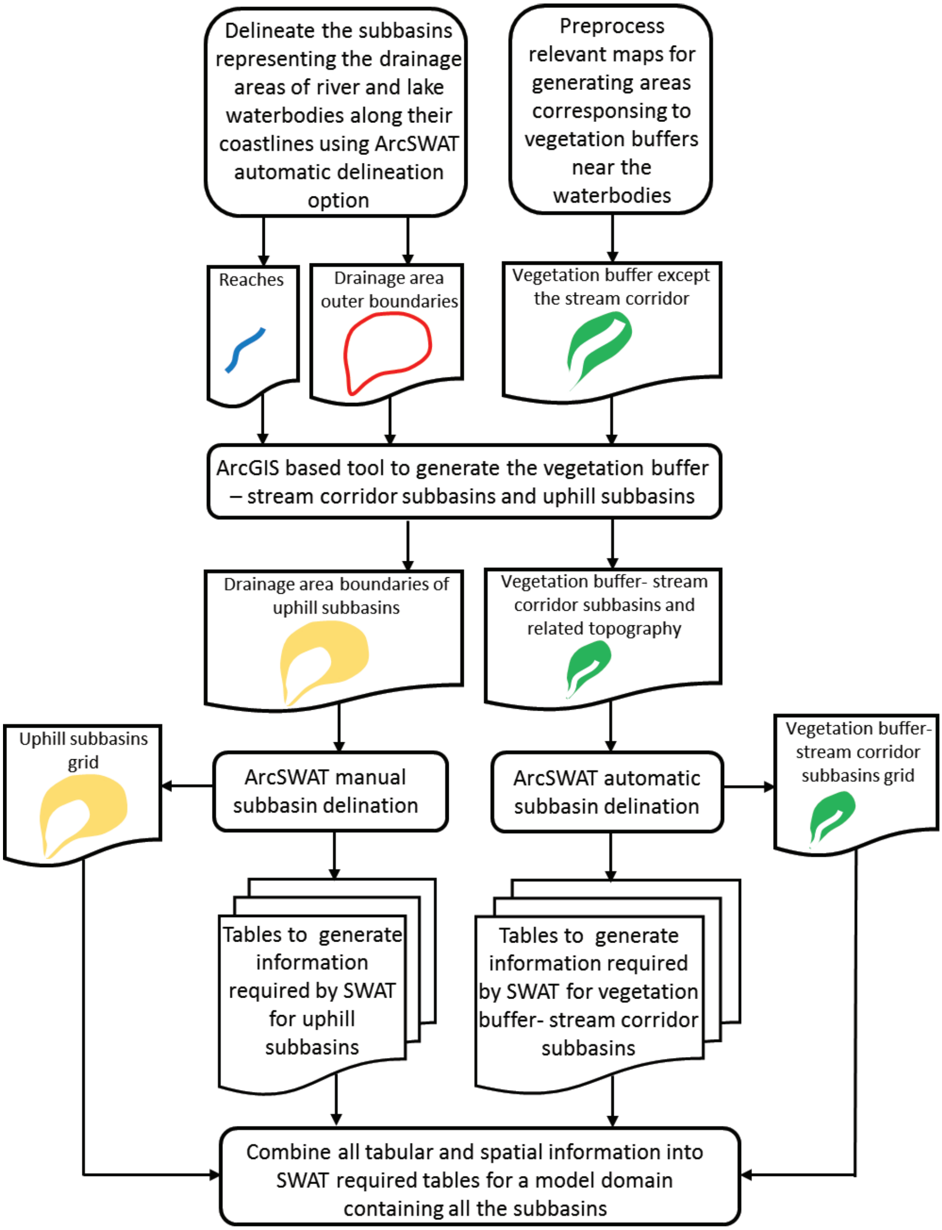

Fig. 2. Summary of the procedure for hillslope based sub-basin delineation created and used in this study

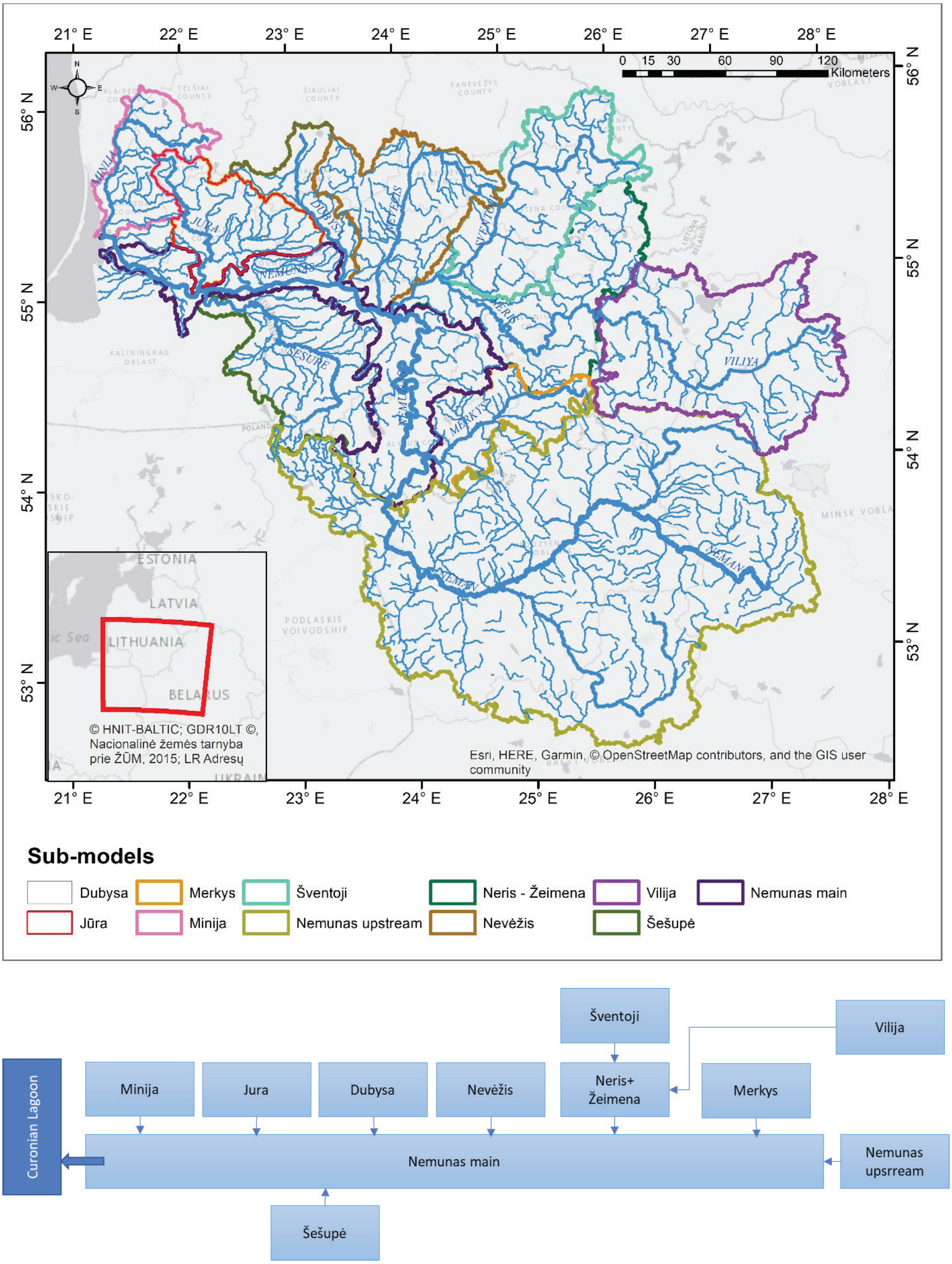

Fig. 3. Nemunas River watershed modelling framework map (top) and connectivity configuration scheme (bottom)

The produced output data for the discharge, sediment, nutrient and bacteria is then further used in the Curonian Lagoon hydrodynamic model (SHYFEM (Umgiesser et al., 2016; Zemlys et al., 2013)) with the microbiological module. An example application of the Curonian Lagoon shallow water hydrodynamic finite element model for the environmental assessments can be found in Paper II.

2.4 Used datasets

Data gathering and pre-processing for a trans-boundary model is a difficult task in many aspects. In most cases, regional high-resolution and measurement data are gathered and stored by the environmental protection agencies and other governmental institutions. Even if the data is obtained, it must be translated to the language of convenience and the measurement units have to be unified. For this study area, the data was obtained referring to several governmental sources in different countries as well as public open access databases. For the list of data sources, refer to Table 3.

Table 3. **Data sources for the SWAT model setup and their original scale**

Data layer	**Lithuania**	**Other countries (BY, RU, PL)**
DEM	National Land Service under the Ministry of Agriculture of Republic of Lithuania (digital spatial laser scanning points data of land surface of the Republic of Lithuania (National Land Service under the Ministry of Agriculture, 2009)	The Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data was used for the DEM of the Republic of Belarus and the Russian Federation Kaliningrad Oblast. ASTER GDEM is a product of NASA and METI (METI and NASA, 2009)
Original scale	5m x 5m	35m x 35m
Landuse	The National Reference Base Data Set (National Land Service under the Ministry of Agriculture, 2017)	WaterBase project database (International Institute for Software Technology and Institute for Water, 2010); Corine landcover 2012 (European Environment Agency (EEA) under the framework of the Copernicus programme, 2016)
Original scale	1:10 000	250m x 250m
Soil	National Land Service under the Ministry of Agriculture (National Land Service under the Ministry of Agriculture, 2001) and Lithuanian Soil atlas (Volungevičius and Kavaliauskas, 2012)	Global Soil FAO-UNESCO (Nachtergaele et al., 2009)

Data layer	Lithuania	Other countries (BY, RU, PL)
Original scale	1:10 000	1:5 000 000
Administrative Data	The National Center for Remote Sensing and Geoinformatics "GIS-Centras" (VĮ "GIS-centras," 2016)	Public cadastral map of the Republic of Belarus (ГУП "Национальное кадастровое агентство," 2013)
Original scale	1:10 000	1:20 000
River network	National Land Service under the Ministry of Agriculture of Lithuania (National Land Service under the Ministry of Agriculture, 2009), corrected by N. Čerkasova	Manual digitization (produced by N. Čerkasova)
Point Sources	Wastewater management accounting data (Aplinkos apsaugos agentūra, 2014)	Data aggregated from different studies in the area (Ministry of natural resources and environmental protection of the Republic of Belarus, 2014, 2009) on point source pollution
Waterbodies	GRPK – Spatial data set of (geo) reference base cadastre (The Ministry of Agriculture of the Republic of Lithuania, 2015); Map of The National Atlas of Lithuania - Distribution of lakes and ponds (Kavaliauskienė and Krikščiūnienė, 2013)	Aggregation of data from the official soviet-time construction documentation (Pluzhnikov (Плужников) et al., 1987), reports of government agencies (Ministry of natural resources and environmental protection of the Republic of Belarus, 2009), fishing enthusiasts portals (Portal of Fisheries in Belarus, 2014). In some cases, the surface area was derived from satellite images by N. Čerkasova
Weather data	Lithuanian Hydrometeorological Service under the Ministry of Environment (Lithuanian Hydrometeorological Service under the Ministry of Environment, 2014)	The Global Weather Data for SWAT from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Dile and Srinivasan, 2014)
Fertilization practices	Agri-environmental indicator - mineral fertiliser consumption (Eurostat, 2017)	Belarus statistical departments (National Statistical Committee of the Republic of Belarus, 2017)
Crop yield	Lithuanian Statistical Yearbook (Lietuvos statistikos departamentas /Statistics Lithuania, 2017)	Belarus statistical departments (National Statistical Committee of the Republic of Belarus, 2017)
Observation data	Lithuanian Hydrometeorological Service under the Ministry of Environment (Lithuanian Hydrometeorological Service under the Ministry of Environment, 2014)	Measurements at the boarders: Lithuanian Hydrometeorological Service under the Ministry of Environment (Lithuanian Hydrometeorological Service under the Ministry of Environment, 2014)

Five sets of global 0.5° General circulation models (GCM) (Table 4) data were originally extracted from ISI-MIP5 (Inter-Sectoral Impact Model Inter-comparison Project) (Hempel et al., 2013) and kindly provided by Karim C. Abbaspour for this particular area.

Table 4. **Atmosphere Ocean General Circulation Models used for climate change impact assessment**

Model abbreviation	Name	Institute
GFDL-ESM2M	Global Coupled Carbon–Climate Earth System Models; Modular Ocean Model	NOAA/Geophysical Fluid Dynamics Laboratory
HadGEM2-ES	Hadley Global Environment Model 2 - Earth System	Met Office Hadley Center
IPSL-CM5A-LR	Institut Pierre Simon Laplace - Earth System Model for the 5th IPCC report: Low resolution	L'Institute Pierre-Simon Laplace
MIROC	Model for Interdisciplinary Research on Climate	AORI, NIES and JAMSTEC
NorESM1-M	Norwegian Earth System Model 1 - medium resolution	Norwegian Climate Center

The data for the GCMs (Table 4) had undergone a bias correction using statistical downscaling against the set of observed data using the Climate Change Toolkit (Ashraf Vaghefi et al., 2017).

2.5 Scenario development and simulation setup

Climate scenarios based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Representative Concentration Pathway (RCP) 4.5 and RCP8.5 (Collins et al., 2013) were defined for this study. The RCP4.5 is a stabilization scenario, where radiative forcing alleviates at 4.5 W m^{-2} in the year 2100 without exceeding that value. The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change, thus resulting in very high greenhouse gas emissions. Altered values for minimum and maximum daily temperature and precipitation data were forced, along with CO_2 concentration change, to produce the runoff, sediment and nutrient response of the modelled area. Other modelled processes, such as management practices, reservoir operations, groundwater nutrient concentrations were not altered, thus producing the "business as usual" conditions. The short term [2040 – 2050] and long term [2090 – 2099] outputs for flow, sediments, TN and TP loads of the scenarios were compared to the baseline scenario [2000 – 2010], which represents the current conditions. The periods for the scenarios were chosen based on available monitoring data and climate projection data. A 5-year warm-up period (from 1995 to 1999) was used to initiate the models, after this, the model was run for 100 years until 2100 and the results have been analysed for the above given periods. An ensemble mean, which is the average of the applied climate model projections for a given variable, was used to quantify the changes in the projection periods.

3

Results and discussion

3.1 Model performance, calibration, validation, and limitations

When setting up the high-resolution sub-models, the calibrated parameter values of the coarse resolution model of the Curonian Lagoon drainage basin (which the Nemunas River watershed is a part of), developed and described in Paper I, were used as initial values. High-resolution sub-model calibration and validation were performed using manual calibration, by adjusting the parameters, associated with specific processes. This research is the first to utilize soft calibration techniques (Arnold et al., 2015) for a large case study with inter-connected models for hydrology and water quality, prior to the hard calibration against measured data. The models were first calibrated for yearly declared crop yields, and in the case of Belarus – the water amount in the managed waterbodies. Paper III can be referred to for further details on the transboundary model calibration. An important finding is that the statistical agreement had improved considerably for measured data, after performing only soft calibration. Nevertheless, additional calibration had to be performed when calibrating monthly and daily flows, TN, TP and sediment loads. The multisite calibration process was carried out according to calibration approach which is standard for hydrological models (Abbaspour et al., 2015; Douglas-mankin, 2015; Feyereisen et al., 2007), where one starts with surface runoff and baseflow, then the sediments and, finally, water quality (in this case – TN, TP).

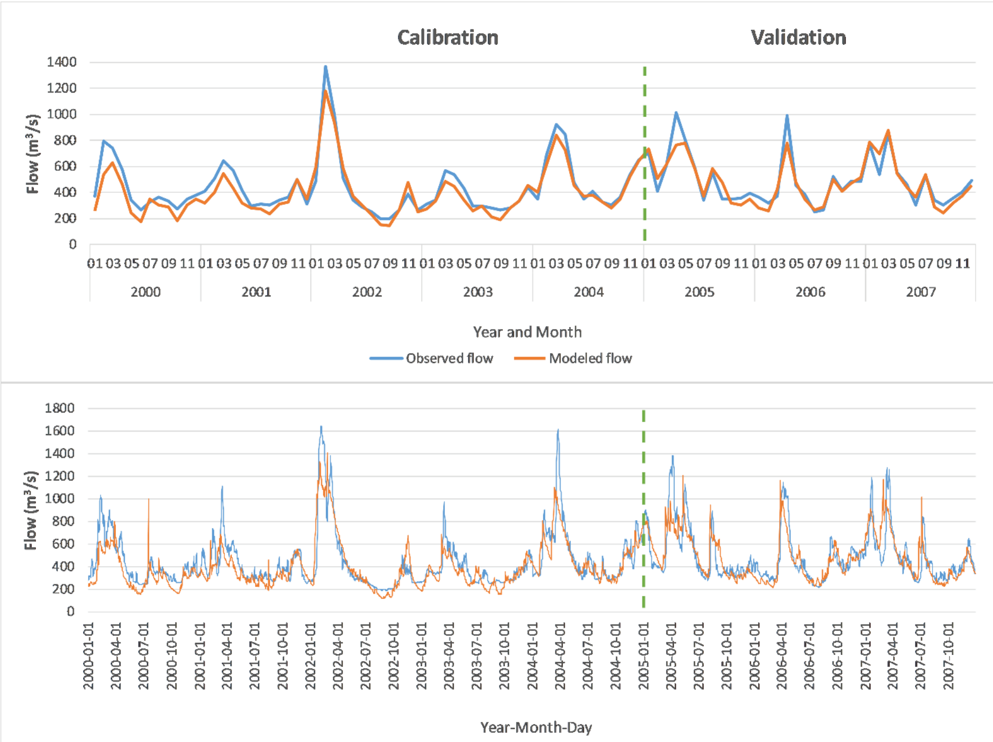

Fig. 4. Calibration and validation examples of monthly and daily flow at the Nemunas-Smalininkai station

Both, visual analysis and statistical methods were used to evaluate the model performance, based on the performance evaluation criteria for the recommended statistical performance measures applied to watershed-scale models (Moriasi et al., 2015). The general model performance through the sub-basins and sub-models was very good to satisfactory for flow, sediment load, TN and TP (summary statistics for each sub-model are presented in Table 5). A general tendency of underpredicting the high flows was observed and further discussed in Paper IV. Calibration and validation example at the Nemunas – Smalininkai station is presented in Fig. 4 for monthly and daily flow and in Fig. 5 for daily values of sediments, TN and TP loads.

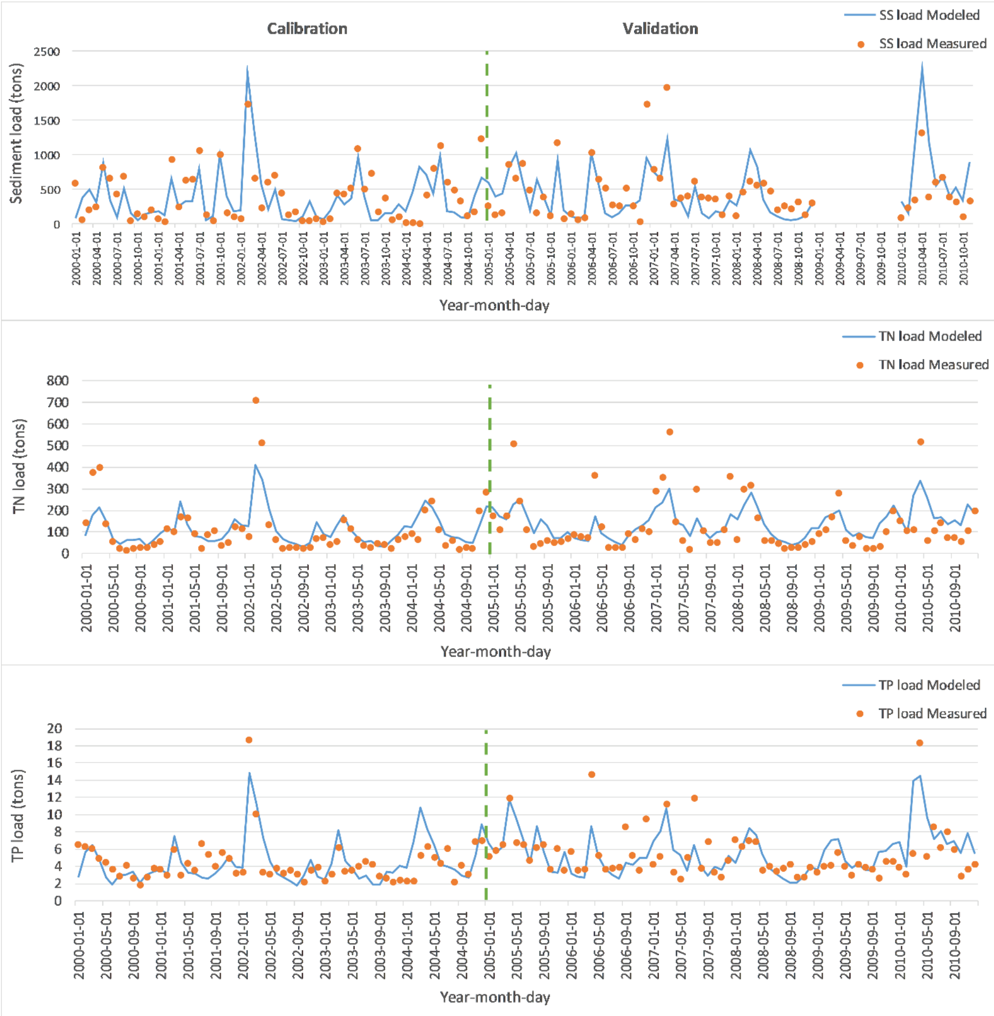

Fig. 5. Calibration and validation examples of sediment, TN and TP daily loads (tons/day) at the Nemunas-Smalininkai station for days, when the observations were available

The Nemunas River watershed modelling framework performed well in reproducing monthly and daily flows and the sediment and nutrient loads for the days, when the measurements were available. Henceforth, the models used in this framework were deemed to be suitable to simulate long-term scenarios and assessing the hydrological and land-based sediment, nutrient and pollutant loads to the rivers.

Table 5. **Calibration and validation performance statistics for every sub-model at the most downstream station: monthly average for flow, daily – for TN, TP and Sediment loads (the calibration and validation periods differ depending on data availability)**

Sub-basin	Country	Performance (calibration/validation)											
		Flow			TN			TP			Sediment load		
		R^2	NS	PBIAS	R^2	NS	PBIAS	R^2	NS	PBIAS	R^2	NS	PBIAS
Vilija	BY	0.80	0.83	-6.09	0.71	0.61	-0.54	0.55	0.52	-6.45	0.44	0.46	-8.39
		0.79	0.76	2.03	0.53	0.56	10.83	0.50	0.48	5.30	0.55	0.44	-15.3
Nemunas upstream	BY, PL	0.75	0.81	5.05	0.69	0.61	-12.4	0.63	0.65	9.7	0.54	0.56	25.3
		0.71	0.79	-4.0	0.67	0.59	-10.8	0.65	0.69	5.89	0.55	0.58	23.65
Šešupė	RU, PL, LT	0.87	0.75	-1.87	0.65	0.64	4.66	0.62	0.58	3.80	0.58	0.49	-11.32
		0.86	0.77	-4.62	0.68	0.65	13.88	0.68	0.55	3.84	0.50	0.54	6.82
Neris-Žeimena	LT	0.83	0.73	8.36	0.75	0.61	18.41	0.62	0.64	3.58	0.61	0.54	-1.21
		0.81	0.70	11.3	0.69	0.59	16.5	0.64	0.63	4.26	0.62	0.58	-1.71
Šventoji	LT	0.74	0.72	1.91	0.66	0.66	-2.88	0.42	0.40	2.35	0.63	0.55	18.83
		0.72	0.7	2.5	0.66	0.65	1.24	0.47	0.45	-9.82	0.59	0.55	24.18
Merkys	LT, BY	0.76	0.74	2.76	0.66	0.63	-1.32	0.58	0.55	0.37	0.64	0.62	2.73
		0.66	0.65	-5.9	0.56	0.58	-6.8	0.55	0.54	-1.8	0.59	0.57	0.8
Nevėžis	LT	0.74	0.73	-9.58	0.58	0.56	3.99	0.60	0.59	-0.38	0.65	0.59	26.68
		0.74	0.74	0.74	0.74	0.68	14.05	0.60	0.58	7.68	0.60	0.50	24.75
Dubysa	LT	0.81	0.8	1.02	0.67	0.65	-3.81	0.56	0.59	0.73	0.62	0.58	-3.33
		0.81	0.79	1.03	0.65	0.65	-2.89	0.57	0.55	1.9	0.63	0.6	0.25
Jura	LT	0.78	0.77	-3.83	0.61	0.55	-5.55	0.67	0.69	-10.37	0.62	0.58	-16.03
		0.80	0.81	10.11	0.59	0.54	14.68	0.6	0.57	-5.5	0.59	0.55	-2.08
Minija	LT	0.75	0.72	9.8	0.85	0.80	−11.0	0.45	0.40	−11.2	0.60	0.54	14.6
		0.70	0.68	7.1	0.63	0.62	−9.3	0.46	0.45	1.8	0.56	0.53	−11.6
Nemunas main channel (Smalininkai)	LT	0.82	0.77	2.72	0.66	0.61	-2.79	0.67	0.58	-2.61	0.56	0.58	16.26
		0.77	0.73	3.73	0.67	0.60	-1.04	0.57	0.58	-2.82	0.59	0.60	12.03

3.2 General climate change impacts on the entire watershed

Although the climate change projections displayed some dissimilarities, some general trends can be established (see Table 6). The general watershed outputs for annual average precipitation, snow-fall, ET can be analysed and compared, alongside with:

- the water stress days (simulated by comparing actual and potential transpiration of the plant),
- temperature stress days (defined as a function of daily average air temperature and the optimal temperature for plant growth),
- nitrogen and phosphorus stress days (quantified by comparing actual and optimal plant nitrogen or phosphorus levels) (Neitsch et al., 2011).

All the models under the conditions of both RCPs produced a decrease in temperature stress days and snow fall (except MIROC and NoerESM1-M under RCP4.5 for snow), meaning that the most likely outcome will be a warmer climate during all seasons. Precipitation patterns differ among the different GCMs, but neither displays significant annual increase or reduction, although the water stress days are projected to increase in all scenarios, with the highest being an almost 5-fold increase, meaning that the possible combined lower precipitation and higher temperatures will result in more arid conditions.

The mean annual results of the Nitrogen and Phosphorus stress days indicate a general tendency of decrease in Nitrogen stress days and an increase in Phosphorus stress days. The simulations were setup under the “business as usual” conditions, meaning that the current and unaltered land management was used for predictions. On average, the model estimated an increased nitrogen load and a slightly decreased phosphorus load in the entire basin. The reasons for dissimilarities in N and P availability could be revealed in the interseasonal assessments of load delivery and the projected changes in the streamflow composition and are further discussed in section 3.2.3.

When assessing the changes to the flow of the Nemunas River and land-based nutrient loads, an ensemble mean for every component was compared to the baseline loads. The projected changes under the conditions of different GCMs vary. Therefore, a prediction band is added to every graph to cover the values of all modelled future outputs (of the entire ensemble) and can be judged as the variation in the prediction data. The multi-model ensemble analysis approach emphasizes the uncertainty in climate predictions resulting from structural differences in the global climate models. To further illustrate the difference between the GCMs, see Fig. 6, where the outputs of every GCM for two RCPs for the long-term scenario are compared to the baseline.

Table 6. **Average annual projected changes (in percent) in the entire projection period of the Nemunas River watershed, compared to the baseline.**

GCM	GFDL-ESM2M		HadGEM2-ES		IPSL-CM5A-LR		MIROC		NoerESM1-M	
RCP	**4.5**	**8.5**	**4.5**	**8.5**	**4.5**	**8.5**	**4.5**	**8.5**	**4.5**	**8.5**
Water stress days	+50.2	+115.5	+425.1	+451.8	+425.1	+108.0	+110.4	+105.6	+251.0	+251.4
Temperature stress days	-9.9	-17.8	-24.8	-28.0	-24.8	-31.9	-25.1	-29.3	-17.2	-20.6
Nitrogen stress days	+0.8	-1.2	-7.0	-13.4	-7.0	-11.7	-7.6	-11.0	-7.9	-13.9
Phosphorus stress days	+16.1	+23.6	+15.3	+8.5	+15.3	+26.0	+22.8	+18.7	+19.0	+14.4
Precipitation	+8.1	+4.1	-4.3	-5.8	-4.3	+5.2	+8.4	+11.1	+0.3	-1.9
Snow fall	-31.4	-17.0	-28.9	-39.7	-28.9	-41.0	+18.0	-19.0	+2.7	-4.1
ET	+9.0	+9.5	+0.5	-0.2	+0.5	+10.0	+14.2	+15.0	+13.5	+12.3

On average, the simulated flow of the Nemunas River under the HadGEM2-ES is less, than the baseline in all the months, while conditions of GFDL-ESM2M result in a decrease in flow only in April, July, August, September, October and November. The IPSL-CM5A-LR, MIROC and NoerESM1-M display a better agreement in the projected interseasonal flow change. The reasons for such different outputs are likely attributed to the uncertainty due to the variations in the climate model initial conditions or model parameterisations. It was reported that HadGEM2-ES outperforms other models especially for surface conditions (Yin et al., 2013), although not in the European region, therefore a more in-depth analysis of climate model performance for the region of Nemunas watershed is needed to identify the sources of such uncertainties and model variations. One good example is given by Lutz et al., (2016), where a 3-stage climate model selection procedure is proposed, which aims at combining the strengths of envelope-based and past-performance-based selection of GCMs for impact studies, and could be adapted in future studies.

Fig. 6. Difference in the average monthly flow of the Nemunas River (at Smalininkai station) for used GCMs under the conditions of RCP4.5 (top) and RCP8.5 (bottom) compared to the baseline scenario

3.2.1 Future trends of the Nemunas River discharge

The Nemunas River watershed modelling framework can produce different outputs, based on the model setup and the research aims (Arnold et al., 2012). Monthly and annual outputs for flow, sediment, TN and TP loads for the specific near-term [2040 – 2050] and long-term [2090 – 2099] periods were of prime interest for this study. However, the analysis may be conducted on the entire simulation period (see Fig. 7) or a different output may be analysed, i.e., bacteria (*E.coli*) load and transport, needed for studies such as described in Paper II.

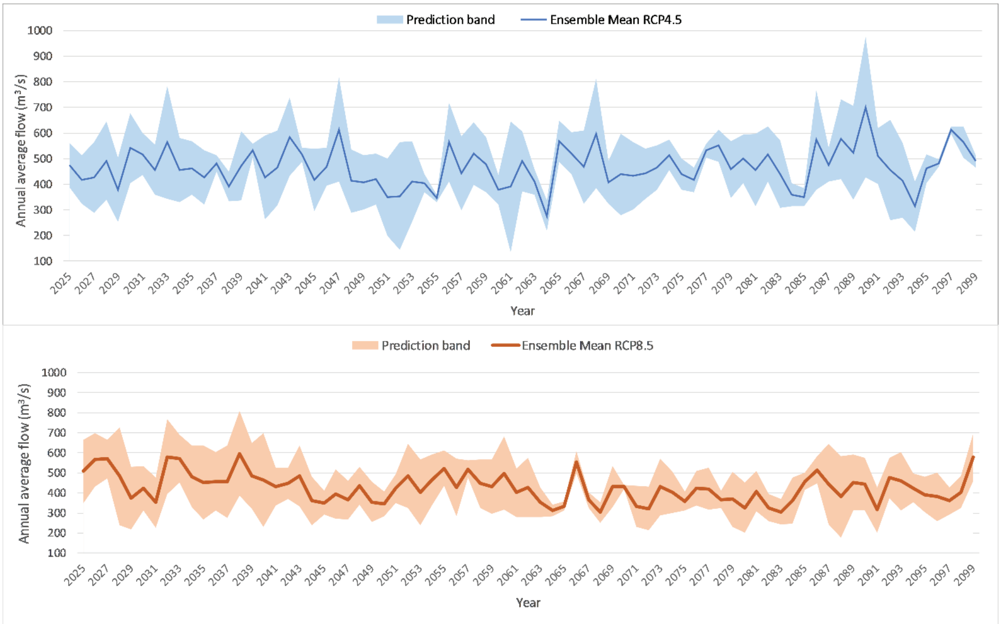

Fig. 7. Annual average projected flow under RCP4.5 (top) and RCP8.5 (bottom): the line represents the ensemble mean; the coloured band – the prediction band

The annual average projections for the Nemunas River discharge show no clear pattern, with no trend detected by the Mann-Kendall (MK) test with 1% significance level (Henry B. Mann, 1945; Kendall, 1975). The variability among the GCMs is higher under the conditions of the RCP4.5. Although there are no clear trends in the projected mean annual flows, the variability between the GCMs becomes smaller by the end of the century, meaning that the outputs for GCMs under RCP4.5 and RCP8.5 are in agreement in the long-term period [2090 – 2099].

Seasonal Kendall Test (SK test) (Gilbert, 1987; Helsel and Hirsch, 1995; Hirsch et al., 1982; Hirsch and Slack, 1984) was used to determine the monotonic trend in monthly projected values for river discharge. No trend was detected in both periods in the RCP4.5 and RCP8.5, although an increasing trend was determined in the baseline period ($p<0.001$, Sens slope = 22.81).

The interseasonal flow change in all scenarios suggests an increase in mid to late-winter water delivery to the Curonian Lagoon, which coincides with the projected snow formation decrease in the entire watershed (see Table 6), meaning the increasing proportion of winter precipitation falling as rain. On average, the projected Nemunas River flow will increase in all winter months under the RCP4.5, both in near and long-term (December: +44%, January: +59.7%, February: +29.3%), while in RCP8.5 near-term shows an increase only in December (+10%) and January (+6.5%) and the entire winter for long-term (December: +22%, January: +44.5%, February: +18.9%) (see Fig. 8).

A clear signal is a reduction of flow in the spring to fall seasons in the RCP8.5, both for near and long-term periods (Fig. 8 on the right). The RCP8.5 is considered a "worst-case" scenario, therefore it is expected that the projected changes will be the strongest in absolute terms. Here, an average flow decrease of Nemunas River is projected under the conditions of all the GCMs (the green baseline falls above the orange projection band in all months from April until November), therefore a likely scenario is a reduction in spring to fall flows if the global development and emission trends follow the RCP8.5.

On the other hand, if the global development and emission trends follow a stabilisation scenario, then it is likely that the Nemunas River flow will experience a hydrologic shift towards higher winter discharges and lower late summer-early fall discharges (Fig. 8 on the left), although the ensemble mean falls much lower in the long-term period in months from June to October, but is still well within the boundaries of the projection band.

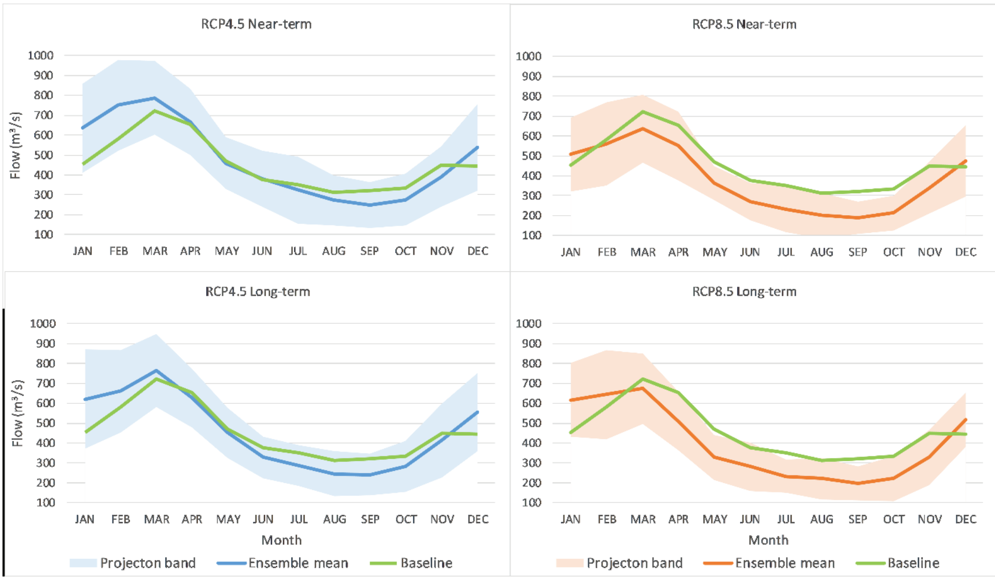

Fig. 8. Interseasonal projected flow at the Nemunas – Smalininkai station compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

These results might indicate a change in the exchange mechanism of the Curonian Lagoon, with higher exchange between the lagoon and the sea in the winter and lower in the summer. This in turn will increase the difference in water residence times

(WRT), lowering already low WRTs in winter even more and increasing already high WRTs in summer (Umgiesser et al., 2016). This decreased exchange may have an influence on the blooming of cyanobacteria and other biota in the lagoon, however, a coupled hydrologic and hydrodynamic model simulation, which would quantify the effect of the Nemunas River inflow and Baltic Sea intrusions on the water residence time in the Curonian Lagoon, is needed to further determine the possible outcomes.

3.2.2 Future trends in sediment loads to the Curonian lagoon

The projected sediment load change follows the same patterns as the flows, although the relationship is not linear, and some variations occur. The largest difference in absolute terms is projected in the RCP4.5 scenario near-term period, where the ensemble mean of sediment load is much higher (two-fold increase) in winter (December to February) and a 20% increase in early spring (March to April) (see Fig. 9 left). An increase is modelled for the long-term period under the same emission scenario as well (93% increase in January-February, and up to 16% in March-April). It is noteworthy that the baseline loads fall well into the bound of the projection band; moreover, the ensemble mean and the baseline are very similar for the most of the months: from May to November.

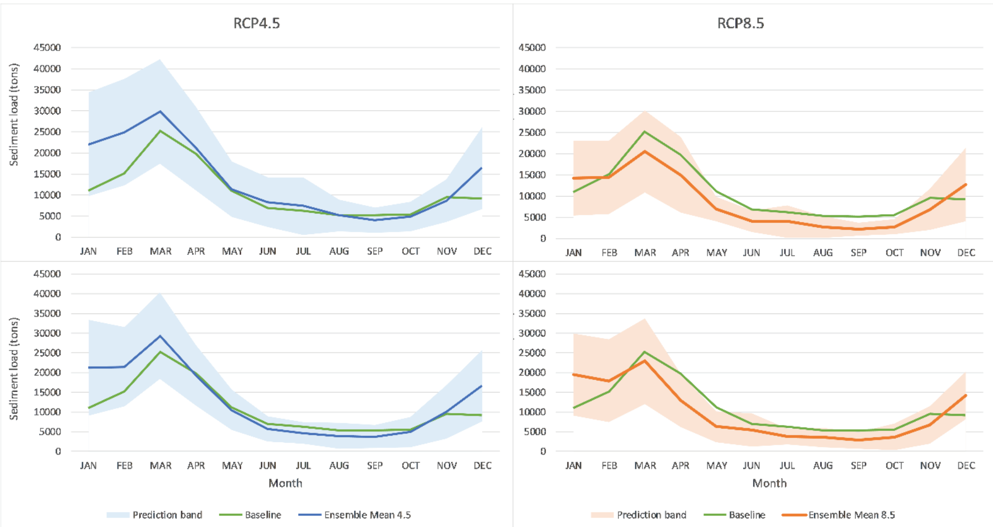

Fig. 9. Interseasonal projected sediment load at the Nemunas – Smalininkai station compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

The simulated sediment loads under the conditions of the RCP8.5 differ: the projected ensemble mean falls much lower than the baseline, which is only covering the upper limit of the projection band (Fig. 9 right). Similarly to the flow, it is likely that the sediment loads, delivered with the Nemunas River to the Curonian Lagoon will decrease from March until November (up to 20% decrease), if the climate follows the RCP8.5 emission scenario. For the winter season, the current baseline falls within the boundaries of the projection band, although lower than the ensemble mean (up to 28% increase). The increased sediment delivery and erosion is likely attributed to lower snow cover in the winter months, when the vegetation goes dormant revealing and exposing the soil to erosion. With soil erosion it is expected that the nutrient loss for winter will increase as well, especially for the particle-bound nutrients. With the increase of particle-bound nutrients delivery to the Curonian Lagoon, two possible outcomes may occur depending on the hydrodynamic conditions in the lagoon: settling or export to the Baltic Sea. It is found that the Curonian Lagoon was a net sink of TP (during 2011 and 2013) (Petkuviene et al., 2016), although a detailed modelling study on how the projected interseasonal TP loads will effect the lagoons capacity to retain TP in the future is needed.

3.2.3 Future trends in nutrient loads to the Curonian lagoon

The resulting TN and TP load change is governed by changes in hydrology as well as land-based processes and displays a similar character to the already discussed hydrologic changes: a net increase of TN delivery to the Curonian Lagoon though the Nemunas River is modelled in winter months (December to February): up to 32%, with a slight increase of the ensemble mean compared to the baseline in spring (March to May): up to 7% (Fig. 10). The resulting changes in other months are minor and fluctuating. The baseline falls within the projection band for the TN in both RCP4.5 and RCP8.5.

An important finding is that despite the projected hydrological changes, increased ET and possible longer vegetation season, the TN delivery is not projected to decrease, even in the conditions of the RCP8.5, although a slight decrease of the ensemble mean compared to the baseline is modelled in the near-term RCP8.5 scenario for summer-fall months (by 27%). This finding strongly suggests that the use of nutrient reduction and retention measures are necessary if Lithuania strives to comply with the Baltic Sea Action Plan and reduce the nutrient loads to the Maximum Allowable Inputs levels (Svendsen et al., 2018).

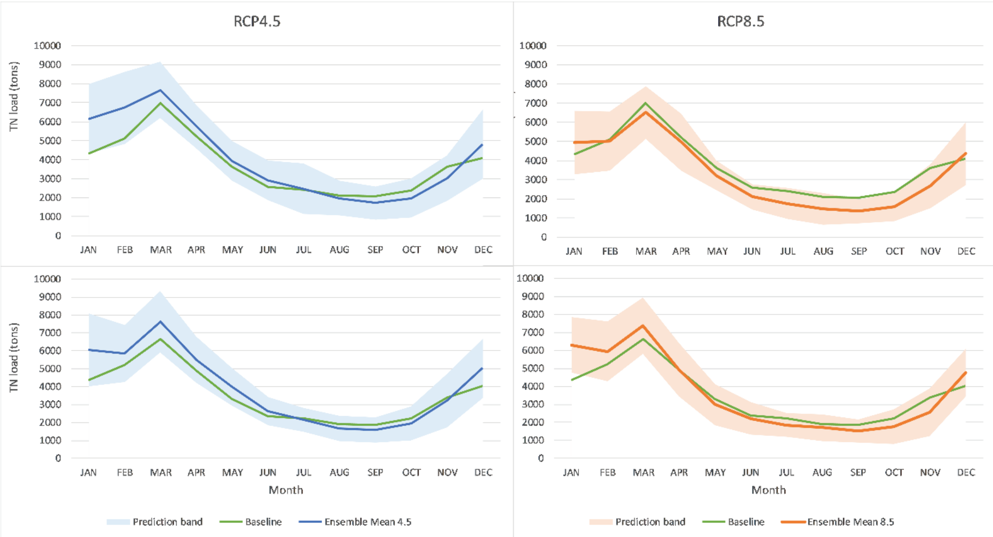

Fig. 10. Interseasonal projected TN load at the Nemunas – Smalininkai station compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

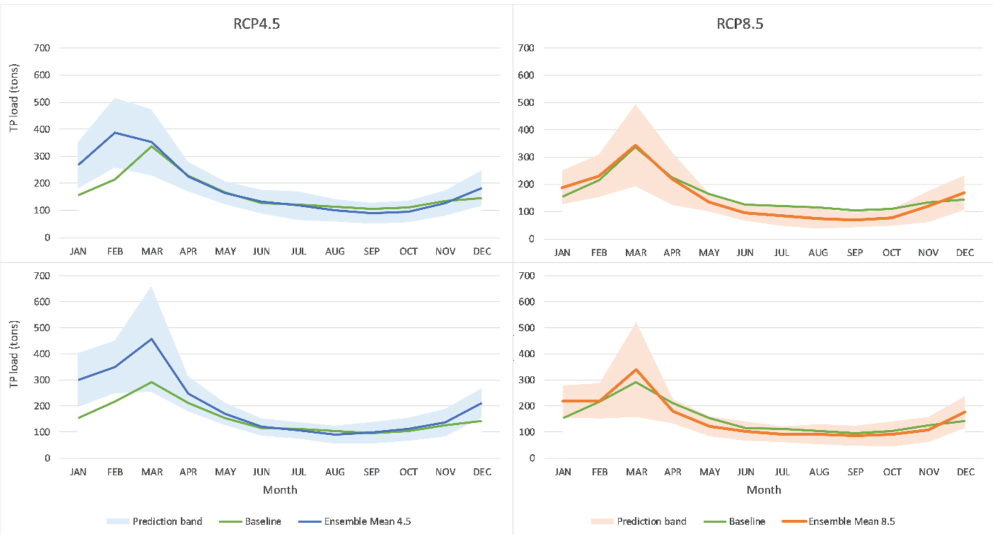

Fig. 11. Interseasonal projected TP load at the Nemunas – Smalininkai station compared to the baseline: top – near-term projections (up to 2050); bottom – long-term projections (up to 2100)

The projected changes to the interseasonal TP loads display a somewhat different trend. The most significant change is projected in the winter and early spring season in months from December to March, especially in the long-term period under the conditions of the RCP4.5: up to 62% increase (Fig. 11 left). The projection mean and band lay well above the baseline in January and February, therefore it is likely that the TP load will increase in this period. The increased TP load is primarily associated with the increased sediment loads during the same period, which is the source of particle bound phosphorus. The delivered forms of phosphorus to the Curonian Lagoon may be retained or get exported. In previous studies, it was determined that in the bloom years the Particulate Phosphorus (PP) export from the lagoon exceeded imports, while in other years it was closely balanced (Vybernaite-Lubiene et al., 2018). Even if the combination of hydrologic changes and the loads might result in a different system behaviour, coupled hydrologic, water quality (watershed-scale) and hydrodynamic (lagoon and transitional zones) models with a water quality module can be used to further test these hypotheses.

Despite the projected reduction of flow under the conditions of RCP8.5 (refer to Fig. 8), the projected TP loads under the same conditions do not decrease substantially (8% decrease for the near-term), and in case of long-term period remain similar to the baseline (Fig. 11 right). The source of the phosphorus load has to be addressed here. While the surface runoff is projected to decrease substantially under the RCP8.5, the groundwater contribution to the streamflow will remain similar. Phosphorus is present in the groundwaters of Lithuania and Belarus (Environmental Protection Agency of Lithuania, 2010; Ministry of Natural Resources and Environmental Protection of the Republic of Belarus, 2014) and is considered in the modelling framework. Although the groundwater phosphorus module is considered to be a rather weak point of SWAT, it can be said that if the groundwater conditions do not improve, the resulting TP load will not decrease under the conditions of projected climate of RCP8.5 scenario. The finding further implies that the effective nutrient load reduction and retention measures have to be implemented through the Nemunas watershed to reduce the nutrient delivery to the Curonian Lagoon and, subsequently, to the Baltic Sea.

The finding of the study suggests that most changes are likely to occur in winter, especially in January and February. A decrease in snow cover across large areas together with the linked greater frequency of soil freeze-thaw cycles may weaken the nutrient retention of soils and increase the losses of carbon, nitrogen and phosphorus at thaw (Wipf et al., 2015). This information can be used to target, assess and implement those nutrient retention measures, which are most effective in the winter season (Judd et al., 2007; NOE and HUPP, 2007; Zhou et al., 2017), alongside with the general nutrient application reductions in the agriculture sectors.

3.2.4 Hydrologic and hydrodynamic model coupling: future trends in microbiological pollution

The created Nemunas River watershed hydrologic and water quality model can be coupled with the Curonian Lagoon hydrodynamic model. The components of such modelling system can be loosely coupled, meaning that the modules can be replaced with alternative implementations that provide the outputs of the same structure.

The SWAT model outputs are written in a standard described in the SWAT I/O Documentation (Arnold et al., 2012). As the Curonian Lagoon hydrodynamic model is developed and implemented in SHYFEM (Ferrarin et al., 2008; Umgiesser et al., 2004), the outputs of SWAT which can be used as boundary conditions (inputs) for SHYFEM should be restructured. This can be achieved in an automated manner by utilising MATLAB, Python or R scripts to pre-process the output files to be successfully read as SHYFEM inputs. The boundary conditions, which can be produced by the Nemunas River watershed modelling framework are: daily flow, sediment concentration, sediment load, Organic N load, NO_3 load, NH_4 load, NO_2 load, Mineral P load, Chlorophyll-a, Carbonaceous biochemical oxygen demand, dissolved oxygen, soluble pesticide, pesticide absorbed to sediment, number of persistent bacteria, number of less persistent bacteria, conservative metal, Total N, Total P, NO_3 concentration, water temperature; where most of these loadings can be further handled by SHYFEM.

The coupled watershed-lagoon modelling system was used to assess the possible future microbiological pollution (with *E.coli* as an example) in the Curonian Lagoon in the light of RCP4.5 and RCP8.5 *E.coli* concentration conditions. It was found that the microbiological pollution reaching the Curonian Lagoon from the Nemunas River will decrease on average by 7% in the RCP4.5 and by 15% in the conditions of RCP8.5 (Fig. 12).

With the simulations of both models carried out it becomes clear that the changed input of microbiological pollution through the Nemunas (which discharges on the eastern side of the Curonian Lagoon) does not influence pollution in other areas of the lagoon, so there might be a risk of exceeding the threshold for sufficient bathing water quality in coastal and transitional waters, according to the Bathing Water Directive (European Parliament and of the Council of European Union, 2006). The time it takes for the bacteria to be transported from one shore of the lagoon to the other is much longer than the *E.coli* typical survival rate, thus no major threats are projected under the conditions of RCP4.5 and 8.5, even if severe meteorological conditions (i.e. stronger winds, which result in higher current speed in the lagoon) are forced. A description of the detailed analysis of the microbiological pollution risk assessment in the Curonian Lagoon can be found in Paper II.

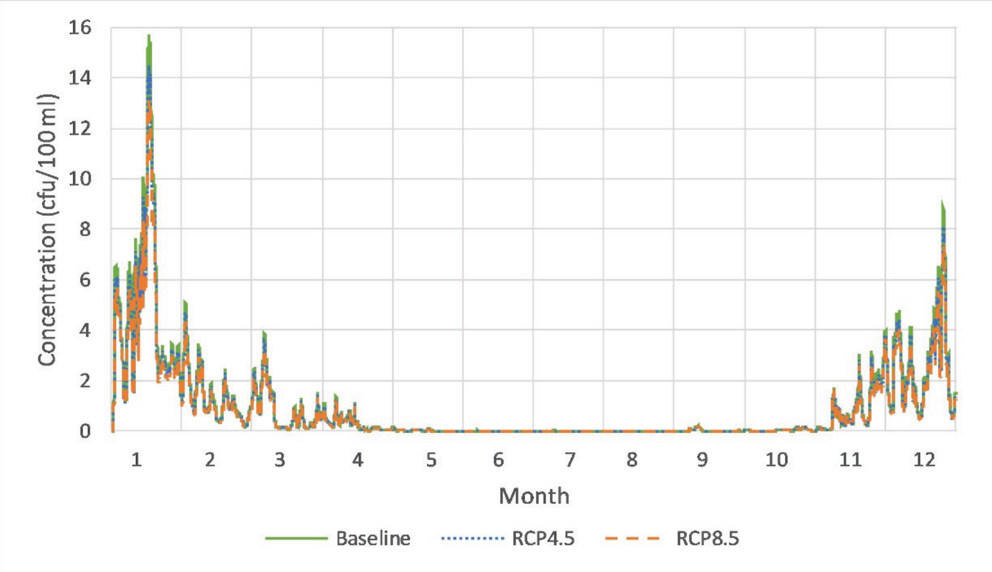

Fig. 12. E. coli concentration in the Nemunas Delta for the baseline scenario and under the conditions of RCP4.5 and RCP 8.5

As the models are loosely coupled, one module can be replaced or enhanced without changing the other modules. This provides a flexible modelling framework for future developments and ensures a long life-cycle of the models and many potential usages of the entire system, where one could model the entire path of an entity from the source (land-based load in the watershed), through the transitional zone (the Curonian Lagoon) to the sink/export point (the Baltic Sea).

3.2.5 Future work and model development

The future work on the Nemunas River watershed includes a more realistic modelling framework development with the use of geographical units, such as wetlands in general, wetlands adjacent to rivers, flood pains and stream corridors. Having incorporated the hillslope discretization in this study was a milestone in that direction. The created Nemunas watershed modelling framework is flexible and can be ported to the newly developed SWAT Plus (J.G. Arnold, K. Bieger, M.J. White, R. Srinivasan, 2017) that is better at addressing the geographical issues. Other works on the framework include the sub-model calibration for different forms of nutrient loadings (PO_4 and Organic P, NO_3, NH_4, NO_2 and Organic N).

The calibrated and validated modelling framework will be used to assess the best management practices for nutrient load reduction and to evaluate the feasibility of the nutrient reduction measures. An evaluation of all the possible nutrient reduction measures will be undertaken, to determine, if Lithuania can possibly reach the nutrient load reduction targets defined by HELCOM (HELCOM Ministerial Meeting, 2007). It is expected that an international collaboration between riparian countries of the Nemunas River watershed is essential to meet the required targets. This study, together with the created tools and methods, can serve as a common platform for decision makers to quantify the effectiveness of nutrient retention or load minimisation measures. The created modelling tools and scripts will be used to setup hydrological watershed models for other regions (e.g., Venice Lagoon watershed) and will be further developed, including the implementation of the landuse dynamics, which the current study lacks.

A coupled Nemunas River watershed – Curonian Lagoon model will serve as a wonderful tool to calculate various scenarios and conduct assessments (climate change impacts, ecosystem impacts, biogeochemical changes, etc.), which will further broaden our knowledge and understanding of the functioning of transitional and coastal systems. In addition, a feasibility study to establish a MREA (Marine Rapid Environmental Assessment) tool for the Curonian Lagoon will be conducted.

4

Conclusions

1. The annual average projections for the Nemunas River discharge show no significant trend. The variability among the GCMs is higher under the conditions of the RCP4.5, than RCP8.5, with a better projection agreement for flow outputs from GCMs under RCP4.5 and RCP8.5 in the long-term period [2090 – 2099].

2. The interseasonal variation in all scenarios suggests an increase in mid to late-winter water delivery to the Curonian Lagoon (by up to 44.3%), which coincides with the projected snow formation decrease in the entire watershed for the near-term [2040 – 2050] and the long-term [2090 – 2099] periods, compared to the baseline. The flow is projected not to change or to decrease slightly in the warmer seasons (late spring to late early fall). This in turn will increase the difference in water residence times, lowering already low water residence times in winter even more and increasing already high water residence times in summer.

3. The largest difference in sediment load change is projected in the RCP4.5 scenario near-term period, where the ensemble mean of the sediment load is two-fold higher in winter (December – February) and 20% higher in the early spring (March – April). Similar changes are modelled for the long-term period under the same emission scenario. The projected ensemble mean for sediment load under the conditions of RCP8.5 falls much lower (by 20%) than the baseline, which is only covering the upper limit of the projection band. Similar to the flow, it is likely that the sediment loads,

delivered with the Nemunas River to the Curonian Lagoon will decrease from March until November, if the climate follows the RCP8.5 scenario.

4. A net increase of TN delivery to the Curonian Lagoon from the Nemunas River watershed is modelled in winter months (December to February) (by 32%), with a slight increase (by 7%) of the ensemble mean compared to the baseline in spring (March to May). The baseline falls within the projection band for the TN in both RCP4.5 and RCP8.5.

5. The most significant change in TP load is projected in the winter and early spring season in months from December to March, especially in the long-term period under the conditions of the RCP4.5 (up to 62% increase). Despite the projected reduction of flow under the conditions of RCP8.5, the projected TP loads under the same conditions do not decrease substantially, and in case of long-term period remain similar to the baseline.

6. Possible future sediment and nutrient load projections strongly suggest that the use of nutrient reduction and retention measures is necessary and will remain such in the future if Lithuania strives to comply with the Baltic Sea Action Plan and reduce the nutrient loads. As the winter season is projected to get warmer in the future in all scenarios, the nutrient export from the watershed will strongly depend on the frequency of freezing and thawing cycles. The findings also show that most changes are likely to occur in January and February, thus the recommended action would be to target, assess and implement those nutrient retention measures, which are the most effective in winter.

7. The microbial pollution (*E.coli*) that is delivered to the lagoon from Nemunas River is likely to decrease by 7% in the conditions of RCP4.5 and by 15% under RCP8.5. There is no immediate risk for the coastal areas of the Curonian Lagoon to exceed the threshold for bathing water quality in coastal and transitional waters, as the *E.coli* typical survival rate is much less that the time it takes for the microbial pollution to be transported from the Nemunas delta to other areas of the lagoon.

8. The combination of the hydrologic changes in the watershed and interseasonal variation of nutrient and sediment loads to the Curonian Lagoon might result in various system behaviour responses, ranging from the increased cyanobacteria blooms to an increase of the net nutrient export to the Baltic Sea. Coupled hydrologic and water quality (watershed-scale) and hydrodynamic (lagoon and transitional zones) models can be used to further test these hypotheses.

5

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7

Summary in Lithuanian

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Temos aktualumas

Upių nuotėkio, mikrobiologinės taršos, maistinių medžiagų ir nuosėdų iškrovos iš upių baseinų į pakrančių regionus. Antropogeninė veikla daro įtaką upių baseinams, pakrančių zonoms ir jūros ekosistemoms pasauliniu mastu ir visais gyvybės kompleksiškumo lygmenimis. Spaudimas, kurį patiria vandens ištekliai, blogėjanti vandens kokybė ir su klimato kaita susijęs neapibrėžtumas sukuria konfliktinę aplinką didelėse ir sudėtingose upių baseinų sistemose (Rouholahnejad et al., 2014). Egzistuoja vis daugiau įrodymų, kad Europos pakrančių sistemos (įskaitant jūrinės zonas ir upių baseinus) sparčiai degraduoja, o tai savo ruožtu kelia didelį iššūkį politinių sprendimų formuotojams ir pakrančių valdytojams (Iglesias-Campos et al., 2015). Vis daugiau tyrimų šiuo metu skiriama sprendžiant, kaip įvairūs socialiniai ir ekonominiai veiksniai, klimato kaita ir žemės valdymo priemonės veikia upių maistinių medžiagų eksportą ir mikrobiologinę taršą upių baseinuose (Magdoff et al., 1997; Mallin et al., 2000). Taršos šaltinių identifikavimas, kiekybinis vertinimas ir prioritetų nustatymas yra esminė užduotis siekiant išskirti pasklidosios taršos įtaka vandens kokybei. Ši užduotis yra sudėtinga dėl daugybės įvairių taršos šaltinių ir riboto duomenų prieinamumo, kas gali lemti nepatikimą vertinimą ir visuomenės suvokimo pasiskirstymą, galiausiai trukdant valdymo veiksmų pažangai (Tosic et al., 2018).

Siekiant įgyti kritines žinias apie tiriamas upių sistemas, dėl šių sistemų sudėtingumo ir didelio masto, rekomenduotina naudoti matematinius modelius. Integruoti hidrologiniai ir vandens kokybės modeliai buvo sukurti ir pritaikyti atlikti įvairius tyrimus, pradedant nuo klimato kaitos poveikio gėlojo vandens prieinamumui vertinimo iki vandens išteklių sudedamųjų dalių analizės, pasėlių derlingumo ir vandens kokybės problemų sprendimo tiek regioninio, tiek viso žemyno kontekste (Abbaspour et al., 2015 Arnold et al., 2000; Bär et al., 2015).

Maistinių medžiagų apkrovos valdymas Baltijos jūros regione. Neseniai paskelbta Baltijos jūros būklės ataskaita rodo, kad daugiau kaip 97 % Baltijos jūros kenčia nuo eutrofikacijos dėl ankstesnio ir dabartinio pernelyg didelio azoto ir fosforo išplovimo (HELCOM, 2018a). Dėl to, kad Baltijos jūros aplinkos apsaugos komisijos valstybės narės (angl. HELCOM) įgyvendina Baltijos jūros veiksmų planą, medžiagų patekimas iš žemyninės dalies gerokai sumažėjo, tačiau šių priemonių poveikis dar nėra pastebimas. Prisitaikymas prie klimato kaitos yra pagrindinis klausimas maistinių medžiagų kiekio mažinimo planavimo ir įgyvendinimo aspekte, taip pat koreguojant maistinių medžiagų kiekio mažinimo schemą, siekiant užtikrinti Baltijos jūros aplinkos apsaugą kintančiame klimate.

Keletas Baltijos jūros regione atliktų tyrimų apėmė klimato kaitos poveikį upių nuotėkiui dideliu (Tarptautinis Baltijos žemės sekretoriatas, Donnelly et al., 2014; Graham, 2004), vidutiniu ir mažu mastais (Rimkus et al., 2011; Stonevičius et al., 2017). Kiti tyrimai buvo susiję su maistinių medžiagų apkrovos kiekio pokyčiais (Cousino et al., 2015; Pilipchuk et al., 2014; Povilaitis et al., 2018) iš įvairių Baltijos jūros baseinų zonų. Kai kurie tyrimai rodo, kad dabartinės klimato kaitos tendencijos regione gali paskatinti papildomai sugriežtinti maistinių medžiagų kiekio mažinimo tikslus (Meier et al., 2012).

Didžioji maistinių medžiagų dalis patenka iš Lietuvos teritorijos į Baltijos jūrą per Nemuną, ketvirtą pagal dydį upę, įtekančią į Baltijos jūrą (HELCOM, 2018b). Nemuno upės baseino hidrologinis modelis gali būti panaudotas siekiant įvertinti hidrologinius, mikrobiologinius, nuosėdų, maistinių medžiagų dinamiką klimato kaitos atžvilgiu bei žemės ūkio praktikas ir kitus veiksnius. Sukurtas modelis turėtų būti lankstus, kad jį būtų galima naudoti didelio masto (visuose baseinuose), vidutinio (pabaseiniuose) ir mažo masto scenarijų skaičiavimo procesuose, taip pat taikyti sujungtoje baseino–pakrančių zonos modeliavimo sistemoje. Sujungtos hidrologinės ir vandens kokybės (upės baseino) bei hidrodinaminės (marių ir pereinamųjų zonų) modeliavimo sistemos gali būti toliau naudojamos vertinant galimas valdymo, politikos sprendimų ir klimato kaitos pasekmes visam regionui.

Nuotekų, maistingųjų medžiagų ir nuosėdų apkrovos įvertinimas ir prognozės Nemuno upės baseine. Nemuno upės baseine buvo taikomi keli hidrologiniai modeliai (HBV, MIKE ir pan.) įvairiuose tyrimuose vertinant skirtingų stresorių poveikį sistemai. SWAT (angl. Soil and Water Assessment Tools – dirvožemio ir vandens vertinimo įrankis) naudojamas Lietuvos aplinkos apsaugos agentūroje kuriant azoto ir fosforo balanso ir susilaikymo skaičiavimo metodikų bei pasiūlymų vandens telkinių apkrovos teršalais skaičiavimo Lietuvos metodikai parengimo bei Lietuvos situacijos pagal parengtas metodikas įvertinimo procese. Nemuno upės baseino prisitaikymo prie klimato kaitos strateginė programa buvo parengta pagal tarptautinį projektą „Upių baseinų valdymas ir prisitaikymas prie klimato kaitos Nemuno upės baseine" remiantis Jungtinių Tautų Europos ekonomikos komisijos programa bei su tarptautinės aplinkosaugos ir saugumo iniciatyvos ir Jungtinių Tautų vystymo programos Baltarusijos Respublikoje (Korneev et al., 2015) parama, kuriose įvertinami galimi vandens išteklių pokyčiai visame baseine. Ši strateginė sistema yra puikus pavyzdys sprendžiant problemas, susijusias su vandens ištekliais baseinų lygmenyje. Tačiau šiame tyrime yra akcentuojami hidrologiniai klausimai ir jis nėra pakankamai išsamus, kad būtų galima įvertinti galimus tarpsezoninius pokyčius, nenurodant nuosėdų arba maistinių medžiagų apkrovas.

Tyrimo tikslas ir pagrindiniai uždaviniai

Šio tyrimo tikslas yra įvertinti Nemuno upės baseino hidrologinę, nuosėdų ir maistinių medžiagų dinamiką klimato kaitos, žemės ūkio ir kitų žmogaus sukeltų veiksnių atžvilgiu ir išanalizuoti galimas maistinių medžiagų ir nuosėdų apkrovas bei mikrobiologinės taršos pasekmes taikant didelės skiriamosios gebos modeliavimo metodus.

Šios disertacijos uždaviniai:

1. pritaikyti hidrologinio modeliavimo metodus ir priemones bei sukurti hidrologinį modelį, kuris gali apibūdinti Nemuno upės baseino vandens, nuosėdų ir maistinių medžiagų dinamiką;
2. pritaikyti sukurtą modelį prognozuojant su klimato kaita susijusias tendencijas ir išanalizuoti galimus hidrologinius, maistinių medžiagų ir nuosėdų išnešimo bei mikrobiologinės taršos pokyčius, įvedant skirtingus scenarijus sudarytus pagal IPCC AR5 RCP4.5 ir RCP8.5 trumpalaikiam (amžiaus vidurio) ir ilgalaikiam (amžiaus pabaigos) laikotarpiams;
3. išanalizuoti galimų būsimų Nemuno upės nuotekų, maistinių medžiagų ir nuosėdų apkrovų poveikį Kuršių marioms; įvertinti hidrologinio ir vandens kokybės (upės baseino) ir hidrodinaminio (Kuršių marių) modelių susiejimo galimybę.

Darbo naujumas

Tyrime nagrinėjami nauji hidrologinio ir vandens kokybės didelio masto smulkios gardeles modelio sudarymo metodai, skirti tarpvalstybiniams regionams Europoje, kuriuose susiduriama su duomenų stoka. Atliktas tyrimas yra pirmasis tokio pobūdžio tyrimas, kur integruojami šlaitinė modelio diskretizavimo schema ir patobulintas hidrologinių atsako vienetų klasifikavimas fiziškai realistiškam modeliuojamos srities atkūrimui, tarpvalstybinių duomenų homogenizavimas ir didelės skiriamosios gebos didelio masto modeliavimas viename tyrime. Be to, šis tyrimas papildo žinias apie Nemuno upės srauto sudėtį, požeminio vandens įtaką ir žemyninės (pasklidosios) taršos transportuojamos Nemunu į Kuršių marias kiekybinį vertinimą.

Nauji šio darbo aspektai yra susiję su (1) patobulinto hidrologinio ir vandens kokybės modelio sudarymo procedūromis, (2) hidrologinio ir hidrodinaminio (nuo upės baseino iki priekrantės zonos) modelių susiejimo galimybės vertinimu, (3) ilgalaikiu nuosėdų, bendrojo azoto (TN) ir bendrojo fosforo (TP) apkrovų vertinimu visame Nemuno upės baseine, įskaitant tarpvalstybines apkrovas, (4) Nemuno upės ir intakų srautų kompozicijos analize. Šis tyrimas yra pirmasis, kuriame analizuojama ir kiekybiškai įvertinama nuosėdų apkrova į Nemuno upės baseiną ir Kuršių marias.

Rezultatų mokslinė ir praktinė reikšmė

Žinios apie maistinių medžiagų ir teršalų kiekio patekimo į upes yra esminis veiksnys siekiant sumažinti antropogeninį poveikį vidaus ir pakrančių vandenyse. Be tiesioginių matavimų, labai svarbu turėti galimybę numatyti galimas ateities maistinių medžiagų ir teršalų apkrovas ir upių sistemų pokyčius skirtingomis sąlygomis, pvz., klimato kaitos kontekste. Šio tyrimo rezultatai gali būti pritaikyti koreguojant HELCOM maistinių medžiagų mažinimo schemą (HELCOM, 2007 m.) ir apskaičiuoti didžiausias leistinas apkrovas Lietuvai besikeičiant aplinkos sąlygoms. Valstybinės aplinkos apsaugos agentūros gali panaudoti rezultatus ir modelį tam, kad identifikuotų „probleminius taškus“ Nemuno upės baseine. Šios žinios gali būti panaudotos kaip sprendimo paramos įrankis sudarant optimalią tręšimo valdymo strategiją, maistinių medžiagų perdirbimo bei vandentvarkos pokyčius siekiant žymiai sumažinti maistinių medžiagų, patenkančių į Kuršių marias per upes, kiekį, o tai savo ruožtu bus naudinga valdant dumblių žydėjimą lagūnoje.

Šis tyrimas suteikia vertingų įžvalgų apie didelio masto hidrologinius, maistinių medžiagų ir nuosėdų pernašos vertinimus, kuomet duomenų apie tiriamąja vietą yra mažai, o matavimai – nenuoseklūs ir išskaldyti. Tyrimas taip pat rodo, kad, siekiant optimizuoti modeliavimo darbus bei išvengti naujo modelio kūrimo kiekvienai atskirai užduočiai, reikia taikyti lanksčių įrankių arba sistemų sudarymo metodikas. Tokios metodikos leidžia lengvai adaptuoti modelį geriausiai atlikti paskirtą užduotį, išvengiant esminio visos sistemos keitimo.

Modelio sudarymo kodas yra licencijuoti licencijuotas – gauta Bendroji viešoji licencija (angl. General Public License – GPL) . Sukurti modeliai ir įrankiai turi ilgą gyvavimo ciklą ir bus toliau tobulinami ir naudojami siekiant (1) įvertinti skirtingų teršalų patekimą į Kuršių marias, (2) kiekybiškai įvertinti antropogeninį poveikį maistinių medžiagų kiekiui, (3) įvertinti žemės naudojimo pokyčių dinamiką, išskirti trendus ir prognozuoti tokių pokyčių įtaką hidrologiniam Nemuno baseino režimui, (4) atlikti socioekonominius vertinimus ir nustatyti susijusių ekosistemų paslaugų gyvybingumą, (5) įvertinti maistinių medžiagų sulaikymo priemonių ir geriausių žemėtvarkos planų veiksmingumą.

TYRIMŲ MEDŽIAGA IR METODAI

Tyrimų rajonas

Nemuno upės baseinas randasi tarp 56º15′–52º45′ šiaurės platumos ir 22º40′–28º10′ rytų ilgumos; bendras upės ilgis yra 937 km, o baseino plotas – 97 928 km2 (The Environmental Protection Agency, 2015). Nemunas yra vienas didžiausių upių sistemų rytinėje Baltijos jūros dalyje ir didžiausia upė Lietuvoje. Apie 90 % viso vandens ir maistingų medžiagų, patenkančių į Kuršių marias, yra atnešama Nemunu (Pilipchuk et al., 2014). Upių baseiną dalijasi Lietuva, Baltarusija, Lenkija, Rusijos Federacija (Kaliningrado sritis) ir Latvija (žr. 1 pav.).

Modelio sudarymas

SWAT (angl. Soil Water Assessment Tool) modelis – vienas iš populiariausių pasaulyje naudojamų upių baseinų hidrologinių modelių. Pagrindiniai modeliuojami procesai yra hidrologiniai procesai, erozija, augalų augimas, maistmedžiagių ciklai, pesticidų dinamika, medžiagų pernaša vandens telkiniuose, vandens tarša bakterijomis ir kraštotvarkos įtaka hidrologiniams parametrams. Nemuno upės SWAT modelis buvo sudarytas panaudojus suprogramuotus Matlab kalba (The MathWorks, Inc., Natick, Massachusetts, United States) kodus pusiau automatiškai sudaryti modelį. Matlab taip pat buvo panaudotas duomenims apdoroti ir rezultatų statistinei analizei atlikti.

Semiant patirtį iš kitų panašaus pobūdžio darbų (Hoang et al., 2017; Jencso et al., 2010; Kraft et al., 2012; Vigiak et al., 2017, 2015; Zhao and Beighley, 2016) buvo nutarta, kad geriausia modelio diskretizavimo schema yra šlaitinė (angl. hillslope).

Toks modeliuojamosios srities diskretizavimas taisyklingai aprašo vandens ir maistinių medžiagų bei teršalų judėjimą tarp upės baseino elementų. Kadangi šiuo metu nėra standartinių įrankių šlaitiniam diskretizavimui realizuoti, buvo sukurti įrankiai ArcGis aplinkoje (ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute) (žr. 2 pav.).

Sudarytas modelis (žr. 3 pav.) buvo kalibruotas ir validuotas rankiniu būdu, keičiant jautrius parametrus, susietus su hidrologiniais reiškiniais, nuosėdų ir maistinių medžiagų apkrovomis bei pernaša. Siekiant įvertinti modelio patikimumą buvo panaudoti statistiniai įverčiai: determinacijos koeficientas (R^2), Nash-Sutcliffe modelio efektyvumo koeficientas (NS) ir procentinė paklaida (PBIAS). Gauti statistiniai modelio patikimumo koeficientai yra pateikti 5 lentelėje; matuojamų ir modeliuojamų upių debitų palyginimo grafikai yra pateikti 4 paveikslėlyje, o nuosėdų, bendrojo azoto ir bendrojo fosforo grafikai – 5 paveikslėlyje. Sukalibruotas ir validuotas modelis buvo įvertintas kaip tinkamas klimato kaitos scenarijams apskaičiuoti ir nuotėkio, nuosėdų ir maistinių medžiagų apkrovų pokyčiui vertinti.

Prognozavimo scenarijai

Ateities Nemuno upės debitų ir maistinių ir nuosėdų skaičiavimas atliktas pagal sudarytus reprezentatyvius koncentracijos kitimo profilius (angl. Representative Concentration Pathways – RCP): RCP4.5 ir RCP8.5. Pakeisti kritulių, temperatūros ir anglies dvideginio pokyčiai buvo panaudoti tam, kad būtų įvertinti pokyčiai trumpalaikiam (amžiaus vidurio – iki 2050 m.) ir ilgalaikiam (amžiaus pabaigos – iki 2100 m.) laikotarpiams, palyginus su baziniu periodu (1995–2010 m.). Klimato kaitos scenarijų periodai buvo parinkti atsižvelgus į turimus duomenis ir globalius klimato kaitos modelius (angl. General Circulation Models – GCM) (4 lentelė). Kiti modeliuojami procesai, tokie kaip žemdirbystė, tręšimas, rezervuarų veikimas et al., nebuvo pakeisti, tokiu būdu sudarant „esamos padėties“ sąlygas. Modelio iniciavimui buvo panaudotas penkerių metų laikotarpis (1995 – 1999 m. imtinai). Modelių grupės vidurkis, kuris yra taikomo klimato modelio prognozių vidurkis tam tikram kintamajam, buvo naudojamas apskaičiuojant prognozavimo laikotarpio pokyčius.

Vertinant Nemuno upės ir sausumos teršalų srautų pokyčius, kiekvieno komponento vidurkis buvo lyginamas su apkrovomis baziniu periodu. Prognozuojami pokyčiai skirtingų GCM sąlygomis kinta, todėl kiekvienai diagramai pridedama prognozavimo arba projekcinė juosta, apimanti visų modeliuojamų būsimų rezultatų vertes ir gali būti vertinama kaip prognozavimo duomenų variacija. Įvairių modelių sudedamųjų analizės metodas pabrėžia klimato prognozių neapibrėžtumą, atsirandantį dėl struktūrinių klimato modelių skirtumų.

REZULTATAI IR DISKUSIJA

Klimato kaitos pasekmės visame Nemuno upės baseine

Nors klimato kaitos prognozėse parodė tam tikrus skirtumus, galima nustatyti kai kurias bendras tendencijas (žr. 6 lentelę). Gali būti analizuojami ir palyginami bendri vandens baseinų rezultatai, esant vidutiniams metiniams krituliams, sniegui, evapotranspiracijai, kartu su:

- vandens stygiaus dienomis (imituojama lyginant faktinę ir potencialią augalų transpiracijas);
- temperatūros stygiaus dienomis (apibrėžiamos kaip vidutinės dienos oro temperatūros ir optimalios augalų augimo temperatūros funkcija);
- azoto ir fosforo stygiaus dienomis (kiekybiškai įvertinamos lyginant faktinius ir optimalius augalų azoto arba fosforo kiekius).

Visi modeliai pagal abiejų RCP sąlygas rodė temperatūros stygiaus dienų ir snygio sumažėjimą (išskyrus MIROC ir NoerESM1-M pagal RCP4.5 sniegui), o tai reiškia, kad labiausiai tikėtinas rezultatas bus šiltesnis klimatas per visus sezonus (žr. 6 pav.). Krituliai skiriasi tarp įvairių GCM, tačiau jų metinis padidėjimas ar sumažėjimas nėra reikšmingas. Prognozuojama, kad visuose scenarijuose vandens stygiaus dienų skaičius didės , o tai reiškia, kad galimas mažesnis kritulių kiekis ir didesnės temperatūros sukels sausesnes sąlygas.

Vidutinis metinis azoto ir fosforo stygiaus dienų rezultatas rodo bendrą azoto stygiaus dienų sumažėjimo ir fosforo stygiaus dienų padidėjimo tendenciją. Modeliavimas buvo atliktas „esamos padėties“ sąlygomis; kas savo ruožtu rodo, kad azoto perteklius yra sumodeliuotas, o fosforas sumažėja. N ir P prieinamumo skirtumų priežastys gali būti atskleistos per sezoninius apkrovos įverčius ir numatomus srauto sudėties pokyčius, tai išsamiau aptarta 3.2.3 skyriuje.

Prognozuojami Nemuno upės debito pokyčiai

Tarpsezoninių debitų pokyčiai visuose scenarijuose rodo žiemos vidurio ir vėlyvos žiemos į Kuršių marias įtekančio vandens kiekio padidėjimą, o tai sutampa su prognozuojamu sniego formavimosi sumažėjimu visame baseine (žr. 6 lentelę). Tai reiškia, kad didėja žiemos kritulių, iškrentančių kaip lietus, proporcija. Vidutiniškai numatomas Nemuno upės srautas didės visais žiemos mėnesiais pagal RCP4.5 tiek artimiausioje, tiek ilgalaikėje perspektyvoje (gruodis – + 44 %, sausis – + 59,7 %, vasaris – + 29,3 %), tuo tarpu RCP8.5 trumpalaikėje perspektyvoje rodo padidėjimą tik gruodį (+ 10 %) bei sausį (+ 6,5%) ir visą žiemą ilgalaikėje perspektyvoje (gruodis – + 22%, sausis – + 44,5 %, vasaris – + 18,9 %) (8 pav.).

Aiškus signalas – tai srauto sumažėjimas nuo pavasario iki rudens sezonų pagal RCP8.5 tiek trumpalaikėje tiek ilgalaikėje perspektyvoje. RCP8.5 yra laikomas „blogiausio atvejo" scenarijumi, todėl tikimasi, kad numatomi pokyčiai bus stipriausi absoliučiąją prasme. Čia numatomas vidutinis Nemuno upės srauto sumažėjimas visų GCM sąlygomis (žalioji bazinė linija krenta virš oranžinės projekcijos juostos visais mėnesiais nuo balandžio iki lapkričio), todėl tikėtinas scenarijus yra pavasario–rudens srautų sumažėjimas, jei pasaulinės plėtros ir išmetamųjų teršalų tendencijos atitiks RCP8.5 scenarijų.

Kita vertus, jei pasaulinės plėtros ir išmetamųjų teršalų tendencijos seks stabilizavimo scenarijų, tikėtina, kad Nemuno upės srautas patirs hidrologinį perėjimą prie aukštesnių žiemos nuotėkių ir mažesnių vasaros–ankstyvo rudens nuotėkio, nors ilgalaikėje perspektyvoje birželio–spalio mėnesiais vidurkis nukrenta daug žemiau, tačiau vis dar patenka į projekcijos juostos ribas.

Šie rezultatai gali reikšti, kad pasikeis Kuršių marių vandens apykaitos mechanizmas, esant aukštesniems apykaitos rodikliams tarp marių ir jūros žiemos metu ir esant žemesniems – vasarą. Tai savo ruožtu darys įtaką Kuršių marių vandens apykaitos režimui, dar labiau sumažinant vandens užsilaikymo laiką žiemą ir didinant ir taip aukštą vandens užsilaikymo laiką vasarą (Umgiesser et al., 2016). Ši sumažėjusi apykaita gali turėti įtakos bakterijų ir kitos biotos žydėjimui mariose, tačiau sujungtas hidrologinis ir hidrodinaminis modelio prognozavimas reikalingas siekiant nustatyti galimas pasekmes.

Prognozuojamos Nemuno upės nuosėdų apkrovos

Numatomas nuosėdų apkrovos pokytis atitinka tuos pačius modelius, kaip ir srautai, nors atsiranda tam tikrų variacijų. Didžiausias absoliutinių dydžių trumpalaikės perspektyvos skirtumas projektuojamas RCP4.5 scenarijuje, kai nuosėdų apkrovos vidurkis yra daug didesnis žiemą (padvigubėja gruodžio–vasario mėn.) ir ankstyvą pavasarį (nuo kovo iki balandžio iki 20 %). Esant tokiam pat emisijos scenarijui ilgalaikėje perspektyvoje taip pat yra modeliuojamas padidėjimas (93 % padidėjimas sausio–vasario mėn. ir iki 16 % padidėjimas kovo–balandžio mėn.). Pažymėtina, kad bazinės apkrovos patenka į projekcinės juostos ribas; be to, prognozuojamas ir bazinis vidurkis per daugelį mėnesių yra labai panašūs: nuo gegužės iki lapkričio mėnesio (9 pav.).

Modeliuojamos nuosėdų apkrovos pagal RCP8.5 sąlygas skiriasi: prognozuojamas vidurkis gerokai mažesnis už bazinę liniją, kuri apima tik viršutinę projekcijos juostos ribą (9 pav.). Panašiai kaip ir su srautu, tikėtina, kad nuosėdų apkrova, patenkanti iš Nemuno upės į Kuršių marias, sumažės nuo kovo iki lapkričio (sumažėjimas iki 20 %), jei klimatas atitiks RCP8.5 emisijos scenarijų. Žiemos sezonui esama bazinė linija patenka į projekcinės juostos ribas, nors ir mažesnė nei vidurkis (padidėjimas iki 28 %). Padidėjęs nuosėdų kiekis ir erozija greičiausiai priskiriami žiemos mėnesiams, kuomet yra sumažėjęs sniego sluoksnis, kai augmenija tampa pasyvi – atidengtas dirvožemio viršutinis sluoksnis ir lengvai paveikiamas erozijos.

Prognozuojamos Nemuno upės maistinių medžiagų apkrovos

Gautus bendrojo azoto ir bendrojo fosforo apkrovos pokyčius reguliuoja hidrologijos pokyčiai, taip pat sausumos procesai. Bendrojo azoto padidėjimas prognozuojamas žiemos mėnesiais (nuo gruodžio iki vasario mėn. – iki 32 %) bei nedidelis padidėjimas pavasarį (nuo kovo iki gegužės– iki 7 %). Nustatyti pokyčiai kitais mėnesiais yra nežymūs ir svyruojantys. Bazinė linija patenka į bendrojo azoto projekcijos juostą tiek RCP4.5, tiek RCP8.5 (10 pav.).

Numatomi tarpsezoninių bendrojo fosforo apkrovų pokyčiai rodo šiek tiek kitokią tendenciją. Svarbiausias pokytis numatomas žiemos ir ankstyvo pavasario mėnesiais (nuo gruodžio iki kovo) ypač ilgalaikėje perspektyvoje pagal RCP4.5 padidėjimas – iki 62 %. Sausio ir vasario mėnesiais prognozuojamas vidurkis ir projekcijos juosta gerokai viršija bazinę liniją, todėl tikėtina, kad bendrojo fosforo apkrova per šį laikotarpį padidės (11 pav.). Padidėjusi bendrojo fosforo apkrova pirmiausia siejama su padidėjusiais nuosėdų krūviais tuo pačiu laikotarpiu, kuris yra dalelinio fosforo šaltinis.

Nemuno upės baseino (hidrologinio) ir Kuršių marių (hidrodinaminio) modelių sujungimas ir mikrobiologinės taršos prognozės

Sukurtas Nemuno upės baseino hidrologinis ir vandens kokybės modelis gali būti siejamas su Kuršių marių hidrodinaminiu modeliu. Tokios modeliavimo sistemos komponentai gali būti laisvai sujungti, o tai reiškia, kad moduliai gali būti pakeisti alternatyviomis realizacijomis, kurios teikia tos pačios struktūros rezultatus. Sujungta vandens baseino-marių modeliavimo sistema buvo naudojama siekiant įvertinti galimą būsimą mikrobiologinę taršą (pavyzdžiui, su *E.coli*) Kuršių mariose, atsižvelgiant į RCP4.5 ir RCP8.5 *E.coli* koncentracijos sąlygas. Nustatyta, kad iš Nemuno upės į Kuršių marias patenkanti mikrobiologinė tarša vidutiniškai sumažės 7 % RCP4,5 ir 15% RCP8.5 sąlygomis (12 pav.). Atlikus abiejų modelių simuliacijas paaiškėjo, kad pakitęs mikrobiologinės taršos patekimas į Nemuną (kurio prietaka yra rytinėje Kuršių marių pusėje) nedaro įtakos taršai kitose marių vietose, kur gali kilti pavojus viršyti maudyklų vandens kokybės ribą pagal Maudyklų direktyvos nuostatas (Europos Parlamentas ir Europos Sąjungos Taryba, 2006).

Kadangi modeliai yra laisvai sujungti, vienas modulis gali būti pakeistas arba patobulintas nekeičiant kitų modulių. Tai sudaro lanksčią modeliavimo sistemą ateities plėtrai ir užtikrina ilgą modelių gyvavimo ciklą bei daugelį galimų visos sistemos naudojimo būdų, kur galima modeliuoti visą objekto kelią iš šaltinio (sausumos apkrovos baseine) per pereinamąją zoną (Kuršių marias) iki eksporto taško (Baltijos jūra).

IŠVADOS

1. Prognozuojamas ilgalaikis metinis vidutinis Nemuno upės nuotėkis neturi trendo. GCM variabilumas yra didesnis pagal RCP4.5 sąlygas, negu RCP8.5, su geresniu nuotėkių projekcijos susitarimu tarp GCM pagal RCP4.5 ir RCP8.5 ilgalaikėje perspektyvoje [2090–2099 m.].

2. Visų scenarijų tarpsezoninės variacijos atvejai rodo, kad padidėja vidurio ir vėlyvos žiemos vandens kiekis, įtekantis į Kuršių marias (iki 44,3 %), o tai sutampa su numatomu sniego formavimosi sumažėjimu visame baseine tiek trumpalaikėje [2040–2050 m.], tiek ilgalaikėje [2090–2099 m.] perspektyvose. Numatoma, kad upės debitas nesikeis arba šiek tiek sumažės šiltuoju metų laiku (pavasarį iki ankstyvo rudens). Visi šie pokyčiai savo ruožtu sumažins jau mažą Kuršių marių vandens užsilaikymo laiką žiemą ir dar labiau padidins vandens užsilaikymo laiką vasarą.

3. Didžiausias nuosėdų apkrovos pokyčio skirtumas prognozuojamas trumpalaikiu RCP4.5 scenarijaus laikotarpiu, kai prognozuojamas nuosėdų apkrovos vidurkis žiemą (gruodžio–vasario mėn.) yra du kartus didesnis ir 20 % didesnis ankstyvą pavasarį (kovo–balandžio mėn.). Prognozuojamas nuosėdų apkrovos vidurkis pagal RCP8.5 sąlygas yra 20 % žemesnis už bazinę liniją, kuri apima tik viršutinę projekcijos juostos ribą. Panašiai kaip ir su debitu, tikėtina, kad nuosėdų apkrova, patenkanti iš Nemuno upės į Kuršių marias, sumažės nuo kovo iki lapkričio, jei klimatas atitiks RCP8.5 scenarijų

4. Nemuno upės baseino bendrojo azoto patekimo į Kuršių marias padidėjimas yra modeliuojamas žiemos mėnesiais (nuo gruodžio iki vasario mėn. – iki 32 %), o vidurkis šiek tiek padidės pavasarį (nuo kovo iki gegužės – iki 7 %). Bazinė linija patenka į TN projekcijos juostą tiek RCP4.5, tiek RCP8.5 scenarijų atvejais.

5. Didžiausias bendrojo fosforo apkrovos pokytis numatomas žiemos ir ankstyvo pavasario mėnesiais (nuo gruodžio iki kovo), ypač ilgalaikėje perspektyvoje pagal RCP4.5 sąlygas (padidėjimas iki 62%). Nepaisant numatomo upės debito sumažėjimo pagal RCP8.5 sąlygas, numatytos TP apkrovos tomis pačiomis sąlygomis nesumažėja, o ilgalaikio laikotarpio atveju išlieka panašios į bazines.

6. Galimos būsimos nuosėdų ir maistinių medžiagų apkrovos prognozės primygtinai rodo, kad maistinių medžiagų kiekio mažinimo ir sulaikymo priemonės yra būtinos ir ateityje išliks tokios, jei Lietuva laikysis Baltijos jūros veiksmų plano ir sieks sumažinti maistinių medžiagų apkrovas. Kadangi numatoma, kad ateityje žiemos

sezonas bus šiltesnis visais scenarijais, maistinių medžiagų eksportas iš baseino priklausys nuo užšalimo ir atšilimo ciklų dažnumo. Rezultatai taip pat rodo, kad dauguma pokyčių gali įvykti sausio ir vasario mėnesiais, todėl rekomenduojamas veiksmas būtų nukreipti, įvertinti ir įgyvendinti tas maistinių medžiagų sulaikymo priemones, kurios yra veiksmingiausios žiemą.

7. Mikrobinė tarša (*E.coli*), kuri patenka į marias iš Nemuno upės, greičiausiai sumažės 7 %, esant RCP4.5 sąlygoms, ir 15 % pagal RCP8.5 scenarijų. Nėra jokios tiesioginės rizikos, kad Kuršių marių pakrantės zonos viršytų maudyklų vandens kokybės mikrobiologinės taršos ribą, nes tipiškas E. coli išgyvenamumas yra daug mažesnis nei laikas, per kurį mikrobiologinė tarša gali būti transportuota iš Nemuno deltos iki kitų Kuršių marių vietovių.

8. Vandens baseino hidrologinių pokyčių ir maistinių medžiagų bei nuosėdų apkrovų sezoninio svyravimo į Kuršių marias derinys gali sukelti įvairius sistemos elgesio atsakus, pradedant nuo padidėjusio melsvadumblio žydėjimo iki maistinių medžiagų eksporto į Baltijos jūrą padidėjimo. Šių hipotezių tolesniam tyrimui gali būti naudojamos sujungtos hidrologinės ir vandens kokybės (baseino lygio) ir hidrodinaminių (marių ir pereinamojo laikotarpio zonos) modelių sistemos.

8

Annexes

***Table 1A.* Landuse types and their percentages in the entire Nemunas River watershed area**

Nr.	Landuse type	Percentage of the total watershed area
1	Cropland/woodland mosaic	38.65
2	Dryland cropland and pasture	9.67
3	Winter Pasture	9.64
4	Pine	6.13
5	Agricultural - General	4.45
6	Forest-Deciduous	3.56
7	Forest-Evergreen	3.09
8	Winter Wheat	2.73
9	Poplar	2.68
10	Range-Brush	1.68
11	Water	1.55
12	Barren	1.44
13	Spring Wheat	1.38
14	Summer rape	1.22
15	Spring Barley	1.21
16	Winter triticale	0.71
17	Evergreen needleleaf forest	0.70
18	Forest-Mixed	0.66
19	Urban Low Density	0.65
20	Urban Terrain	0.61
21	Oats	0.54
22	Smooth Bromegrass	0.53
23	Water bodies	0.50
24	Urban Medium Density	0.48
25	Urban High Density	0.48
26	Wetlands-Forested	0.46
27	Rye	0.45
28	Wetlands-Mixed	0.43
29	Spring Canola-Argentine	0.39
30	Oak	0.34
31	Buckwheat	0.29
32	Mixed forest	0.21
33	Sugar beet	0.19
34	Mix of legumes with other crops	0.17
35	Potato	0.17
36	Garden or Canning Peas	0.15
37	Corn Silage	0.15
38	Orchard	0.14
39	Urban Medium Density	0.13

Nr.	Landuse type	Percentage of the total watershed area
40	Summer triticale and summer rye	0.13
41	Winter wheat (straw fields)	0.12
42	Corn	0.12
43	Urban Industrial	0.09
44	Deciduous broadleaf forest	0.08
45	Summer wheat (straw fields)	0.08
46	Cropland/grassland mosaic	0.08
47	Lupine	0.06
48	Spring Canola-Polish	0.05
49	Summer rape (straw fields)	0.05
50	Vetch	0.05
51	Summer barley (straw fields)	0.05
52	Green Beans	0.04
53	Celery	0.04
54	Winter triticale (straw fields)	0.04
55	Red Clover	0.04
56	Grassland	0.04
57	Alfalfa	0.04
58	Willow	0.04
59	Carrot	0.03
60	Rye (straw fields)	0.03
61	Soybean	0.02
62	Winter Barley	0.02
63	Deciduous needleleaf forest	0.01
64	Summer Rye	0.01

***Table 2A.* Soil types and their percentages in the entire Nemunas River watershed area**

Nr.	FAO soil unit code	Soil type	Percentage
1	PDe	Eutric Podzoluvisols	43.65
2	HSs	Terric Histosols	8.63
3	ARh	Haplic Arenosols	8.45
4	LVg	Gleyic Luvisols	5.79
5	LVh	Haplic Luvisols	4.21
6	CMg	Gleyic Cambisols	3.88
7	GLe	Eutric Leptosol	2.39
8	PZg	Gleyic Podzols	2.36
9	ARb	Cambic Arenosols	2.28
10	SDg	Gleyic Arenosols	2.01
11	LVk	Calcic Luvisols	1.85
12	Fle	Eutric Fluvisols	1.75
13	GLm	Mollic Gleysols	1.57
14	FLu	Umbric Fluvisols	1.55
15	PLb	Eutric Planosols	1.49
16	PDd	Dystric Podzoluvisols	1.14
17	GLk	Calcic Gleysols	1.08
18	RDk	Calcic Cambisols	0.97
19	HSf	Fibric Histosols	0.74
20	HSi	Gelic Histosols	0.66
21	FLc	Calcaric Fluvisols	0.48
22	ARh	Haplic Arenosols	0.47
23	PLd	Dystric Planosols	0.43
24	PDg	Gleyic Podzoluvisols	0.41
25	LPk	Rendzic Leptosols	0.30
26	FLd	Dystric Fluvisols	0.30
27	PZh	Haplic Podzols	0.25
28	FLm	Mollic Fluvisols	0.23
29	GLd	Dystric Gleysols	0.21
30	LVj	Stagnic Luvisols	0.19
31	PDj	Stagnic Podzoluvisols	0.13
32	LPk	Rendzic Leptosols	0.12
33	CMe	Eutric Cambisols	0.03
34	ARb	Cambic Arenosols	0.01
35	PZf	Ferric Podzols	0.00

Klaipėdos universiteto leidykla

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