KLAIPĖDA UNIVERSITY

Jovita MĖŽINĖ

ASSESSMENT OF THE SEDIMENT TRANSPORT IN THE BALTIC COASTAL LAGOON: THE NUMERICAL MODELLING APPROACH

DOCTORAL DISSERTATION

Natural sciences,
ecology and environmental sciences (N 012)

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KLAIPĖDOS UNIVERSITETAS

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NUOSĖDŲ PERNAŠOS BALTIJOS JŪROS LAGŪNOJE VERTINIMAS TAIKANT MATEMATINĮ MODELĮ

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Abstract

In this study the sediment transport mechanisms in the biggest lagoon in Europe, the Curonian Lagoon, with high river discharge and sediment loadings, were evaluated using numerical modelling. An already developed hydrodynamic model and sediment transport model were applied to the domain that represents the Curonian Lagoon. A new formula for particle settling velocity was developed and introduced into the model that allowed achieving good agreement between the modelled and measured values (40-72%). The formula is based on the findings that the organic material plays a crucial role in the system especially in the presence of cyanobacteria in high water temperatures. The model was applied for different scenarios and purposes, i.e., to calculate the sediment budget, show deposition patterns, and evaluate extreme events caused by strong winds. The analysis of all these results provided the first detailed overview of the status of the Curonian Lagoon environment, showing the important role of the Nemunas River and the influence of ice cover for the sedimentation processes in the lagoon. Moreover, the impact of the sediment resuspension in the Curonian Lagoon was evaluated and climate change scenarios were applied. Climate change projections revealed that the lagoon will accumulate more sediments in the future, forming three main accumulation zones: in the Nemunas Delta front, in the southern part of the lagoon and south of Klaipėda Strait. The developed model is a valuable tool for further analysis of the south-eastern coasts of the Baltic Sea, the Curonian Lagoon and other transitional environments as well.

Key words

Sediment dynamics, SHYFEM, the Curonian Lagoon, settling velocity, climate change

Reziumė

Šio tyrimo tikslas – taikant matematinį modeliavimą įvertinti nuosėdų pernašos mechanizmus didžiausioje Europos lagūnoje, Kuršių mariose, pasižyminčiose gausiu upių nuotėkiu ir didele nuosėdų prietaka. Kuršių marias reprezentuojančiai akvatorijai buvo pritaikytas anksčiau sukurtas hidrodinaminis ir nuosėdų pernašos modelis. Į nuosėdų pernašos modelį buvo inkorporuota naujai sukurta dalelių nusėdimo greičio formulė, leidusi pasiekti aukštą sumodeliuotų ir išmatuotų reikšmių panašumą (40–72%). Formulė yra paremta tyrimais, kurie nustatė reikšmingą organinės medžiagos įtaką sistemoje, ypač vasaros sezono metu, kai vyravo melsvabakterės ir buvo aukštos vandens temperatūros. Matematinis modelis buvo pritaikytas įvairiems tyrimo tikslams ir scenarijams: apskaičiuoti nuosėdų balansą, nustatyti erozijos–akumuliacijos vietas, įvertinti stiprių vėjų ir klimato kaitos įtaką. Pirmą kartą buvo atlikta išsami Kuršių marių aplinkos būklės apžvalga nuosėdų atžvilgiu, atkreipianti dėmesį į Nemuno upės vaidmenį ir ledo dangos įtaką sedimentacijos procesams. Taip pat įvertinta nuosėdų resuspensijos įtaka Kuršių marių ekosistemai ir pritaikyti klimato kaitos RCP4.5 ir RCP8.5 scenarijai ateities prognozėms. Klimato kaitos prognozės parodė, kad ateityje akumuliacijos greičiai mariose didės, suformuodami tris pagrindines akumuliacines zonas: Nemuno avandeltoje, pietinėje Kuršių marių dalyje ir Klaipėdos sąsiaurio pietinėje dalyje. Sukurtas modelis yra vertinga priemonė tolimesniems tyrimams Kuršių mariose, pietryčių Baltijos jūroje ir kitose tranzitinėse sistemose.

Reikšmingi žodžiai

Nuosėdų dinamika, SHYFEM, Kuršių marios, nusėdimo greitis, klimato kaita

Contents

1

Introduction

1.1 Relevance of the dissertation

Seabed and water interactions together with hydrodynamic and wave conditions cause sediment transport processes. Sediments enter surface waters from many sources and their behaviour depends on the processes of sediment erosion, transport and deposition (Ji, 2008). These processes can cause siltation in harbours and navigational channels, insufficient sunlight for water plants growth or survival because of reduced water transparency, transportation of pollutants, alteration on habitats of benthic organisms, etc. The understanding of sedimentation processes can help to define environmental problems such as eutrophication, contaminant transport, sediment bed erosion, siltation, and waste disposal. However, the analysis of the sediment transport mechanisms is a very complicated task since it is hard to obtain a complete dataset. Numerical modelling is one of the methods to describe the dynamics of water, sediment movement and bed evolution.

Numerical modelling has grown substantially in the last decades and is now largely used by the scientific community through applications of hydrodynamic, sediment transport, meteorological, ecological and climate change models (García-Oliva et al., 2019; Friedland et al, 2019, Saraiva et al., 2019). The main advantage is that calibrated and verified numerical models can represent the waterbody realistically and can be easily applied to complex studies where the coupling of a few models is needed to define the possible changes, consequences and future evolution in the system. Well-calibrated models can be used as a tool to support the decision-making process.

This study is focused on the investigation of sediment transport mechanisms in the south-eastern coastal area of the Baltic Sea with a focus on the Curonian Lagoon area via the application of numerical models. Large amounts of sediments that are transported through the Curonian Lagoon and their pathways are still poorly understood. As a result, the sediment transport model could be a perfect tool to analyse sediment patterns in the river-lagoon-sea environment. To date, mostly experimental methods were used to investigate the sediment transport processes in the lagoon that provided only a very general understanding of sediment dynamics in the system and its influence to the ecological processes (Pustelnikovas, 1994; Galkus and Jokšas, 1997; Galkus, 2003a,b). The SHYFEM modelling system for the Curonian Lagoon sedimentation processes was used in 2007 (Ferrarin, 2007). The two-dimensional hydrodynamic model coupled with the spectral wave model has been applied to the Curonian Lagoon to investigate the variability of the combined (current and wave) bed shear stresses. The actual boundary conditions and forcing were used for a one-year long simulation. The more detailed studies of the sediment transport for Klaipeda Strait, which is the harbour area and which connects the Curonian Lagoon to the Baltic Sea, using the DHI 2-D numerical modelling system MIKE-2 were carried out by Kriaučiūnienė et al. (2006) and by Kriaučiūnienė and Gailiušis (2004). Nevertheless, these studies are not sufficient to estimate the long-term sediment dynamics and morphological changes in the Curonian Lagoon system.

In this thesis, the analysis and evaluation of the sediment patterns in the Curonian Lagoon will fill the gaps of the sediment dynamics in the lagoon that was still not fully understood, will provide the possible basis for evaluation of resuspension, and will forecast trends due to climate change scenarios. The effects of the biological material in the water column on trapping sediment particles and the role of the ice cover for the suspended sediment distribution will be analysed.

1.2 Aim and objectives

The aim of this study is to investigate sediment transport mechanisms in the lagoon with high river discharge and sediment loading through the applications of a numerical model.

To reach the study aim the following objectives were defined:

1. To integrate the available environmental and hydrodynamic data into the unique, well calibrated, sediment transport model for multiple scenario simulations in the lagoon;

2. To analyse the erosion and accumulation pattern and predict the sediment budget;
3. To evaluate the impact of sediment resuspension to the lagoon environment;
4. To forecast how the sedimentation pattern in the lagoon will change according to RCP4.5 and RCP8.5 climate change scenarios.

1.3 Novelty

There is a big variety of studies where numerical models were applied to study the sediment dynamics in the estuaries, lagoons and seas (Maicu et al., 2019; Ferrarin et al., 2008b and 2010; Lesser et al, 2004). In this study the numerical model is applied to study the sediment transport mechanisms in the biggest lagoon of Europe, Curonian Lagoon. The applied SEDTRANS05 model was previously calibrated for the Venice Lagoon and widely used for the studies in the Mediterranean Sea region (Ferrarin et al., 2010a,b; Neumeier et al., 2008, Ferrarin et., 2008b). However, the hydrodynamic conditions and sediment transport mechanisms in the Curonian Lagoon differs from the Venice Lagoon.

The novelty of this study is that the SEDTRANS05 model was applied for the lagoon, where the organic material in the water column influences the sediment transport significantly. To analyse the sediment mechanisms in this system, a new formula for particle settling velocity was developed. This formula is based on the findings from Bukaveckas et al. (2019) where low particle settling velocities were found due to the impact of cyanobacteria bloom in summer and autumn. The cyanobacteria bloom occur during specific conditions, where one of the factors is a high water temperature. Therefore, the new settling velocity formula is a function of the water temperature.

The new aspects presented in this thesis are 1) the study of erosion-deposition patterns in the Curonian Lagoon through the application of numerical modelling; 2) the evaluation of the influence of ice cover and the impact of extreme events on the sediment dynamics in the lagoon; 3) the study of resuspension events analysing the modelled morphological changes; 4) modelling of climate change scenarios for possible sedimentation changes in the Curonian Lagoon.

1.4 Scientific and applied significance of the results

The development of a new formula for the settling velocity allowed the adaptation of the sediment transport model for the Curonian Lagoon and the construction of a valuable tool for further analysis of the sediment dynamics in the Curonian Lagoon, south-eastern coasts of the Baltic Sea and other environments as well. The results of this study provided a detailed overview of the hydrodynamic and sediment transport mechanisms in the lagoon and coastal areas showing the differences in temporal and spatial scales. An important role of the Nemunas River and the influence of the ice cover on the sedimentation processes were defined by the model results. It was found that the organic material plays a crucial role in the system showing the differences between the Curonian and Venice lagoons.

The sediment transport model deals with both cohesive and non-cohesive sediments and can be applied for various studies: to analyse the resuspension events, to evaluate the bedload transport, to map water turbidity and others. Model results can contribute to marcophyts studies or modelling of microbial pollution patterns and other studies as well. The climate change scenarios can be used for future management plans in the lagoon area. However, more effort is needed to apply the model for harbour studies due to the need of high resolution in the harbour area, and the boundary condition as well as the calibration data in the Baltic Sea area.

1.5 Scientific approval

Results of this study were presented in 7 international and 4 regional conferences:

8th Scientific-Practical Conference “Marine Research and Technologies” – 2014, Klaipėda, Lithuania, April 2014;

12th international conference Littoral 2014, Klaipėda, Lithuania, September 2014;

10th Baltic Sea Science Congress, Riga, Latvia, June 2015;

9th Scientific-Practical Conference “Marine and Coastal Research” – 2016, Klaipėda, Lithuania, April 2016;

10th Scientific-Practical Conference “Marine and Coastal Research” – 2017, Klaipėda, Lithuania, April 2017;

Eurolag 8th European Coastal Lagoons Symposium, Athens, Greece, March 2018;

11th Scientific-Practical Conference “Marine and Coastal Research” – 2018, Klaipėda, Lithuania, May 2018;

7th IEEE/OES Baltic Symposium Clean and Safe Baltic Sea and Energy Security for the Baltic countries, Klaipeda, Lithuania, June 2018;

11th International SedNet Conference. Sediment as a dynamic natural resource – from catchment to open sea, Dubrovnik, Croatia, April 2019;

12th Baltic Sea Science Congress, Stockholm, Sweden, August 2019;

15th International conference on Cohesive Sediment Transport Processes (INTERCOH) 2019, Istanbul, Turkey, October 2019.

The material of this study was presented in 3 original publications, published in peer-reviewed scientific journals:

Mėžinė, J., Zemlys, P., Gulbinskas S., 2013. A coupled model of wave-driven erosion for the Palanga Beach, Lithuania. *Baltica*, 26 (2) 169-176. Vilnius. ISSN 0067–3064. doi:10.5200/baltica.2013.26.17

Umgiesser, G., Zemlys, P., Erturk, A., Razinkovas-Baziukas, A., **Mėžinė, J.,** and Ferrarin, C. 2016. Seasonal renewal time variability in the Curonian Lagoon caused by atmospheric and hydrographical forcing. *Ocean Science*, 12, 2043–2072. doi:10.5194/os-12-391-2016

Mėžinė, J., Ferrarin, C., Vaičiūtė, D., Idzelytė, R., Zemlys, P. and Umgiesser, G. 2019. Sediment transport mechanisms in a lagoon with high river discharge and sediment loading. Water, 10(11), 1970. doi: 10.3390/w11101970

1.6 Thesis structure

The dissertation includes eight chapters: introduction, literature review, material and methods, results, discussion, conclusions, references. The material is presented in 83 pages, 35 figures and 6 tables. The dissertation refers to 144 literature sources. The dissertation is written in English with an extended summary in Lithuanian language.

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1.8 Abbreviations and symbols

Abbreviation and symbols	Explanation
ν	Kinematic viscosity [m^2 s^{-1}]
ρ_0	Average density of the sea water [kg m^{-3}]
ρ_{dry}	Dry bulk density [kg m^{-3}]
ρ_s	Sediment density [kg m^{-3}]
ρ_w	Water density [kg m^{-3}]
τ_0	Bed shear stresses [N m^{-2}]
τ_{ce}	Critical shear stress for erosion [N m^{-2}]
τ_{crb}	Critical shear stress for initiation of bedload motion [N m^{-2}]
τ_{cs}	Instantaneous skin-friction current shear stress [N m^{-2}]
τ_{cws}	Instantaneous skin-friction combined shear stress [N m^{-2}]
τ_{solid}	Solid-transmitted stress [N m^{-2}]
τ_x^l	Internal stress terms at the bottom of layer l in *x* direction [N m^{-2}]
τ_y^l	Internal stress terms at the bottom of layer l in *y* direction [N m^{-2}]
ζ	Water level [m]
A_H	Horizontal eddy viscosity [m^2 s^{-1}]
Adv_l^x	Advective term in *x* direction
Adv_l^y	Advective term in *y* direction
Chl-*a*	Chlorophyll *a*
D	Median sieve grain diameter [m]
D_*	Dimensionless grain size
E	Source/sink term
E_0	Empirical coefficient for minimum erosion (5.88)
F	Fetch [m]
f	Coriolis parameter [s^{-1}]
g	Gravitational acceleration [m s^{-2}]
h	Water depth [m]
h_a	Averaged water depth [m]
h_l	Layer thickness [m]
H_l	Depth at the bottom of layer [m]
H_{m0}	Significant wave height [m]
K_H	Horizontal turbulent diffusion coefficients

Abbreviation and symbols	Explanation
K_V	Vertical turbulent diffusion coefficients
k_{cd}	Coefficient (2800)
m_{cd}	Coefficient (1.03)
l	Vertical layer [m]
P_e	Proportionality coefficient for erosion ($1.95 \cdot 10^{-5}$)
P_s	Dimensionless probability coefficient of resuspension (range 0-0.2)
p_a	Atmospheric pressure [Pa]
r_e	Mass erosion rate [kg m^{-2} s^{-1}]
SSC	Suspended sediment concentration [mg l^{-1}]
S_l	Tracer concentration (salinity, water temperature) at a layer l
s	Ratio of the density of sediment and water
SWH	Significant wave height [m]
T_a	Coefficient ($6 \cdot 10^{-10}$)
T_b	Coefficient (3.0)
T_c	Coefficient (3.47)
T_d	Coefficient (-1.915)
T_m	Dimensionless shear stress parameter
T_p	Wave period [s]
TSS	Total suspended solids [mg l^{-1}]
U_A	Wind speed [m s^{-1}]
U_l,	Horizontal transport of layer l in x direction [m^2 s^{-1}]
u^*_{crs}	Critical shear velocity for erosion [N m^{-2}]
u_l	Horizontal velocity of layer l in x directions [m s^{-1}]
V	Filtered amount of water [l]
V_l	Horizontal transport of layer l in y direction [m^2 s^{-1}]
v_l	Horizontal velocities in y directions [m s^{-1}]
W_f	Tare filter weight [mg]
W_{f550}	Filter weight with suspended matter after muffling in 550 °C [mg]
W_{f60}	Filter weight with suspended matter after drying in 60 °C [mg]
W_s	Settling velocity [m s^{-1}]
W_{sb}	Settling velocity defined after the model calibration in [m day^{-1}]
w_l	Velocities in z directions [m s^{-1}]
z_0	Bed roughness [m]

2

Literature review

2.1 Sediment transport processes in transitional zones

Estuaries and coastal lagoons are transitional zones between land and sea. Transitional waters are defined as water bodies with strong physico-chemical gradients and environmental fluctuations because of connection to coastal waters and are substantially influenced by freshwater flows (Pérez-Ruzafa et al., 2011). Lagoons are the most valuable components of coastal areas in terms of both the ecosystem and natural capital. Coastal lagoons are usually shallow aquatic ecosystems between coastal and marine ecosystems (Gonenc and Wolflin, 2004), separated from the open sea by one or more barrier islands or peninsulas. The connection with the sea allows the water exchange and the flushing of the lagoon basin. Coastal lagoons are important ecosystems connected to the surrounding environments they develop mechanisms for structural and functional regulation, which result in specific biological productivity and carrying capacities (Gonenc and Wolflin, 2004).

Sediment transport is simply the process of eroding sediment from one place, carrying it in the flow and depositing it in another place (Ji, 2008). In shallow environments, the main drivers of sediment transport are waves and currents, influenced by other physical, chemical, and biological processes that complicate the system and increase the difficulties to describe sediment dynamics. In general, sediments are a matrix of materials and consist of four main components: interstitial water, inorganic sediment, organic sediment and contaminants (nutrients, polychlorinated biphenyls (PCBs), heavy metals, etc.) (Ji, 2008). This study is focussed only on the dynamics of the inorganic sediments.

The process of sediment transport depends on the dynamic feedback interactions between the hydrodynamics, sediment properties (size, density and shape) and bedforms (for sand) (Soulsby, 1997, Nielsen, 2009). The total sediment load is a sum of suspended load and bedload. The bedload is described by the rolling, sliding or saltation of the bed particles (mostly the particle size varies from 0.1 mm to 1 mm) that are transported a short distance downstream (Bagnold, 1966). The suspended sediments are transported in the water column when bedshear velocity exceeds the particle fall velocity and are much finer compared with the bedload particles (van Rijn, 1984). The ratio between the bedload and total load differs from one environment to another. In rivers it mostly varies from 1% to 33% (Joshi and Xu, 2017; Aga et al., 2019), with an average of 10%. Similar trends were found in the Venice Lagoon, where the bedload transport through the inlets was about 17% of the total sediment transport (Ferrarin et al., 2010a).

The main variables that describe the sediment transport mechanisms are the distribution of suspended sediment concentration, erosion-accumulation zones, bed shear stress and grain size distribution of sand. It is difficult to obtain all these parameters from *in situ* measurements due to temporal and spatial heterogeneity. Therefore, numerical models can be powerful tools to estimate the sediment transport mechanisms in complex systems such as lagoons. The research on sediment transport mechanisms is important for understanding many environmental factors (Zilius et al., 2016). The sediment balance in a semi-enclosed coastal basin is the result of many factors, such as eutrophication, contaminant transport, sediment bed erosion, siltation, waste disposal (Ji, 2008), pollutant and bacteria dynamics (Kataržytė et al., 2018) and biogeochemical processes of a complex interaction of the above as well. These processes occurring inside the basin are also regulated by the interactions between the tidal motion at the inlets and the longshore transport (see de Swart and Zimmerman, 2009 and references therein).

The global climate change scenarios forecast higher water levels, water temperatures, increased frequency and intensity of storms and extreme precipitation events over most mid-latitude lands (IPPC, 2014). All these processes may increase erosion and sediment suspension in the system. The Second Assessment of Climate Change for the Baltic Sea Basin indicates that in the areas characterised by spring floods, the riverine floods are likely to occur earlier in the year and their magnitude is likely to decrease due to less snowfall and a shorter snow accumulation period. As a consequence, sediment transport and the risk of inundation are likely to decrease (BACC II Author Team, 2015). Studies focussed on the sediment supply from the rivers have already showed the decreased amounts of the sediment loads (Čerkasova et al., 2019; Walling and Fang, 2003).

2.1.1 Sediment transport mechanisms in the Curonian Lagoon

On the southern and south-eastern Baltic Sea coast, large coastal water bodies as bays and lagoons are common. The Curonian Lagoon is the largest lagoon in Europe. The sediment transport mechanisms in this transitional zone are still very little explored. The lagoon bottom sediments were investigated in several studies (Gulbinskas, 1995; Galkus and Jokšas, 1997; Pustelnikovas, 1998; Trimonis et al., 2010; Jokšas et al., 2003). These studies were mostly focused on the lithological composition of the lagoon bottom sediments and their geochemical properties, suspended sediment concentration and simple sediment budget calculations. The lack of field data allowed drawing only very general lagoon circulation patterns. The investigation of currents and water turbidity provided additional data allowing a better definition of the processes taking place in the Curonian Lagoon (Galkus and Jokšas, 2002; Galkus 2003a,b; Galkus, 2004). Still there is a lack of detailed research of sediment dynamics, fluxes and erosion-accumulation rates in the lagoon. It is known that the sediment dynamics in the lagoon mostly depends on the sediments coming from the rivers, especially from the Nemunas River and its tributaries, wind waves and currents but the analysis of each factor separately was not performed (Galkus and Jokšas, 1997).

Table 1. **The sediment budget elements for the Curonian Lagoon referring to the literature sources**

Source	**INPUT**				**OUTPUT**	
	From the rivers, 10^6 kg y^{-1}	From the sea and atmosphere, 10^6 kg y^{-1}	Abrasion, erosion and aeolic transport, 10^6 kg y^{-1}		To the sea, 10^6 kg y^{-1}	Accumulation, 10^6 kg y^{-1}
Blazhchishin, 1984	781.0	-		-	-	-
Pustelnikovas, 1995	397.0	7.2		50.0	117.0	337.2
Galkus and Jokšas, 1997	267.2	64.75 (atmos.) 15.6 (sea)	65.2		318.0	132.8

The summary of the studies for the sediment budget calculation is presented in Table 1. According to Pustelnikovas (1998) 87.4 % of the total amount of all incoming terrigenous material comes from rivers, 1.6 % comes from the atmosphere and the sea, 11% from the bottom and shore erosion and aeolian processes. Galkus and Jokšas (1997) found that the rivers bring 59.3% of the total amount of incoming material, the atmosphere and the sea bring 17.8% and other sources such as erosion, aeolic transport bring 14.5%. The sediments coming to the system settle in the southern part of the lagoon or are carried through the narrow Klaipėda Strait into the Baltic Sea (Pustelnikovas, 2008). According to Pustelnikovas (1994) the mean sedimentation rate (about 3.2 mm y^{-1}) was estimated, while higher sedimentation rates up to 3.6 mm y^{-1} were found for the areas deeper than 3 m.

2.1.2 Ice cover influence for the sediment transport

The annual cycle of ice cover formation and melting changes the hydrodynamic conditions in the waterbody and influences the sediment dynamics in the system. The ice cover significantly affects the sea level oscillations, transfers of momentum and heat (Idzelytė et al., 2019). The key factors that encourage the changes are the amount of ice formed and the number of days with ice cover. In the lagoon systems the ice cover eliminates wind forcing, determining that water exchange with the sea and river discharge become the main forcing factors bringing sediments to the system that after the ice melting are redistributed throughout the lagoon (Chubarenko et al., 2019). The ice cover significantly affects the deposition of the sediments (Szymczak and Szmytkiewicz, 2014) due to low or no waves and low bed shear stress. A few studies have been published on the sedimentation properties under ice cover in lagoons (Shirasawa and Lepparanta, 2003; Kawamura et al., 2004; Shirasawa et al., 2005; Morimoto et al., 2010).

Idzelytė et al. (2019) summarized the spatial and temporal ice cover properties in the Curonian Lagoon for the period 2002-2017. The results showed that the ice cover in the lagoon is present from 10 to 90 days with the lagoon average of 71 days. The longest duration of the ice cover is in the south eastern part of the lagoon (Idzelytė et al., 2019).

The results of global climate change scenarios showed that the snow cover in spring in the Northern Hemisphere area is likely to decrease by 7% for RCP2.6 and by 25% in RCP8.5 by the end of the 21st century for the multi-model average (IPPC, 2014). According to the climate change scenario simulations, the drastic decrease of sea ice was indicated in the Baltic Sea in the future (BACC II Author Team, 2015). The increased water temperature will cause the ice cover to be thinner, less extensive, and to be present for a shorter period. This could lead to major changes in the sediment transport and cause the changes in the ecology of the system.

2.2 Sediment processes and ecology

The dynamics of suspended sediments in the water column is one of the key process influencing the ecology of shallow systems. Concentration of total suspended solids strongly affects light penetration and photosynthetic processes in the water column and at the sediment surface (Whipple et al., 2018) that can limit the submerged vegetation (Teeter et al., 2001) and also affect the benthic fauna.

The sediment transport mechanisms can be an important factor for the evaluation of ecological processes in the aquatic systems, especially in the shallow lagoons, where it can affect mineralization, nutrient recycling and productivity (Fanning et al., 1982). The benthic-pelagic coupling could help to answer the questions related to water quality, benthic vegetation, ecosystem services or others (Capet et al., 2016). The sediment resuspension can increase the suspended sediment concentration and influence the sediment redistribution. In shallow systems, resuspension is caused by wind waves or tidal currents (Ward et al., 1984). The resuspension of the thin layer of sediments can release nutrients to the system (Fanning et al., 1982) that causes eutrophication problems. These processes are poorly studied in the shallow Baltic lagoons.

2.3 A review of sediment transport models

Sediment transport models can be divided into three main categories in general: (i) empirical – based on the analysis of observations and seek to characterise the response from these data; (ii) conceptual – based on the composition of concepts; and (iii) physics-based models (Merrit et al., 2003 and references therein). The physics-based models solve the fundamental physical equations for water flow, sediment transport, and mass and momentum conservation.

The sediment transport modelling started with the development of one-dimensional (1-D) models (Dyer and Evans, 1989; Ross and Mehta, 1989). New technologies, computer power and advances in hydrodynamic and wave modelling meant that two- (U.S. Army Corps of Engineers, 2000; Warren, 1992) and three-dimensional models were developed (Lesser et al., 2004; Umgiesser et al., 2004) with two main numerical methods: (i) finite difference and (ii) finite element.

There is a big variety of models, all with advantages and limitations. For example, Sed2D model developed in the United States (U.S. Army Corps of Engineers, 2000) is a two-dimensional, vertically averaged finite element, numerical sediment transport model for open-channel flows capable of computing deposition, erosion, and transport patterns for bedload sediments. However, Sed2D can consider only one grain size during the simulation that is not suitable for the analysis of a complex system such as a lagoon. MIKE 21 and MIKE 3 (www.mikepoweredbydhi.com) are 2-D and 3-D commercial software for the simulation of hydraulics and hydraulic-related phenomena in estuaries, coastal waters and seas, where various modules of the system simulate hydrodynamics, advection-dispersion, short waves, sediment transport, water quality, eutrophication and heavy metals (Warren and Bach, 1992; Moharir et al., 2014). The model is widely used for many coastal environments including the Baltic Sea (Lumborg, 2005; Violeau et al., 2002; Forsberg et al., 2019). There are three sediment modules (Sand Transport, Mud Transport and Particle Tracking) that model erosion, transport and deposition of sediments as well as littoral and dredging processes. Another model was developed by Deltares is Delft-3D – a numerical model based on the finite difference method (Lesser et al., 2004). The sediment transport and morphology module of Delft-3D supports both bedload and suspended load transport of non-cohesive sediments and suspended load of cohesive sediments. In the module, sediment interactions are taken into account although a couple of processes are lacking, especially in sand-mud interactions (Deltares, 2019). The model was applied in a variety of studies (Tu et al., 2019; Escobar and Velásquez-Montoya, 2018 and others).

The highest precision can be reached applying 3D models. For the shallow environments, it is crucial to have a model with good adaptability to complicated geometries and bathymetry. Models based on a finite element method are well suited for applications in very shallow lagoons and coastal seas. SHYFEM is a modelling system that has been extensively applied to Venice Lagoon, for which all its modules have been developed and tested (Umgiesser et al., 2004). SHYFEM has a separate model for the sediment transport called SEDTRANS05. The development of the SEDTRANS models started by one-dimensional numerical model developed at the Geological Survey of Canada and Atlantic (GSCA) and designed for sediment transport problems on continental shelves and in coastal environments (Davidson and Amos, 1985). Three more versions were developed due to new findings in cohesive and non-cohesive sediment studies: Sedtrans92 (Li and Amos, 1995), Sedtrans96 (Li and Amos, 2001) and the latest version SEDTRANS05 (Neumeier et al., 2008). The SEDTRANS05 has been applied for Venice Lagoon and other sites in the Mediterranean Sea, including the Marano-Grado Lagoon and Adriatic Sea (Ferrarin et al., 2016; Ferrarin et al., 2010a,b).

There are more sediment transport models that can be applied for the analysis of sediment dynamics. The reader is referred to the publications of Merritt et al. (2003), Le Normant (2000) and Bever and MacWilliams (2013) where other sediment models are presented.

2.3.1 Sediment transport models for the Curonian Lagoon

The modelling studies for the Curonian Lagoon are mostly focused on hydrodynamics, by applying SHYFEM. The SHYFEM model has been previously validated in studies reproducing water level, water temperature and salinity fluctuations and the structure of the flow in the Klaipeda Strait. The horizontal and vertical circulation patterns were studied in Ferrarin et al. (2008a) and Zemlys et al. (2013), the water renewal time in Umgiesser et al. (2016). For the investigation of sediment dynamics the numerical models were applied only in a few studies.

The SHYFEM modelling system for sedimentation processes was applied first by Ferrarin (2007) when the two-dimensional hydrodynamic model coupled with the spectral wave model has been used to investigate the variability of the combined (current and wave) bed shear stress. The more detailed studies of the sediment transport for the Klaipeda Strait, which is the harbour area and connects the Curonian Lagoon with the Baltic Sea, using the DHI 2-D numerical modelling system MIKE-2 were carried out by Kriaučiūnienė et al. (2006) and by Kriaučiūnienė and Gailiušis (2004). However, these studies does not take into account the Curonian Lagoon in terms of the sediment transport and morphological changes.

This study aims to identify the propagation of the suspended sediments in the river-lagoon-sea (Nemunas-Curonian Lagoon-Baltic Sea), to map the erosion-accumulation zones due to the sediment dynamics, calculate the sediment budget and forecast the possible sedimentation trends according to climate change scenarios.

3

Materials and methods

3.1 The study area

The Curonian Lagoon (Fig. 1) is a shallow coastal water body in the southeastern part of the Baltic Sea with the only one narrow connection to the sea in the north (Klaipėda Strait) and separated from the sea by a narrow sandy barrier (Curonian Spit, 1-3 km width). The lagoon is a transboundary area between Lithuania and Kaliningrad Oblast of the Russian Federation with the monitoring programs carried out by each state independently. The total surface area of the lagoon is about 1584 km^2, the volume is 6.3 km^3, the length from the north to the south is 93 km, the maximum width in the southern part is 46 km and the mean depth is 3.8 m (Žaromskis, 1996).

The Curonian Lagoon is a transitory freshwater basin. It is a terrestrial runoff dominated system, the hydrology of which is strongly related to the discharge of the catchment area. The main rivers which enter the lagoon are Nemunas (Neman), Minija, Deima and Danė. The Nemunas is the largest low land transboundary river in Lithuania, with a catchment area of 100,500 km^2 (Gailiušis et al., 2001), that covers 98% of the lagoon basin area and on average brings about 21.8 km^3 of water per year to the lagoon (~700 m^3s^{-1}) (Jakimavičius, 2012). The major part of the Nemunas discharge flows into the lagoon through the northern branches of the Atmata and Skirvytė, and its smaller part flows into the southern part of the lagoon through the Matrosovka (Gilija) branch (Dumbrauskas and Punys, 2003). The Nemunas River enters the la-

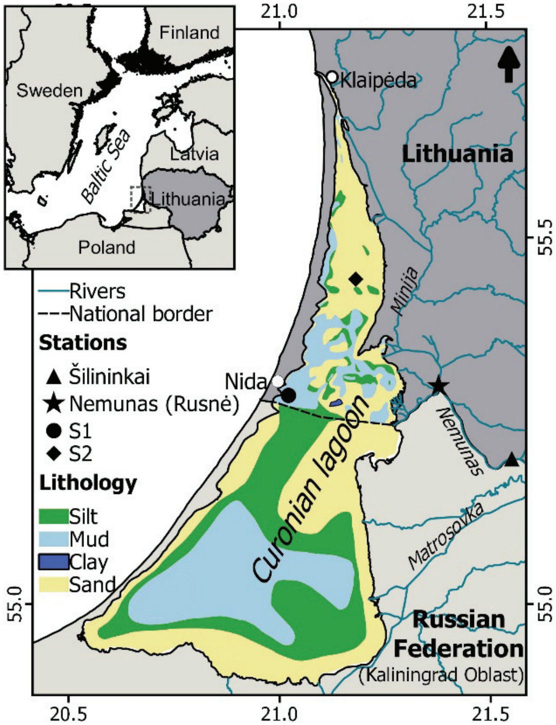

Figure 1. The study site with the sampling stations and bottom sediments in the Curonian Lagoon (the bottom sediment data acquired after Gelumbauskaitė et al. (1999) and Gulbinskas and Žaromskis (2002))

goon in the middle of the eastern coast and every year carries a large volume of fresh water that exceeds the water volume of the lagoon itself by about 3.6 times. Therefore, the southern and central parts of the lagoon are freshwater with the average annual water salinity of 0.08 and is oligohaline in the northern part, where the average annual salinity is 2.45 with irregular Baltic Sea water intrusions (salinity up to 7) (Dailidienė and Davulienė, 2008). The Curonian Lagoon is non-tidal lagoon, where a natural horizontal gradient of the water surface towards the sea is formed. The outflow from the lagoon dominates because of normally higher water level in the lagoon compared to the sea (Zemlys et al., 2013) (see Fig. 4A). This lagoon can be formally divided in two sub-basins (Ferrarin et al., 2008a): a northern area influenced by both the freshwater flow and the lagoon–sea exchange and a southern basin where hydrodynamics is mostly influenced by the wind.

3.1.1 Characteristics of the sediments

The bottom sediment map for this study was compiled from the available bottom sediment maps from Gelumbauskaitė et al. (1999) and Gulbinskas and Žaromskis (2002) (see Fig. 1). The analysis of the map data showed that in the northern part of the lagoon the sandy sediments dominate, while the central and southern parts are mainly covered with silty and muddy sediments. In the western near shore part of the lagoon, medium sand has accumulated as a result of aeolian activity (from the blown dunes) whereas the central and eastern parts are dominated by the sandy material of the Nemunas River (Trimonis et al., 2003). The latest study of Trimonis et al. (2003) showed that the greatest part of the Lithuanian bottom is covered by the medium sand (0.5-0.25 mm), fine sand (0.25-0.1 mm), coarse silt (0.1-0.05 mm) and fine silty mud (0.05-0.01 mm). The dominant sediment fraction in the Klaipeda Strait is 0.05-0.01 mm (Trimonis et al., 2010).

The lagoon is a shallow water body with active water dynamics and high sediment loads due to river discharges. The high river discharges and wave activity are the main factors causing the bottom sediment redistribution in a short time span. The highest amount of sediments is spread throughout the lagoon when the flood season starts (Galkus and Jokšas, 1997). The suspended sediments are transported in particulate form and settle to the bottom (with 70% to 98% of soil pollutants) (Galkus and Jokšas, 1997). The lagoon sediments are rich in organic material (Remeikaite-Nikiene et al., 2016) and has fluffy sediments that can be easily resuspended (Zilius et al., 2014). As a result, the parametrisation of the sediment transport mechanisms in the Curonian Lagoon is crucial for many ecological processes.

3.2 SHYFEM numerical model

In general, to understand and predict the sediment transport and evolution of the lagoon morphology an integrated model is needed. For this study the framework of open source numerical models SHYFEM (Shallow water HYdrodynamic Finite Element Model, http://www.ismar.cnr.it/shyfem) was applied to the domain that represents the Curonian Lagoon and coastal area of the Baltic Sea. The unstructured grid based numerical model consisted of a 3-D hydrodynamic model, a transport and diffusion model, wind wave model, sediment transport model and bed model (Fig. 2). In the vertical, the water depth is divided into terrain following ς (sigma) levels.

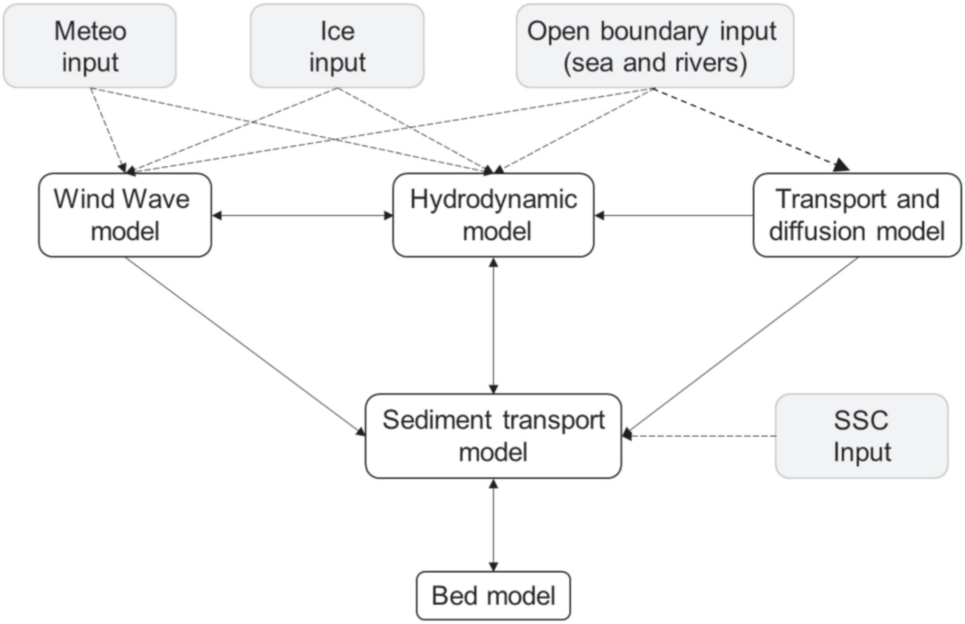

Figure 2. The SHYFEM model structure for this study.

3.2.1 Hydrodynamics

SHYFEM uses the finite element method for the horizontal spatial discretization, which is well suited to describe the complex morphology of the investigated coastal system. The model resolves the 3-D primitive shallow water equations, vertically integrated over each layer, in their formulations with water levels and transports as follows (equation of momentum balance in *x* direction (Eq. 1), equation of momentum balance in *y* direction (Eq. 2) and equation for mass conservation (Eq. 3)):

$$\frac{\partial U_l}{\partial t} + Adv_l^x - fV_l = -gh_l\frac{\partial \zeta}{\partial x} - \frac{gh_l}{\rho_0}\frac{\partial}{\partial x}\int_{-H_l}^{\zeta}\rho' dz - \frac{h_l}{\rho_0}\frac{\partial p_a}{\partial x} + \frac{1}{\rho_0}(\tau_x^{l-1} - \tau_x^l) + \frac{\partial}{\partial x}\left(A_H\frac{\partial U_l}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial U_l}{\partial y}\right), \quad (1)$$

$$\frac{\partial V_l}{\partial t} + Adv_l^y + fU_l = -gh_l\frac{\partial \zeta}{\partial y} - \frac{gh_l}{\rho_0}\frac{\partial}{\partial y}\int_{-H_l}^{\zeta}\rho' dz - \frac{h_l}{\rho_0}\frac{\partial p_a}{\partial y} + \frac{1}{\rho_0}(\tau_y^{l-1} - \tau_y^l) + \frac{\partial}{\partial x}\left(A_H\frac{\partial V_l}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial V_l}{\partial y}\right), \quad (2)$$

$$\frac{\partial \zeta}{\partial t} + \sum_l\frac{\partial U_l}{\partial x} + \sum_l\frac{\partial V_l}{\partial y} = 0. \quad (3)$$

Where in momentum equations advective terms are as follows:

$$Adv_l^x = u_l \frac{\partial U_l}{\partial x} + v_l \frac{\partial U_l}{\partial y}, \tag{4}$$

$$Adv_l^y = u_l \frac{\partial V_l}{\partial x} + v_l \frac{\partial V_l}{\partial y}. \tag{5}$$

Here l indicates the vertical layers, U_l, V_l are the horizontal transport at each layer, Adv_l^x, Adv_l^y are advective terms that can be expressed by Equations 4 and 5, f is the Coriolis parameter, p_a is the atmospheric pressure, g is the gravitational acceleration, ρ_0 the average density of the sea water, $\tau_x^{l-1}, \tau_x^l, \tau_y^{l-1}, \tau_y^l$ are the internal stress terms at the top and bottom of each layer, h_l is the layer thickness, H_l the depth at the bottom of layer, l, ζ is the water level, A_H are the horizontal eddy viscosity and u_l, v_l the velocities in x and y directions.

For the parametrization of the horizontal eddy viscosity (A_H) the Smagorinsky's formulation (Smagorinsky, 1963; Blumberg and Mellor, 1987) is used. The horizontal space integration is made using a finite element method, while the integration in time is made through a semi-implicit scheme. The Coriolis force, the barotropic pressure gradient terms in the momentum equation, and the divergence term in the continuity equation are treated semi-implicitly, while all the vertical shear stress terms are treated fully implicitly for stability reasons. The model adopts automatic internal sub-stepping over time to enforce numerical stability with respect to advection and diffusion terms. For the computation of the vertical viscosities and diffusivities a turbulence closure scheme is used. This scheme is an adaptation of the k-ε module of GOTM (General Ocean Turbulence Model) described in Burchard and Petersen (1999).

The model solves the 3-D advection and diffusion equation to compute water temperature and salinity (Eq. 6):

$$\frac{\partial S_l}{\partial t} + u_l \frac{\partial S_l}{\partial x} + v_l \frac{\partial S_l}{\partial y} + w_l \frac{\partial S_l}{\partial z} = \frac{\partial}{\partial x}\left(K_H \frac{\partial S_l}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H \frac{\partial S_l}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_V \frac{\partial S_l}{\partial z}\right) + E \tag{6}$$

where S_l is a tracer concentration (salinity, water temperature) at a layer l, u_l, v_l, w_l are velocities in x, y and z directions, K_H, K_V are the horizontal and vertical turbulent diffusion coefficients respectively and E is a source/sink term. The transport and diffusion equation is solved with a first order explicit scheme based on the TVD scheme (Darwish & Moukalled, 2003). For a more detailed description of the model equations and discretization methods the reader could refer to Umgiesser et al. (2004) and for its

3D implementation to the Curonian Lagoon in Zemlys et al. (2013) and other environments to Bellafiore and Umgiesser (2010).

3.2.2 Wind waves and ice cover

Wind generated waves are one of the main factors causing sediment resuspension that is a main source of fine sediments to the water column. The SHYFEM model has several modules for wave simulation. In this study the parametric wave model was applied that utilises empirical equations for shallow water (CERC, 1984) to calculate significant wave height H_{m0} (Eq. 7) and period T_p (Eq. 8).

$$\frac{gH_{m0}}{{U_A}^2} = 0.283\tanh\left[0.530\left(\frac{gh_a}{U_A^2}\right)^{3/4}\right] tanh\left(\frac{0.00565\left(\frac{gF}{U_A^2}\right)^{1/2}}{\tanh\left[0.530\left(\frac{gh_a}{U_A^2}\right)^{3/4}\right]}\right), \qquad (7)$$

$$\frac{gT_p}{U_A^2} = 7.54\tanh\left[0.833\left(\frac{gh_a}{U_A^2}\right)^{3/8}\right] tanh\left(\frac{0.0379\left(\frac{gF}{U_A^2}\right)^{1/3}}{\tanh\left[0.833\left(\frac{gh_a}{U_A^2}\right)^{3/8}\right]}\right),$$

where U_A is the wind speed (m s^{-1}), h_a is the averaged water depth along a fetch F (m).

The presence of ice cover has been accounted by weighting the wind drag coefficient by the fractional ice concentration. This corresponds to scaling the momentum input through the surface by the area free of ice. The ice concentration is a value between 0 (ice free) and 1 (fully ice covered) and can be a fractional number. Where ice concentration equals 1 the momentum transfer to the sea is inhibited. No ice–ocean stress was considered in this study. Ice concentration was also used to properly calculate the albedo to be used in the heat flux model.

3.2.3 SEDTRANS05 model

The SEDTRANS05 (Neumeier et al., 2008) is the latest version of Sedtrans92 (Li and Amos, 1995) and Sedtrans96 (Li and Amos, 2001) models for the sediment transport integrated to SHYFEM modelling system. It can simulate cohesive and non-cohesive sediment dynamics induced by wind waves and currents. The water density and dynamic viscosity are computed from the water temperature and salinity according to the equation of state for seawater EOS80 (Fofonoff, 1985) and expression of Riley and Skirrow (1965) respectively.

The sediments are divided into several grain classes to represent the variability of the natural environment better. In the model each sediment class acts independently and is characterized by its own settling velocity $W_{s(l)}$ and concentration C_l.

In the model, the bed is divided in many homogeneous layers that are characterized by their own grain size distribution, dry bulk density ρ_{dry} and critical stress for erosion τ_{ce} values. The linear relationship is assumed between two levels. More details about the sediment model are presented in the next sections.

For the better bed representation the sediment transport model uses a 3D grid underneath of the hydrodynamic grid. The bed is subdivided in several layers and level. The model assumes that each layer is homogeneous and well mixed. The fractions of each sediment class are considered for every grid point. Each bottom level has its own dry bulk density ρ_{dry} and critical shear stress value for the erosion τ_{ce}. The linear relationship is considered between the different bottom layers. This type of bottom representation allows modelling the morphodynamics of a system.

The uppermost layer is an active layer available for the sediment suspension. The layers below are unavailable for resuspension until the active layer is completely eroded. In the situation when only a part of the layer is eroded, the layer values for ρ_{dry} and τ_{ce} is updated. If the deposition occurs new sediments are added increasing the layer thickness with new ρ_{dry} and τ_{ce} values.

The bed roughness and critical shear stress for each grid node are computed form the average grain sizes based on the sediment fractions. The morphological model takes into account time and spatial dependent sediment distribution and bed armouring. Modifications to bed elevation and to the grain size distribution are updated at each time step based on the net erosion and deposition rates. The new depth is used to compute the hydrodynamics in the subsequent time step.

3.2.3.1 Bed shear stress and critical shear stresses

The bed shear stresses (τ_0) and the velocity profile in the bottom boundary layer are computed by the Grant and Madsen (1986) continental shelf bottom boundary layer theory under the influence of currents and waves. The bed shear stress values can be corrected due to drag reduction of high SSC and the presence a solid-transmitted stress (τ_{solid}) to the bed covered by the algae (Neumeier et al., 2008). For non-cohesive sediments, the friction factor and the bed roughness (z_0) is computed from the grain size and the predicted bedform (ripple) while for cohesive sediments the default values of 0.0022 for friction factor and 0.0002 m for bed roughness proposed by Soulsby (1997) are used.

Depending on the bed shear stress and critical shear stresses values, the erosion or deposition processes can take place in the system. The critical shear velocity for erosion (u^*_{crs}) that initiates the non-cohesive sediment transport by causing sediment suspension is computed following the Van Rijn method (Van Rijn, 1993):

$$1 < D_* \leq 10: \quad \frac{u^*_{crs}}{W_s} = \frac{4}{D_*}, \qquad or \ \Theta_{crs} = \frac{16}{D_*^2}\frac{W_s^2}{(s-1)gD}$$

$$D_* > 10: \quad \frac{u^*_{crs}}{W_s} = 0.4, \qquad or \ \Theta_{crs} = 0.16\frac{W_s^2}{(s-1)gD} \tag{9}$$

where D_* is the dimensionless grain size computed by Eq. 10, u^*_{crs} is the critical shear velocity for suspended-load transport, W_s is the settling velocity calculated by Eq. 11, g is the acceleration due to gravity, D is the median sieve grain diameter.

$$D_* = \left[\frac{g(\rho_s/\rho_w - 1)}{\nu^2}\right]^{1/3} D \tag{10}$$

where ρ_s is the sediment density, ρ_w is the water density and is the kinematic viscosity.

The W_s is calculated separately for each sediment class with the coarser particles being deposited faster using the Soulsby (1997) equation:

$$W_s = \frac{\nu}{D}[(10.36^2 + 1.049D_*^3)^{0.5} - 10.36]. \tag{11}$$

The critical shear stress for erosion (τ_{ce}) of cohesive sediments is applied as a function of erosion depths and is linked to the sediment density. For the bed surface the τ_{ce} is calculated by the Eq. 12 and for the other layers the modified formula is used (Eq.13):

$$\tau_{\text{ce}} = a\rho_{dry}^b \tag{12}$$

$$\tau_{\text{ce}} = T_{\text{a}}\rho_{\text{dry}}^{\text{T}_b}(1 + T_{\text{c}}(1 - \exp(T_{\text{d}}m_{\text{o}}))) \tag{12a}$$

where ρ_{dry} is the dry bulk density, $T_{\text{a}}, T_b, T_c, T_d$ are coefficients with the default values of $6\cdot10^{-10}$, 3, 3.47, -1.915 respectively. Coefficients were fitted using Amos et al. (2000, 2004) studies.

The critical shear stress for deposition τ_{cd} is computed for each cohesive W_s class using the relationship proposed by Mehta and Lott (1987) or the relationship defined by Bagnold (1973):

$$\tau_{cd} = k_{cd} W_s^{m_{cd}} \tag{13}$$

$$\tau_{cd} = 0.64 \rho_w W_s^2 \tag{13a}$$

where m_{cd} and k_{cd} are coefficients with the default values of m_{cd}=1.03 and k_{cd}=2800.

3.2.3.2 Erosion and deposition processes

The erosion and deposition processes are updated with each time step under the following order:

- the computation of the effective bed shear stress taking into account correction due to high SSC and solid transmitted stress;
- computation of the mass of eroded sediment and erosion of the bed (first part);
- calculations for deposition: deposition rate for each *Ws* class, removal of the deposited mass from the suspended sediment load, and the freshly deposited sediment added to the bed;
- the mass of eroded sediment is added to the suspended sediment load (second part of erosion calculation);
- consolidation of the bed (optionally).

Erosion of cohesive sediments occurs when the shear stress applied to the sediment bed τ_0 exceeds a critical value of the shear stress τ_{ce} while deposition takes place only when the bed shear stress τ_0 is less than the critical shear stress for deposition τ_{cd}. The mass erosion rate r_e is defined using a standard formula for beds with variable τ_{ce} (Amos et al., 1992; Parchure and Mehta, 1985; Van Rijn, 1993):

$$r_e = \frac{\partial m}{\partial t} = E_0 \exp[P_e (\tau_0 - \tau_{ce(z)})^{0.5}] \tag{14}$$

where E_0 is an empirical coefficient for minimum erosion, P_e is the proportionality coefficient for erosion, and $\tau_{ce(z)}$ is the critical shear stress for erosion as a function of erosion depth. The default coefficient values that can be changed during the calibration process are E_0 = 5.88 and P_e = $1.95 \cdot 10^{-5}$.

For the deposition the equation from Krone (1993) is used. This equation can be expressed as a (i) deposition rate or (ii) can be integrated over time to compute the concentration remaining in suspension C_t after a time interval *t* as a fraction of the initial concentration C_0:

$$r_d = \frac{\partial m}{\partial t} = CW_s\left(1 - \frac{\tau_0}{\tau_{cd}}\right)(1 - P_s) \tag{14}$$

$$C_t = C_0 \exp[-W_s\left(1 - \frac{\tau_0}{\tau_{cd}}\right)(1 - P_s)\frac{t}{h}] \tag{15}$$

where P_s is a dimensionless probability coefficient of resuspension in the range 0-0.2 (default value equals to 0), h is a water depth. If the concentration of the grain class decreases until 0.0001 kg m^{-3}, all sediment of that class is deposited.

The freshly deposited cohesive sediments are considered as a fluid mud with the default density of 50 kg m^{-3} (Whitehouse et al., 1999). In the model, the τ_{ce} for the freshly deposited sediments is set to 10% higher than the τ_o to avoid the immediate sediment resuspension but τ_{ce} can not be greater than the underlying bed surface.

The SEDTRANS05 has an optional module for the sediment consolidation where the sediment density is expressed as a function of the initial sediment density, mass of overlaying sediments, depth and time step.

3.2.3.3 Bedload transport equations

Five methods to simulate the sediment transport for non-cohesive sediments are introduced into the model. The methods of Einstein–Brown (Brown, 1950), Yalin (1963), Van Rijn (1993), Engelund and Hansen (1967) and Bagnold (1963) can be selected in the simulation set-up according to the grain sizes. The Van Rijn (1993) equations, recommended for a large grain size range, were applied for prediction of the bedload transport rates in the Curonian Lagoon. This method assumes that the motion of the bedload particles is dominated by saltation under the influence of hydrodynamic fluid forces and gravity and was already successfully applied for the Venice Lagoon (Ferrarin et al., 2008b). The bedload transport rate (q) is defined as the product of the particle velocity, the saltation height and the bedload concentration. For the pure current case the bedload transport rate is expressed as:

$$q = \alpha(s-1)^{0.5} g^{0.5} D^{1.5} D_*^{-0.3} T_m^{2.1} \tag{16}$$

Where s is the ratio of the density of sediment and water, α is a constant (0.053), T_m is the dimensionless shear stress parameter, expressed as:

$$T_m = \frac{\tau_{cs} - \tau_{crb}}{\tau_{crb}} \tag{17}$$

where τ_{cs} is the instantaneous skin-friction current shear stress and τ_{crb} is the critical shear stress for initiation of bedload motion.

The instantaneous bedload transport rate for the combined current and wave case is

$$q = 0.25\alpha D D_*^{-0.3} \left(\frac{\tau_{cws}}{\rho}\right)^{0.5} T_m^{1.5} \tag{16a}$$

where $\alpha = 1 - (\frac{H_{m0}}{h})^{0.5}$ is a calibration factor with H_{m0} – the significant wave height and h – the water depth, τ_{cws} is the instantaneous skin-friction combined shear stress. Then the T_m for the combined-flow case is defined as

$$T_m = \frac{\tau_{cws} - \tau_{crb}}{\tau_{crb}} \tag{17a}$$

The time-averaged bedload transport rate is obtained averaging over a wave period.

3.3 Simulation setup

In this study a numerical grid with variable size elements was used. The course grid with more precise resolution in the fairway of the Curonian Lagoon, the Nemunas Delta front and coastal area of the Baltic Sea was developed for this study. The resolution of the elements varied from 250 m to 3 km. The vicinity of the Klaipeda Strait had the finest resolution. The grid consisted of 3269 elements and 2021 nodes (Fig. 3). A part of the Baltic Sea shelf was included in the numerical grid in order not to disturb the computations of the exchanges through the Klaipeda Strait. In the vertical, 5 sigma layers have been inserted.

Several numerical simulations have been carried out in this study. The numerical experiments are divided into three groups: (i) short term simulations for the model calibration, validation and sensitivity tests; (ii) analysis of present situation (long-term simulations) for the simulation period 2004-2015, including calculations of erosion-accumulation rates and sediment budget, and (iii) the future perspectives according to the climate change scenarios. The calibration/validation results for hydrodynamic and sediment parts are presented independently.

The following numerical simulations were carried out in this study (Table 2):

(i) CAL: simulation for the sediment transport model calibration for the period from 1st of January 2013 until the end of 2015. The year 2013 was used as a spin up time and was excluded from the analysis.

VAL: simulation for the sediment transport model validation for the period 1st

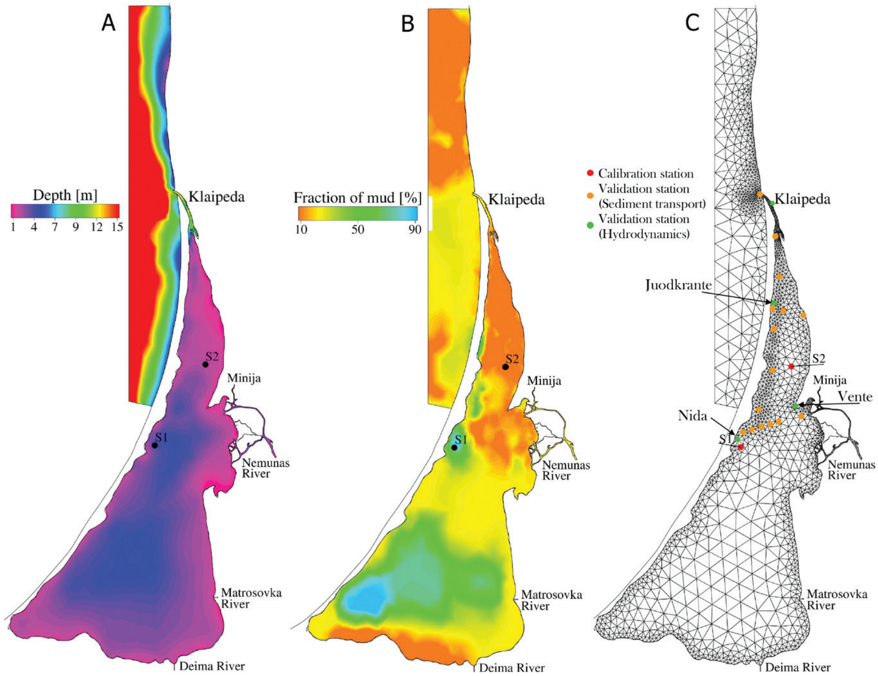

Figure 3. (A) Initial bathymetry, (B) initial percentage of cohesive sediments, (C) numerical grid with calibration and validation stations.

of January 2015 until the end of 2016. The year 2015 was used as a spin up time.

NoICE: 3 year-long simulation for analysis of ice influence on the sediment transport mechanisms in the Curonian Lagoon. Simulation period and set-up are the same as simulation CAL, but without ice cover data.

(ii) LONG: long-term simulation (13 years) for the validation of hydrodynamic model and analysis of the sediment transport mechanisms in the Curonian Lagoon. Simulation period 2004-2016. The spin up time for hydrodynamics was three months, for the sediment transport model the year 2004 was extracted as a spin up time.

(iii) RCP4.5: simulation of the climate change scenario based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Representative Concentration Pathway (RCP) 4.5 (Collins, 2013) for the period 2007-2033.

RCP8.5: simulation of the climate change scenario based on IPCC AR5 RCP8.5 (Collins, 2013) for the period 2007-2033.

Table 2. **Summary of numerical simulations carried out in this study.**

Scenario	Period	Description
CAL	2013-2015	Simulation for sediment model calibration (also used for sensitivity tests)
VAL	2015-2016	Simulation for model validation
NoICE	2013-2015	As CAL, but without ice cover data
LONG	2004-2016	13 years simulation, validation of hydrodynamic model
RCP4.5	2007-2033	RCP4.5 climate change scenario for the sediment dynamics
RCP8.5	2007-2033	RCP8.5 climate change scenario for the sediment dynamics

3.4 Data collection

Data sets were needed for the development and calibration/validation of the hydrodynamic and sediment transport models. Firstly, the data was collected from the different available data sources. Secondly, the data was sampled during several field campaigns to fill the gaps of the required data for the model set-up. The data was used to check model quality and as an input for the numerical model simulations.

3.4.1 Available data for the model set-up

Open Sea. The open sea boundary water temperature (°C), salinity and water levels (m) were obtained from three different sources. For the year 2004-2006 the boundary data was taken from the operational hydrodynamic model MIKE21 provided by the Danish Hydraulic Institute (DHI). For the year 2007-2009 and 2014-2016 the data was obtained from the operational hydrodynamic model HIROMB (Funkquist, 2003) provided by the Swedish Meteorological and Hydrological Institute with a spatial interpolation of 1 nautical mile. For the year 2010-2013 the data was taken from the model MOM (Modular Ocean Model) provided by the Leibniz Institute for Baltic Sea Research in Warnemünde, Germany.

Meteorological data. The meteorological forcing of rain (mm day^{-1}), solar radiation (W m^{-2}), air temperature (°C), humidity (%), cloud cover (0 – clear sky, 1 – overcast sky), 10 m high wind velocity in x and y directions (m s^{-1}) and atmospheric pressure (Pa) were used as surface forcing. For the years 2009-2010, the meteorological forcing fields were provided by the Lithuanian Hydrometeorological Service under the Ministry of Environment from the operational meteorological model HIRLAM (http://www.hirlam.org). For the other years (2004-2008 and 2011-2015), the meteorological data from European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int) were used. The ECMWF model air temperature and wind speed data was checked with the measured values for the station S1. Results are

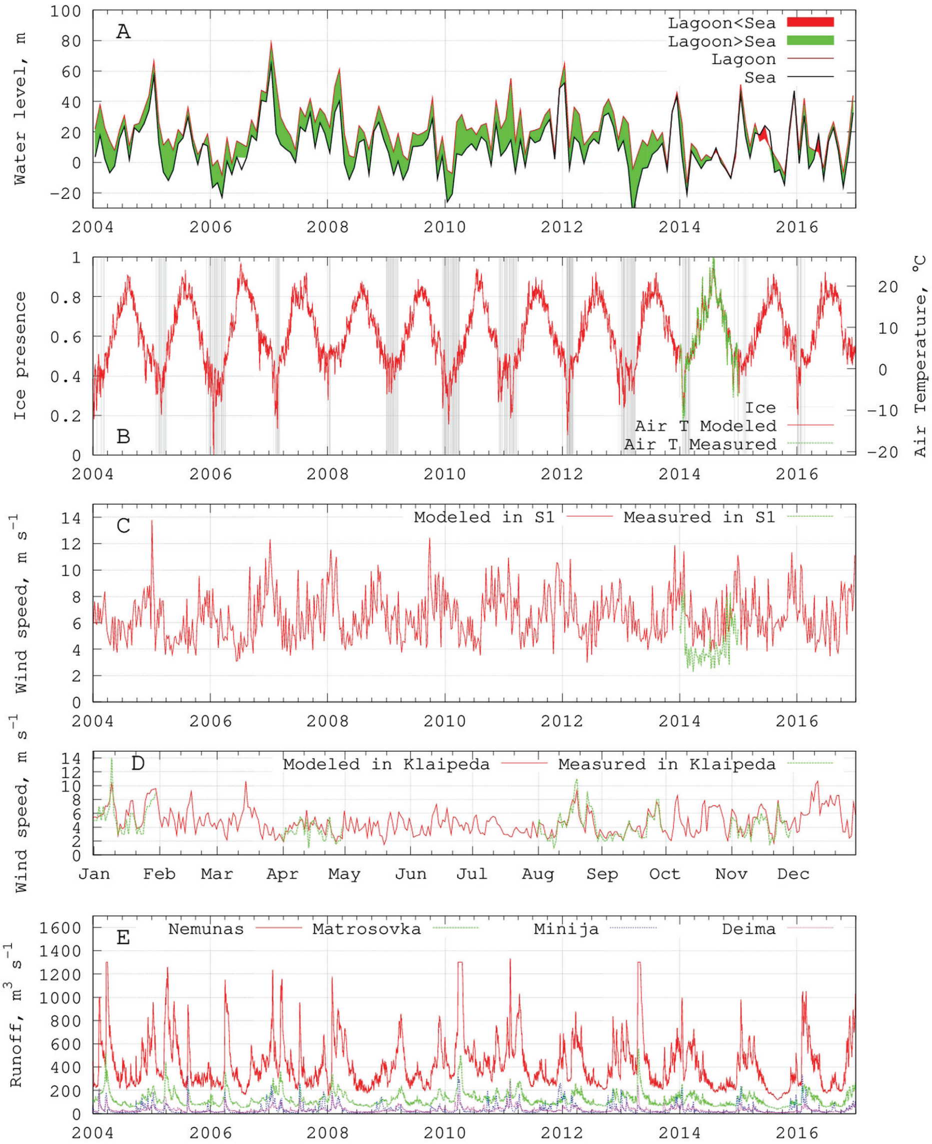

Figure 4. Time series of (A) measured water levels in Klaipeda Strait and Nida; (B) Measured/modelled (ECMWF) air temperature in Nida and ice cover (grey band) presence in the lagoon from satellite data; (C) Measured/modelled (ECMWF) weekly averaged wind speed for S1, (D) daily measured/modelled (ECMWF) wind speed in Klaipeda for the year 2014 (E) fresh water discharge into the lagoon.

shown in Figures 4B and 4C respectively. The statistical analysis showed a strong relationship between measured and modelled air temperature data (R^2=0.97), while the analysis of wind data is more complicated. Results showed that the ECMWF model overestimates wind speed close to the Curonian Spit by 30%, but in Klaipėda station the R^2 between measured and modelled values was equal to 0.75.

River runoff. Daily discharge data ($m^3\ s^{-1}$) for the rivers were provided by the Lithuanian Hydrometeorological Service under the Ministry of Environment. The Nemunas River discharge was measured at the Smalininkai monitoring station about 90 km from the model boundary. Therefore, the Nemunas River discharge for the open boundary conditions near Šilininkai (see Fig. 1) was considered as the discharges sum from the Nemunas near Smalininkai, Šešupė, Jūra and Šešuvis rivers minus Matrosovka (Gilija) branch discharge (Gilija discharge is accounted as a separate river input in the model, assumed to be 29% of the Nemunas discharge near Smalininkai) (Jakimavičius, 2012). The time necessary for the water to reach Šilininkai starting from Smalininkai was calculated from flow velocity obtained from Manning equation (Chen, 1992). It is known that during the spring flood water coming from the Smalininkai station overflows before reaching the model boundary (Vaikasas, 2009). The model does not simulate the overflow of the water, and as a result, the calculated Nemunas River discharge was limited to 1300 $m^3\ s^{-1}$ to avoid the overestimation of the current speed in the riverbed. In order to conserve the total discharged water volume, the flood period was extended from two weeks to up to one month depending on the water amount. The final river discharge for the model boundary is presented in Figure 4E. In all, about 2.5% of the simulation period had higher discharges than 1000 $m^3\ s^{-1}$.

Ice cover. The satellite ice cover data (Figure 4B) needed for the model set-up was provided by the Klaipeda University PhD student Rasa Idzelytė (Idzelytė et al., 2019). The data was acquired from the synthetic aperture radar (SAR) measurements from three Earth observation missions: Envisat ASAR, RADARSAT-2 and Sentinel-1A and 1B, complemented by cloud-free Moderate Imaging Spectroradiometer (MODIS) images. For the period 2004-2015 in total 475 SAR and 64 MODIS images were processed by manually digitizing ice polygons using ArcGIS software, which were then validated with ground observations, showing that satellite data in many cases has better performance than *in situ* data for defining the key stages of ice cover formation and decay. These polygon datasets were converted to regular grid points and then used to spatially interpolate onto the finite element grid. The ice cover presence in the model input file is set to a value of 0 (no ice) or 1 (ice cover). In all simulations, the Baltic Sea has been considered as ice free area.

Sediment. The open boundary data for the suspended sediment concentrations coming from Matrosovka and Deima rivers were obtained from the study of Galkus and Jokšas (1997). The average SSC values for different seasons were found close to the river mouths and were used as an input for the sediment model. The SSC coming from the Nemunas River was sampled during the PhD studies (see section 3.4.2)

The initial bottom sediment composition for this study was compiled from two data sources: (i) a map of (Gelumbauskaitė et al., 1999) for the southern part of the lagoon and the sea and (ii) a map of (Gulbinskas and Žaromskis, 2002) for the northern part of the Curonian Lagoon. As an input file for the initial bottom sediments, the regular grid was constructed with nine sediment classes (clay – <0.002 mm and 0.002-0.005 mm, fine silt – 0.005-0.01 mm, coarse silt – 0.01-0.063 mm, very fine sand – 0.063-0.1 mm, fine sand – 0.1-0.25 mm, medium sand – 0.25-0.5 mm, coarse sand – 0.5-1.0 mm and very coarse sand – 1.0-2.0 mm) that were considered ranging from clay to coarse sand. The initial bottom sediment composition in the model is divided into nine sediment classes which were presented as a percentage of total suspended sediment concentration for each class. The initial percentage distribution of mud fraction and the computational grid is shown in Figure 3.

Suspended sediments. Additional TSS and SSC data for sediment model calibration and validation was collected from two projects carried out by dr. Diana Vaičiūtė and funded by 7BP INFORM (Contract No. 606865) and Lithuanian Research Council (Contract No. VAT- MIP-040/2014) for the years 2014-2016. The data was collected using the same methodology described in the Section 3.4.2.

Chlorophyll *a*. For the analysis of biological processes affecting the sediment transport the Chlorophyll *a* (Chl-*a*) concentration data and the composition of the phytoplankton groups were needed. The data of the sample campaigns organized in 2014-2015 for these parameters was provided by dr. Diana Vaičiūtė, Klaipėda University. These assessments of the phytoplankton groups do not take into account the environmentally variable production rates of accessory pigments, diurnal variation in fluorescence yield due to non-photochemical quenching, or state transitions in cyanobacteria. Therefore, only a qualitative estimate of the cyanobacteria percentage from the total abundance of phytoplankton was used.

Nutrient concentration. The biogeochemical group of Marine Research Institute in Klaipeda University provided an averaged seasonal nutrients concentration in the pore water. The sampling campaigns were organized in 2015, the samples were taken using intact cores. The reader could refer to Zilius et al. (2018) for more information on sampling methods.

Validation data. For the validation of the hydrodynamic model, the measured water temperature, salinity, water level and wave data were necessary. The data were provided by the Marine Research Department of Lithuanian Environmental Protection Agency under the Lithuanian Ministry of Environment for the Lithuanian part of the Curonian Lagoon. The data were collected for the Klaipeda Strait, Juodkrantė, Nida and Ventė stations marked in green in Fig. 3. In Juodkrantė station the measured values were obtained for the period 2004-2009, in the Klaipėda Strait and Nida stations for the period 2004-2015 and in Ventė station for the year 2010.

Climate change projections. The climate change data for meteorological forcing and boundary conditions were collected from the available models lead by the Swedish Meteorological Hydrological Institute (SMHI). Predicted meteorological data was obtained from the global EC-Earth climate model downscaled to the ICHEC model performed on the Irish Centre for High-End Computing Stokes. The open sea boundary data was collected from the SMHI model RCO–SCOBI. Data was collected for climate change scenarios based on Representative Concentration Pathways (RCP). Two scenarios were chosen for this study: RCP4.5 and RCP8.5 under the reference and "business as usual" conditions respectively.

Table 3 summarizes the dataset used in the model applications.

Table 3. **The summary of the model set up data.**

Data	Period	Description
Open sea boundary	2004-2006 2007-2010 2011-2013 2014-2016	DHI model MIKE 21 SMHI model HIROMB IOW model MOM SMHI model HIROMB
Meteo forcing	2004-2008 2009-2010 2011-2016	ECMWF model data Lithuanian hydrometeorological service model HIRLAM ECMWF model data
River discharges	2004-2016	Lithuanian hydrometeorological service
Ice coverage	2004-2016	Satellite data provided by KU MRI (Idzelytė et al., 2019)
Initial bottom sediment composition	-	Gelumbauskaitė et al. (1999) and Gulbinskas and Žaromskis (2002)
Climate change	2007-2033	Meteorological data from EC-Earth (ICHEC), River discharges from SMHI Sea boundary from SMHI (RCO–SCOBI model)

3.4.2 *In situ* sampling and analysis

Several field campaigns were organized from March 2015 until February 2016 for sampling the Nemunas River and Curonian Lagoon waters. Samples were taken only from the surface layer, approximately 0.5-1.0 m depth. The analysis was divided into two parts: (i) The total suspended solid concentration (TSS, mg l^{-1}) and suspended sediment concentration (SSC, mg l^{-1}) measurements and (ii) analysis of the sediment grain sizes. The data was sampled in the Rusnė Village in the Nemunas River (see Fig.

1) once or twice per month, while in the lagoon stations (S1 and S2, see Fig. 1) only once per season except winter. The main characteristics of the sampling stations are presented in the Table 4.

Table 4. **The main characteristics of the monitoring stations**

Station	Location	Depth, m	Median bottom grain size, µm	Percentage of mud, %	Number of samples		
					Sampled in 2015	Additionally collected (see Section 3.4.1)	In total
S1	55.286017 N 21.021400 E	3.35	35	77	3	22	25
S2	55.444483 N 21.182733 E	1.90	210	1.6	3	17	20
Nemunas	55.298228 N 21.380543 E	2.00	-	-	15	-	15

The Nemunas station was 2 m in depth, where in total 15 samples were taken, covering all seasons and the flood period. Selected lagoon stations represented the sites with the different sediment properties. The Station S1 was 3.35 m deep with muddy bottom sediments (initial percentage of mud 77%) while S2 station was 1.9 m depth and the bottom was mostly covered with the fine sand (initial percentage of mud 1.6%). Three samples for each lagoon station were sampled.

The methodology for the data collection is presented in Figure 5. Depending on the season, the hydrological conditions and phytoplankton vegetation period, from 20 to 40 l of water was sampled in the field and transported to the laboratory for further investigation. From 300 ml to 1500 ml of sample were filtered in triplicate through combusted (4 hours at 550°C) and pre-weighed Whatman GF/F (47 mm in diameter, pore size of 0.7 µm) glass fiber filters (tare weight). After filtration, samples were dried at 60°C until the weight was stable. The TSS concentration was determined gravimetrically by the difference between dry weight and tare weight via Equation 18 (Strickland and Parsons, 1972). The inorganic part of the sample was determined after 4h in a NOBERTHERM muffler furnace at the temperature of 550°C. The SSC was determined gravimetrically by the difference between muffled filter weight and tare weight via Equation 19.

$$TSS = \frac{W_{f60} - W_f}{V}, \tag{18}$$

where W_{f60} is a filter weight with suspended matter after drying in 60°C (mg), W_f is a tare filter weight (mg), V is a filtered amount of water (l).

$$SSC = \frac{W_{f550} - W_f}{V}, \tag{19}$$

where W_{f550} is a filter weight with suspended matter after muffling in 550°C (mg), W_f is a tare filter weight (mg), V is a filtered amount of water (l).

The rest of water sample was used for the analysis of suspended particles. Water tanks were left for 4 days until suspensions settled. The suspensions were concentrated to 1 l. Suspensions were centrifuged and concentrated to two 50 ml tubes for grain size analysis. Two types of analysis were done: (i) grain size analysis of total suspension composition and (ii) grain size analysis without organic material. To eliminate the organic matter from the sample, 30% H_2O_2 were added to the concentrated material and heated to 80°C. The granulometric analysis was done from the liquid/wet sample by laser diffraction method using laser particle analyser Analysette 22 MicroTec Plus, Fritsch (measuring range 0.08-2000 μm). These results were used to calculate the percentage of concentration for each grain class used in the model.

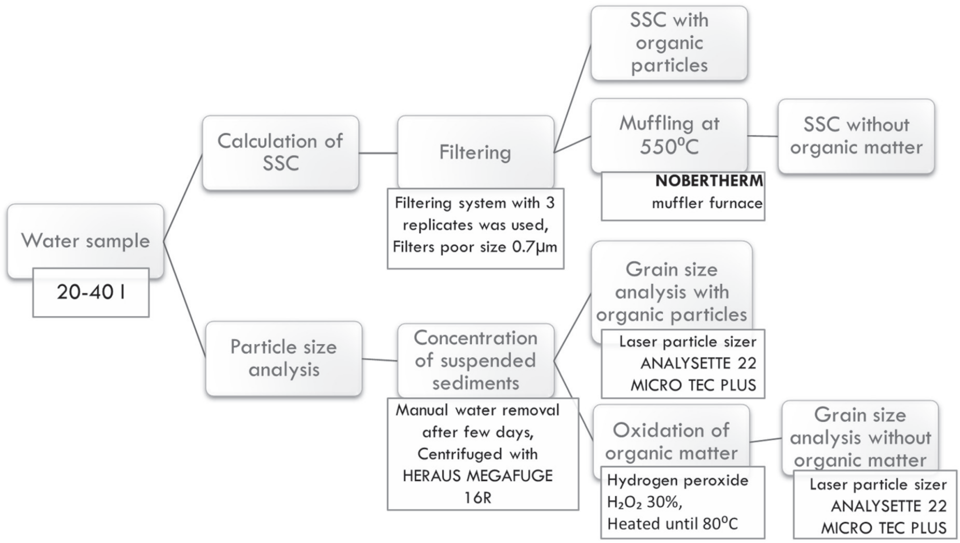

Figure 5. The scheme of data collection

The suspended sediment concentration data from the Nemunas River available for one year were used for regression analysis to estimate the relationship between water discharge and suspended sediment concentration. The power law formula suggested by (Asselman, 2000), called a sediment rating curve, to predict the suspended sediment concentration was used to get continuous input data for all model simulation periods. The daily SSC open boundary data in the model was presented as a matrix of sediment class concentrations. The averaged percentage of each class was calculated from the granulometric analysis of the samples. Each sediment class has its own concentration for each river discharge input value.

3.5 Model calibration/validation methods

In total 25 samples for Station S1 and 20 samples for Station S2 were collected for sediment model calibration (Table 4). Moreover, 25 samples in the spatially varying stations in the Curonian Lagoon (see Fig. 3) were collected for the model validation. The analysis of the biological components in the water column were included as a part of the sediment model calibration.

The models were calibrated and validated comparing measured and modelled values. For the calibration of the sediment transport model the measured and modelled SSC values in the water surface were compared in two Curonian Lagoon stations with different sediment characteristics (stations S1 and S2 see Fig. 1). The model calibration results were expressed in terms of the relative discrepancy defined as the ratio between measured and modelled SSC values (Davies et al., 2002). It was assumed that the model performance is satisfactory if the number of the relative discrepancy ratio values falling into the range 0.5-2 (further called double relative discrepancy interval) exceeds 50% of all values. It means that predicted values should not be less than half and more than twice the observed values.

Statistical analysis results for the hydrodynamic model performance were expressed in terms of the root-mean-square error (RMSE) and correlation coefficient between model results and observations (R) or the determination coefficient between modelled and observed values (R^2).The data performed by the Marine Research Department in Juodkrantė and Klaipėda Strait stations were used to validate the model performance for salinity. The data from Nida and Klaipėda Strait stations were used to validate the model performance for water levels and water temperature. Modelled waves were validated in the Ventė station.

4

Results

4.1 Analysis of the collected suspended matter data

The observations of the monitoring stations for the sediment parameters are presented in Figure 6. The analysis of measured suspended sediment concentration showed that in spring, summer and autumn at the Nemunas station varies from 4 to 13 mg l^{-1} with the maximum values (> 20 mg l^{-1}) in the end of winter or beginning of spring, when the river flooding season starts. The sampling campaigns cover all seasons and flood period. During the flood period, the samples were taken only in the beginning and in the end of the period, due to over-flooded regions in the delta area. Usually, the flood season starts when the ice and snow cover melts and shows the highest values of total suspended solids as well. A strong relationship between measured TSS and SSC values was found in the Nemunas (Rusnė) monitoring station (Fig. 7).

In the Curonian Lagoon the highest concentrations off TSS=57 mg l^{-1} and SSC=31 mg l^{-1} were found in S1 station in summer and autumn during the algal bloom, when chlorophyll-*a* concentration peaked up to 300 mg m^{-3}. The analysis of the Curonian Lagoon stations showed that the deeper S1 station had higher Chl-*a* concentrations. However, the cyanobacteria was dominated in both stations in summer and autumn.

In general, the measured SSC varied form very low values (1-2 mg l^{-1}) to 30 mg l^{-1}. The TSS varied from 11 to 57 mg l^{-1}.

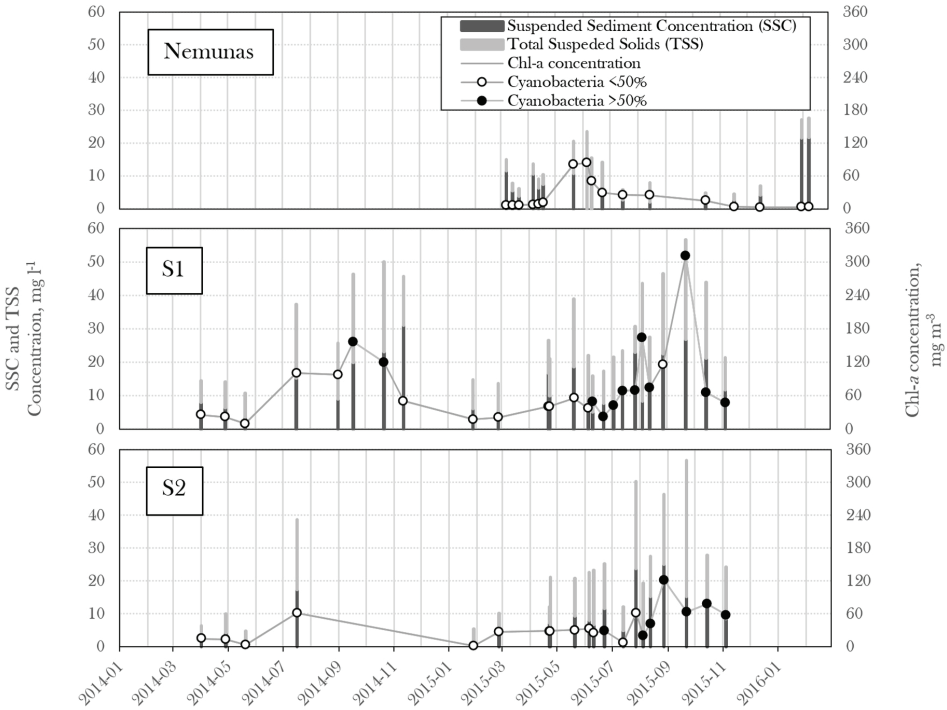

Figure 6. The time series of total (TSS), mineral sediment (SSC) and Chl-*a* concentrations and percentage of the cyanobacteria from the total phytoplankton community for monitoring stations Nemunas, S1 and S2. Columns without SSC values indicate field campaigns where only TSS were measured.

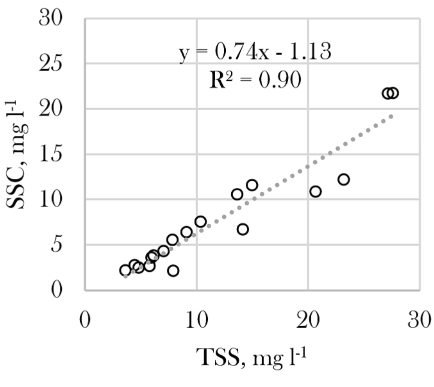

Figure 7. The relationship between measured TSS and SSC values in the Nemunas River

The measured SSC in the Nemunas River was used for preparing the river boundary conditions for the sediments model. For the sediment transport model only the mineral sediment concentrations were used. The developed power-law function is presented in Figure 8. The moderate relationship between river discharge ($m^3 s^{-1}$) and suspended sediment concentration was found, R^2=0.67. The formula of the sediment rating curve was applied for all simulation period from 2004 to 2016 for the Nemunas discharges at the model boundary, where the averaged recalculated discharge near Šilininkai (see section 3.4.1.) was 320±171.3 $m^3 s^{-1}$ in 2015 and the average discharge for the all modelling period was 424.4±217.4 $m^3 s^{-1}$.

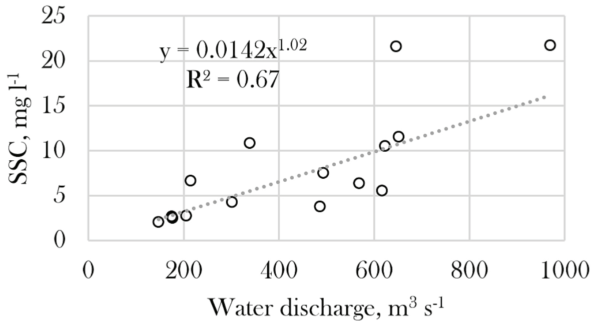

Figure 8. Relationship between SSC and the Nemunas River discharge.

4.2 Model calibration and validation

4.2.1 Hydrodynamic model

The SHYFEM model has been validated in previous works reproducing water level, water temperature, salinity fluctuations and the structure of the flow in the Klaipeda Strait (Ferrarin et al., 2008a; Zemlys et al., 2013, Umgiesser et al., 2016). However, even if the calibration and validation has already been carried out in a former work, this study shows one more time the validation for the salinity, water temperature and levels because the numerical grid has been changed. In Zemlys et al. (2013) one year study with much finer grid resolution was presented, while in Umgiesser et al. (2016) a coarser resolution has been used compared to the present study (12 year).

Statistical analysis results for salinity are reported in terms of correlation coefficients between model results and observations (R) and RMSE (Table 5). The salinity was validated in two stations (Klaipėda and Juodkrantė) with hydrodynamic conditions where salinity can change from 0 to 7 in a very short time scale. The correlation between modelled and observed salinity values was 0.70 in the Klaipėda Strait for the period 2004-2016. The first three months (January-March 2004) of 2004 were excluded from the analysis as a spin-up time. Due to the lack of data, the correlation coefficient for the Juodkrantė station was calculated for the period 2004-2009 and it decreased until 0.53. The results showed that RMSE is 2.194 in the Klaipėda Strait and 1.89 in the Juodkrantė station. The comparison of the modelled and observed salinity values are presented in Figure 9. The model performance is not the same through the year. In some years in winter and spring, the model produced higher salinity peaks than observed in Klaipeda Station while in Juodkrantė the higher modelled peaks could be found in all seasons but in general the model performance is acceptable.

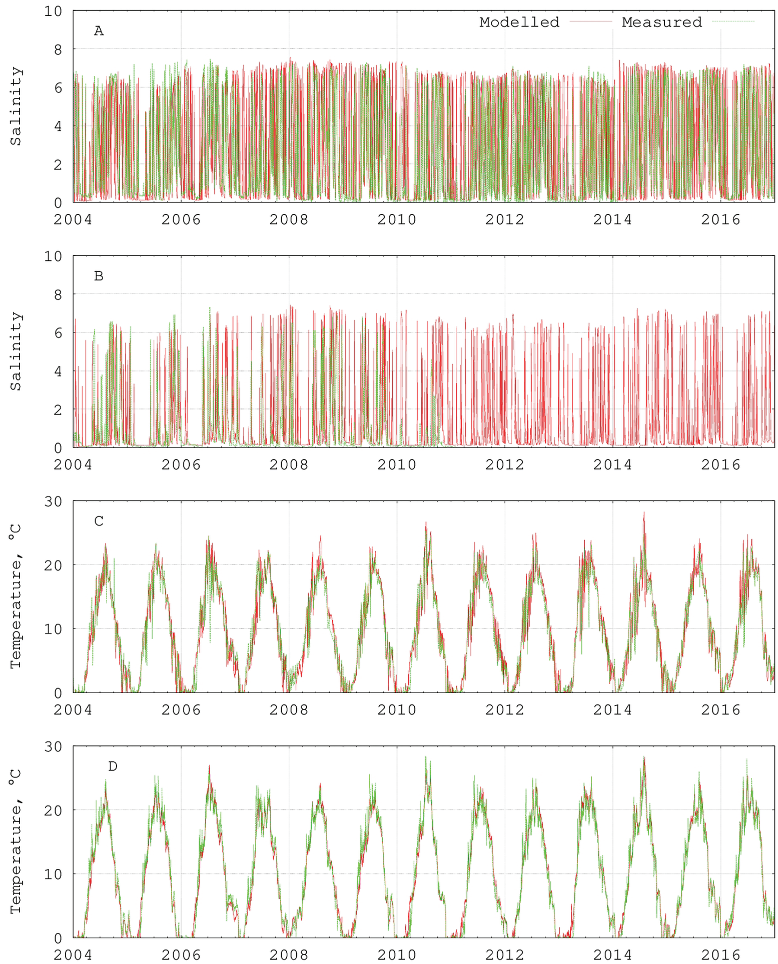

Figure 9. Comparison of modelled and measured values. (A) Salinity values in Juodkrante (the measured values were obtained only for the period 2004-2009); (B) salinity values in Klaipeda; (C) water temperature values in Klaipeda; (D) water temperature values in Nida.

The hydrodynamic model described well the seasonal cycle of the surface water temperature and water levels that were validated for the Klaipeda Strait station and the Nida station in the middle of the Curonian Lagoon (see Fig. 3C). The validation period was 2004-2016, excluding the spin-up time. In both stations the R values for the water temperature were more than 0.97 with R^2 value for Klaipėda Strait of 0.95 and 0.98 for the Nida station (Table 5, Fig. 9). The RMSE values were equal to 1.58°C and 1.13°C respectively. The correlation coefficient between modelled and observed water levels for Klaipeda Strait was 0.97 (R^2=0.93) with RMSE value 0.06 m. In Nida station the calculated R value was equal to 0.86 (R^2=0.75) and RMSE 0.10 m (Fig. 10).

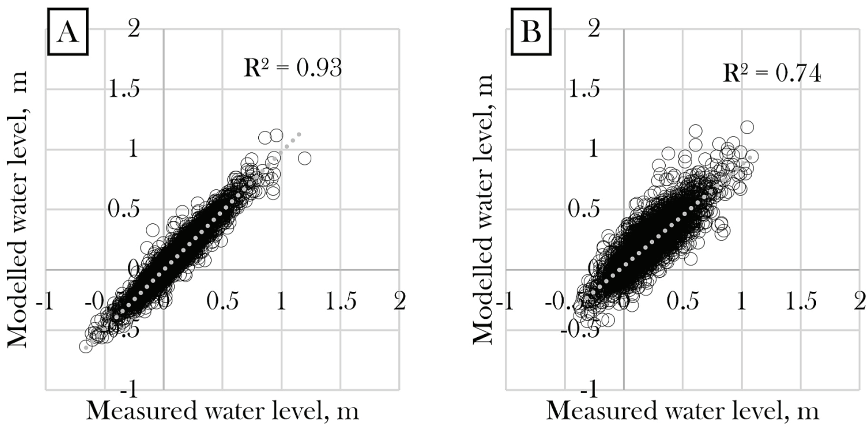

Figure 10. The scatterplots of the observed and modelled parameter values. (A) Water level in the Klaipėda station, and (B) water level in the Nida station.

The wind wave model was validated comparing measured wave heights in Ventė station located on the eastern coast of the Curonian Lagoon (see Fig. 2C) with the modelled significant wave height (SWH). The model was validated only for the year 2010. Validation results are shown in Figure 11 and Table 5. A strong relationship was found between measured and modelled values, but it can be seen, that the model underestimated the maximal measured values.

The comparison of statistical analysis with previous studies is presented in Table 5. In Umgiesser et al. (2016) the results showed that the model with ice cover data gives much better results comparing with the reference simulation without the ice data. Zemlys et al. (2013) results showed that the model with higher resolution represents salinity variations better and PhD study results are in between these two previous studies.

Table 5. **Comparison of the model validation results in different studies.**

Study		Umgiesser et al., 2016	Umgiesser et al., 2016	Zemlys et al., 2013	This study
Simulation scenario		**12 years (2004-2015). Reference without ice**	**12 years (2004-2015) Scenario with ice data interpolated from inland stations**	**One year without ice**	**13 years (2004-2016) with satellite ice cover data**
Resolution		**Coarse**	**Coarse**	**Fine**	**Coarse with finer elements in the Delta front and fairway**
Salinity					
Calibration period		**2004-2010**	**2007-2010**	**2009**	**2004-2016 (2007-2010/2009)**
Station	**Klaipėda Strait**	R=0.58 RMSE=2.4	R=0.64 RMSE=2.3	R=0.74 RMSE=2.3	*R=0.70 (0.71/0.73)* *RMSE=2.2 (2.3/2.3)*
Station	**Juodkrantė**	R=0.40 RMSE=2.1	R=0.43 RMSE=2.1	R=0.67 RMSE=1.6	*R=0.53* (- /0.55)* *RMSE=1.9* (- /1.9)*
Temperature					
Calibration period				**2009**	**2004-2016 (2009)**
Station	**Klaipėda Strait**			R=0.99 RMSE=1.2ºC	*R=0.98 (0.99)* *RMSE=1.6* ºC *(1.2* ºC*)*
Station	**Nida**			R=0.99 RMSE=1.4 ºC	*R=0.99 (0.99)* *RMSE=1.1* ºC *(1.2* ºC*)*
Water level					
Calibration period				**2009**	**2004-2016 (2009)**
Station	**Klaipėda Strait**			R=0.98 RMSE=3.2 cm	*R=0.97 (0.97)* *RMSE=5.5* cm *(3.9* cm*)*
Station	**Nida**			R=0.98 RMSE=3.1 cm	*R=0.86 (0.82)* *RMSE=10.4* cm *(8.7* cm*)*
Waves					
Calibration period					**2010**
Station	**Ventė**				*R=0.89* *RMSE=12.3* cm
* the period 2004-2009					

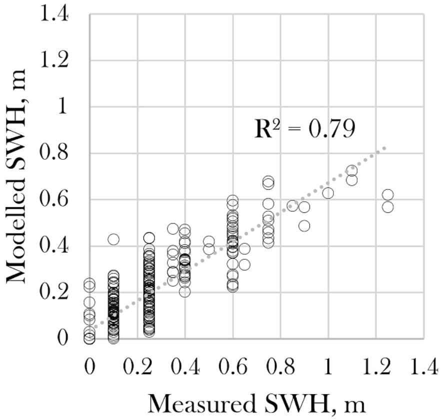

Figure 11. The comparison of observed and modelled SWH in the Ventė validation station.

4.2.2 Sediment transport model

The sediment transport model has several parameters that need to be adjusted during the calibration process. Default model parameter values were obtained for the Venice Lagoon and could not be equally used for this study site. The Van Rijn method for the prediction of the non-cohesive sediment transport was chosen for the Curonian Lagoon. The initial critical shear stress value of 0.3 N m^{-2} for erosion was calculated from the measured wet bulk density in the S1 monitoring station according to the proposed formula by Amos et al. (2004). The density for the freshly deposited mud was set to 775 kg m^{-3} (clay).

The model performance quality criteria for calibration and validation were expressed in terms of the relative discrepancy defined as the ratio between measured and modelled SSC values. The model performance quality is calculated as a percentage of measured values falling in to the range 0.5-2 (further called double relative discrepancy interval). It was assumed that the model performance quality is satisfactory if the number of the relative discrepancy ratio values falling into the range 0.5-2 exceeds 50% of all values (Davies et al., 2002; Ferrarin et al., 2010a).

The first simulation for the period 2013-2015 was carried out with the real forcing data and sediment transport model parameters mentioned above. The model calibration results showed the sediment model performance quality was only 12.5% in station S1 (RMSE=0.013 kg m^3) and 15% in station S2 (RMSE=0.009 kg m^3). The highest discrepancies were found for summer and autumn seasons (Fig. 12). Unsatisfactory calibration results required the analysis of the other processes that could influence the sediment transport mechanisms in the Curonian Lagoon.

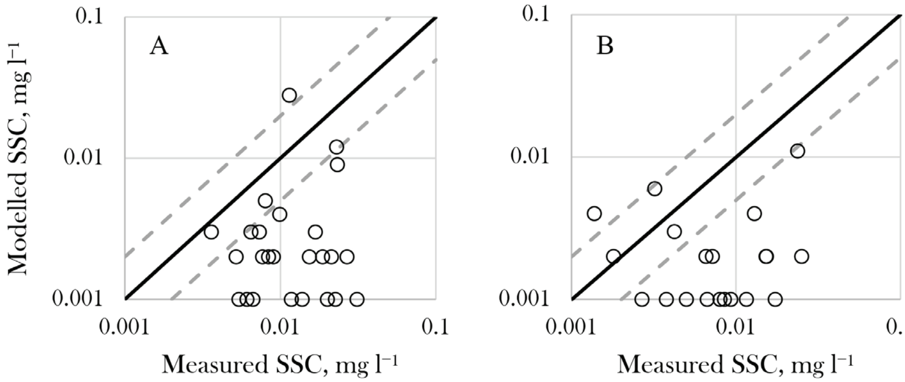

Figure 12. Comparison between measured and modelled surface SSC values after first calibration steps in S1 station (A) and S2 station (B). Scatterplots are made using a logarithmic scale, where the solid line indicates absolute agreement with the measurements; the dashed lines correspond to the endpoints of double relative discrepancy intervals.

As highlighted above, the analysis of measured TSS and SSC showed that in the lagoon higher values were found during the summer-autumn period. However, results of the sediment transport model showed lower SSC values if compared with the measurements. The authors of Bukaveckas et al. (2019) found that in the Curonian Lagoon the settling velocities of total suspended solids decrease in the summer months when positively buoyant cyanobacteria are present. Their calculated settling velocity for TSS in summer was about 0.3 m day^{-1} and the TSS concentrations in the lagoon correlated with Chl-*a* concentrations. There was no relationship found between river discharge and Chl-*a*. It indicated the autochthonous origin of the suspended material. Also, it is known that diatoms and cyanobacteria biofilms can act as a trap for sediments because of the adhesive surface (Larson et al., 2009). Figure 6 shows that in summer and autumn seasons cyanobacteria dominated in the Curonian Lagoon, especially in S1 station, where concentrations were very high. According to Pilkaityte and Razinkovas (2006) one of the factors controlling the phytoplankton blooms is water temperature. Based on these studies a new formula (20) for fine sediments settling velocities as a function of water temperature was introduced into the model. The following new settling velocity equation was developed for the water temperatures higher than 8°C:

$$W_{sb} = a \cdot T + b, \tag{20}$$

where W_{sb} is the settling velocity in m day^{-1}, T the water temperature in °C (only used with T>8°C).

After calibration the values a=-0.03443 and b=1.251117 were used and with the introduction of these changes the model performance increased to 40% (RMSE=11.5 mg l^{-1}) in station S1 (Figures 13A, 13B) and to 60% (RMSE=5.7 mg l^{-1}) in station S2 (Figures 13C, 13D).

The results of the second simulation for the period 2015-2016 (VAL) were used for the model validation. The model results were compared with the measured data for the end of August and first days of September in 2016, from the validation dataset. The 15 validation stations were spread in the northern part of the Curonian Lagoon, to represent different properties of sedimentation (yellow dots in Figure 3C). Validation results showed that the modelled SSC values were in a good agreement with the measured data with model performance quality 72% (Fig. 14).

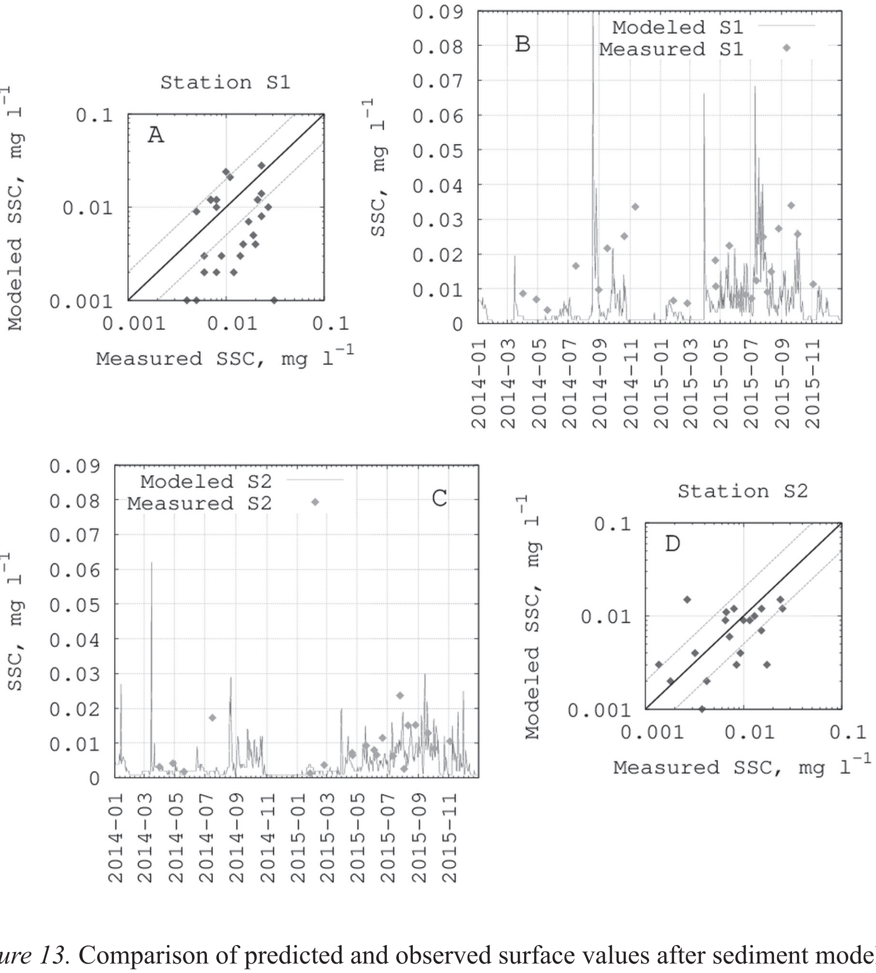

Figure 13. Comparison of predicted and observed surface values after sediment model calibration for station S2 (**A, B**) and S1 (**C, D**). Scatterplots (**B, D**) are made using a logarithmic scale, where the solid line indicates absolute agreement with the measurements; the grey lines correspond to the endpoints of double relative discrepancy intervals

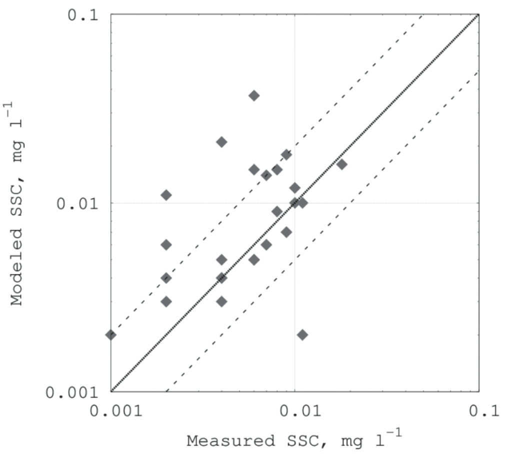

Figure 14. Scatterplot of the sediment transport model validation plotted on a logarithmic scale. Solid line indicates absolute agreement with the measurements, dashed lines corresponds to the endpoints of double relative discrepancy intervals. Data are sampled in 15 different places during August-September 2016.

4.3 Simulations of present situation (2004-2016)

4.3.1 Hydrodynamics in the Curonian Lagoon

4.3.1.1 General circulation

General circulation in the lagoon is analysed through the residual water currents in the Curonian Lagoon (Fig. 15). Residual currents are the mean currents over a certain period (here season) where all fluctuations have been removed. The seasonal maps showed that the average circulation is stable through the seasons. Only in the spring the lower currents in the southern part were formed. In general, the lowest current speed is in the southern-eastern part of the lagoon and increases going to the north. The strongest currents are formed in the harbour area, where current velocities of more than 0.15 m s^{-1} were simulated. The averaged velocities simulated for the southern part were 0.006 m s^{-1} in spring and 0.01 m s^{-1} for other seasons. The northern part of the lagoon is strongly influenced by the Nemunas River, therefore the higher current velocities were found in this area. For winter, spring and autumn were 0.03 m s^{-1}, for summer 0.02 m s^{-1}.

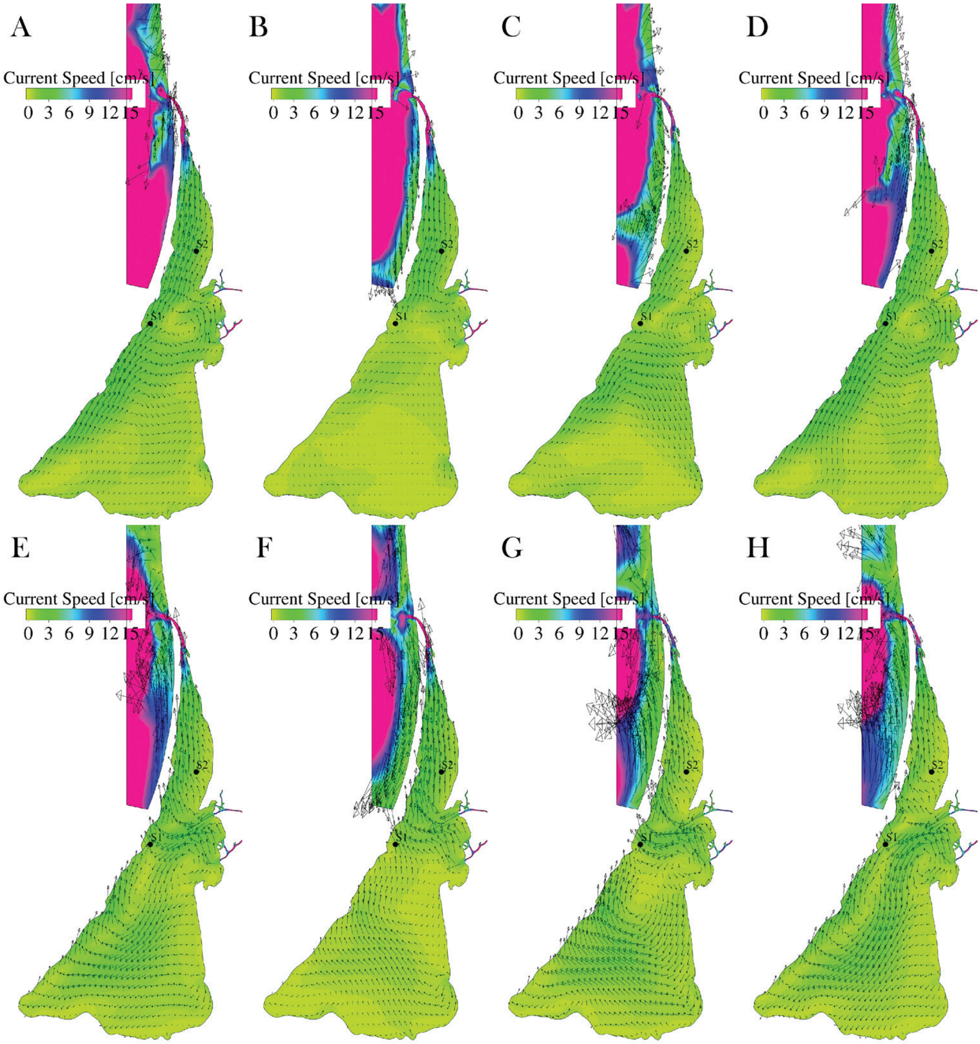

Figure 15. Seasonal maps of averaged residual currents over the period 2004-2016 (except spin up time): surface currents (A) winter, (B) spring, (C) summer, and (D) autumn and bottom currents (E) winter, (F) spring, (G) summer, and (H) autumn.

In front of the Nemunas Delta, a surface cyclonic circulation was present in all seasons. In the Nemunas Delta front, the currents were spread to the southwest and northwest directions. In the northern part the northward currents were dominantly due to the river influences. The stronger northward currents were formed on the western coast.

4.3.1.2 Salinity gradients

The 13 year simulation (LONG) allowed the estimation of the averaged seasonal salinity distribution in the Curonian Lagoon (Fig. 16). In Figure 16 and 17 the southernmost isoline always indicates the salinity value of 1. The results showed that the strongest gradients can be found in the Klaipėda Strait, especially in spring, when large amounts of fresh river water meets the brackish water of the Curonian Lagoon (salinity ~6-7). The averaged seasonal maps showed the higher salinity values in the autumn season, with a large zone of salinity of more than 2 in the northern part of the lagoon. The seasonal salinity maps depend a lot on the simulation period, which is averaged.

The maximum salinity values found during all simulation period are present in Figure 17. It is important to mention that this is the maximum value found for each element of the computational grid not depending on the time and duration. The results showed that brackish Curonian Lagoon waters could reach the middle of the Curonian Lagoon in winter-summer seasons and even the southern part in autumn. The Curonian Lagoon is a fresh waterbody and even a short duration of these high salinity values in the lagoon could have a significant influence for the ecological processes.

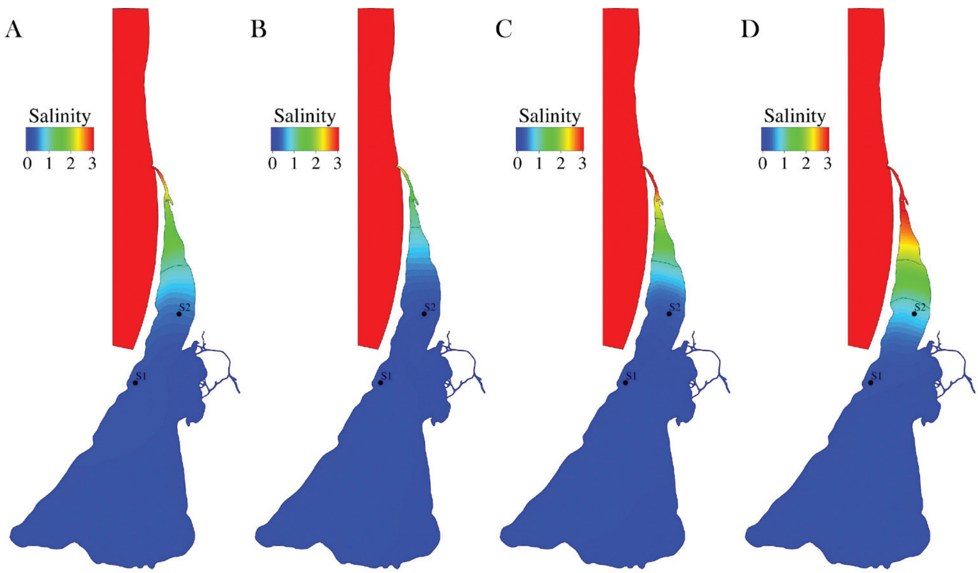

Figure 16. Seasonal maps of salinity distributions averaged over the period 2004-2016 (except spin up time): (A) winter, (B) spring, (C) summer, and (D) autumn. The southernmost isoline indicates the salinity value of 1. The salinity in the Baltic Sea is more than 6.

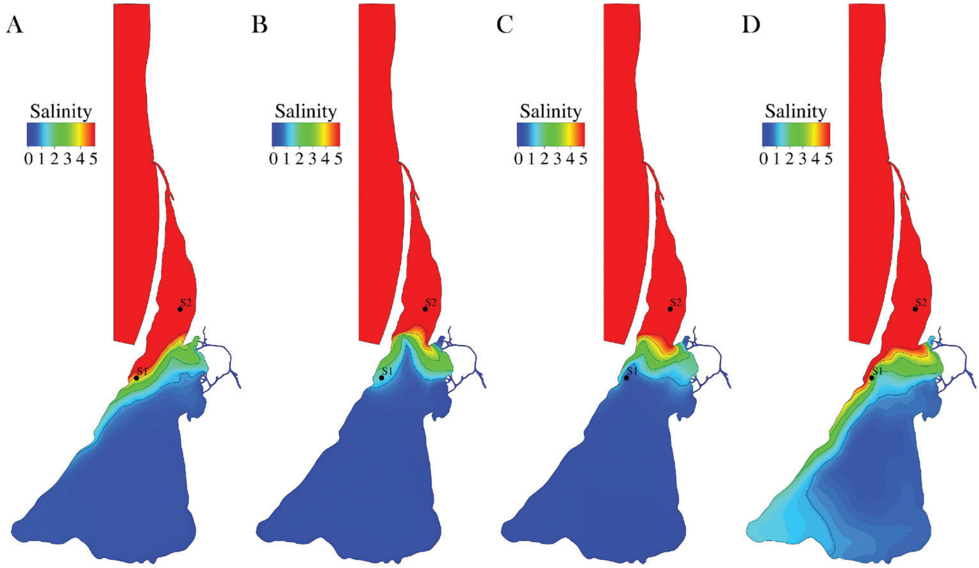

Figure 17. Seasonal maps of maximum salinity distributions over the period 2004-2016 (except spin up time): (A) winter, (B) spring, (C) summer, and (D) autumn. The southernmost isoline indicates the salinity value of 1. The salinity in the Baltic Sea is more than 6.

4.3.1.3 Temperature gradients

Water temperature is important for the biological activity in the water column. The Curonian Lagoon is a well mixed water body without strong vertical temperature gradients in the system. The seasonal maps of the water temperature are presented in Figure 18. It can be seen that the shallower eastern part has higher variability of the water temperature during the year, with lower temperatures in winter and higher in summer.

The average water temperature for the whole lagoon in winter was 1.7±0.6°C (the Baltic Sea is excluded), with lower values in front of the river mouths. The average water temperature in spring was 7.4±1.4°C, with higher values in the southern part. The summer values in the lagoon are about 6°C higher than the water temperature in the Baltic Sea, with an average value of 19.5±1.8°C. Due to high water temperature in September, the values in autumn are higher compared to spring, with the average water temperature of 10.8±0.8°C.

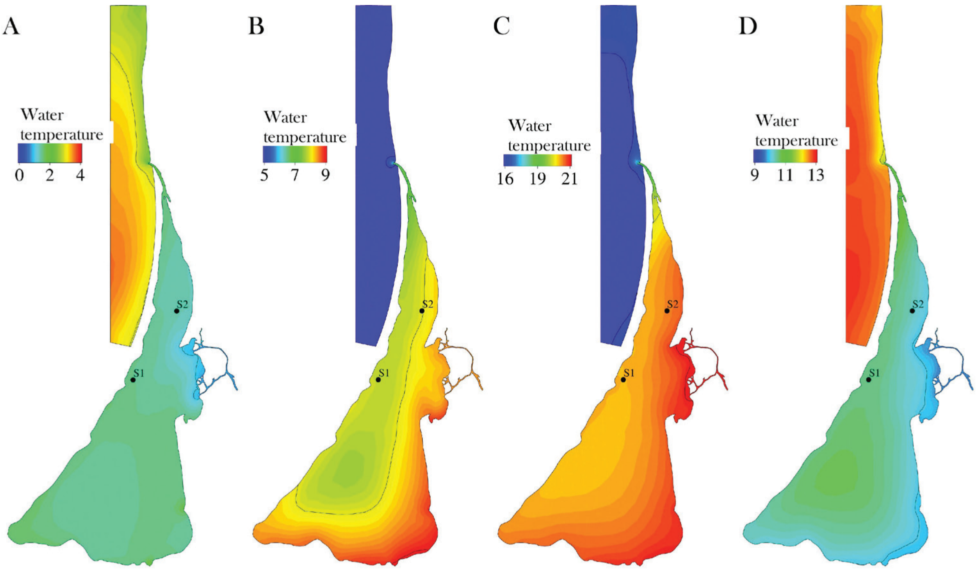

Figure 18. Seasonal maps of water temperature gradients over the period 2004-2016 (except spin up time): (A) winter, (B) spring, (C) summer, and (D) autumn. Be aware that seasons have a different colour scale.

4.3.1.4 Wave climate

Wave climate plays a crucial role for the sediment resuspension and the sediment transport processes. The main factors controlling wave simulation in the model are wind speed and wind fetch. The analysis of the long-term simulation results showed that the southern and central part of the Curonian Lagoon has higher waves than the northern part (Fig. 19). The highest waves are formed in autumn due to the stronger wind events, while the lower values are in winter season due to the ice periods.

It is important to mention that the analysis of the wave height is not enough to evaluate the impact of the sediment dynamics. The waves, bathymetry and the morphometric conditions should be analysed together.

The analysis of the averaged significant wave height showed the highest values in the deepest areas of the Curonian Lagoon. It is expected that the higher waves in the deeper areas have lower influence for the resuspension than the lower waves in the more shallow areas in the Nemunas Delta front or the northern part of the lagoon. Wave period is an important parameter for the formation of the oscillatory flow that forms the ripples (only for non-cohesive sediments) and influences the bed roughness.

In the southern part of the lagoon, the average wave heights were 0.19±0.04 m, 0.22±0.04 m, 0.28±0.05 m and 0.33±0.07 m with the average wave period of

1.19±0.16 s, 1.63±0.18 s, 2.02±0.23 s and 2.22±0.29 s for winter, spring, summer and autumn respectively. While in the northern part of the lagoon, the average wave heights were 0.16±0.04 m, 0.19±0.05 m, 0.24±0.06 m and 0.30±0.08 m with the average wave period of 1.06±0.16 s, 1.51±0.21 s, 1.83±0.28 s and 2.08±0.32 s for winter, spring, summer and autumn respectively.

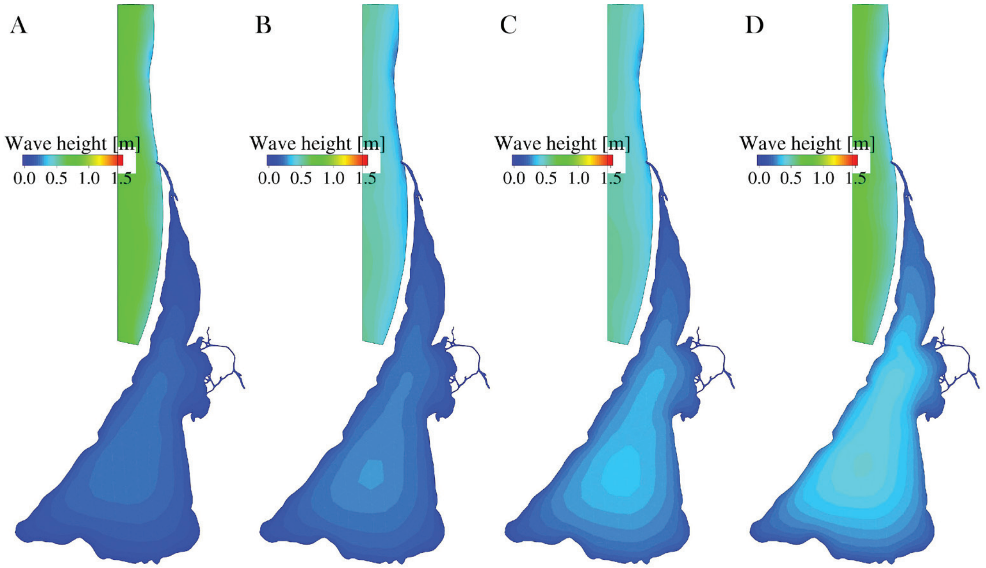

Figure 19. Seasonal maps of the averaged significant wave height for the period 2004-2016 (except spin up time): (A) winter, (B) spring, (C) summer, and (D) autumn.

4.3.2 Results of the sediment transport model

4.3.2.1 Bed shear stress

Firstly, the results of the sediment transport model from the long-term simulation (LONG) were used to analyse the bed shear stress values. Averaged seasonal maps were prepared to see the changes of the bed shear stress values (Fig. 20). The zones with higher bed shear stress values were found in the shallower areas in the delta front and northern part of the lagoon. The maximum values of the bottom currents close to the Klaipėda Strait were induced by the narrowing of the lagoon. Autumn season had the highest waves and strongest currents; as a result, the shallow areas were much more influenced by the wave- and current-induced stress and had higher bed shear stress values.

The analysis of the bed shear stress maps indicated the most vulnerable areas, where the erosion zones could be found. It can be seen that the eastern part of the Curonian Lagoon has the highest bed shear stress values that cause higher erosion rates and more sediments from these regions are transported further into the system.

The analysis of seasonal wave maps and seasonal maps of the residual currents showed that the highest bed shear stress values occurred together with the strongest bottom currents, while the biggest waves do not explain the changes on the bottom. This study was not designed to evaluate the factors controlling bed shear stress but in general, it can be seen that the Nemunas River is an important factor.

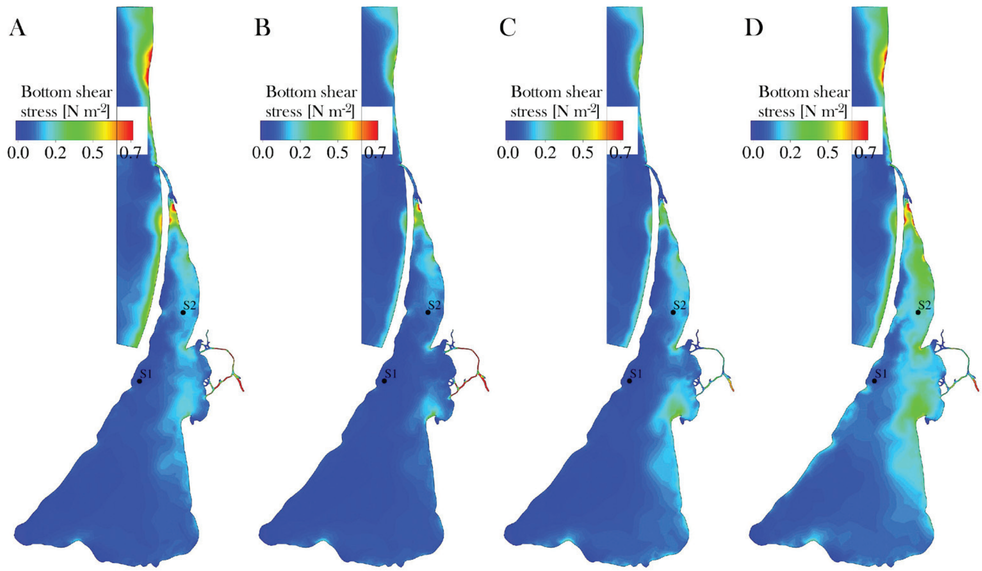

Figure 20. Seasonal maps of the averaged bed shear stress for the period 2004-2016 (except spin up time): (A) winter, (B) spring, (C) summer, and (D) autumn.

4.3.2.2 Analysis of suspended sediment concentration

The general dynamics of the sediments in the Curonian Lagoon was evaluated using the long-term simulation results. The distribution of suspended sediments was analysed for the period 2005-2016. The year 2004 was considered as a spin up time and therefore was not considered in the analysis. The maps of averaged seasonal suspended sediment concentrations are shown in Figure 21.

The averaged seasonal values were calculated only for the Curonian Lagoon area, excluding the Baltic Sea and the river mouths, showing temporally averaged model results other the water column. The lowest SSC values were found in winter with an average value of 3±1 mg l^{-1}. In spring the highest SSC values were in the Nemunas Delta with the average of 23±10 mg l^{-1} and the Lithuanian part of the lagoon (average 12±6 mg l^{-1}). The average spring concentration for all lagoon were 6±6 mg l^{-1}. In summer the concentrations varied from 40 mg l^{-1} on the eastern coasts to 10 mg l^{-1} in the western part of the lagoon with an average value of 19±18 mg l^{-1} for the lagoon. The SSC values in the autumn were more homogeneous. An average concentration of 20 mg l^{-1} in the southern part and lower concentrations on the eastern coast were found. The average autumn season value was 19±15 mg l^{-1}.

It is important to remember that a value of zero for the SSC was assumed on the model open sea boundary, because of the absence of measured suspended sediment data. According to this, the SSC was not analysed in the coastal area of the Baltic Sea.

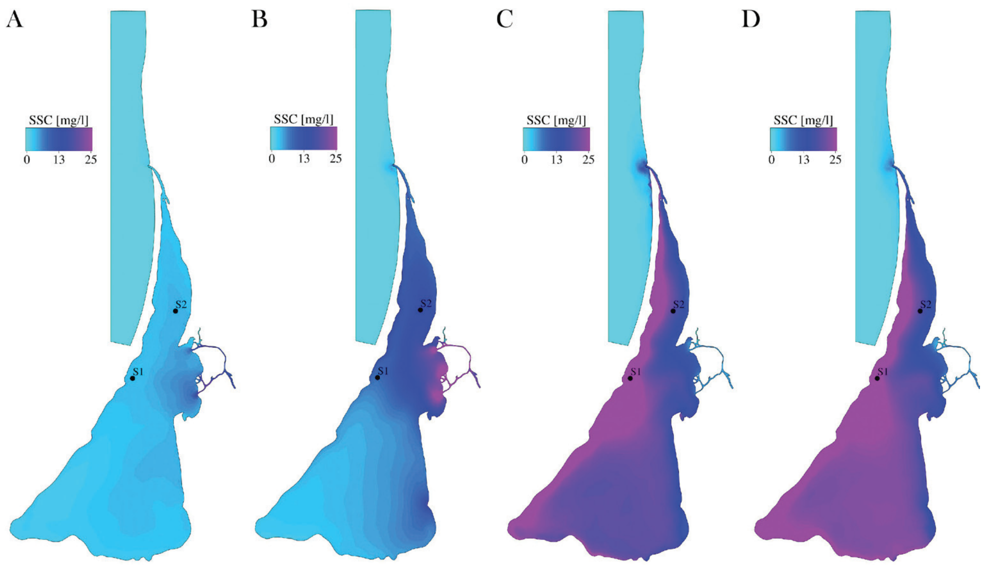

Figure 21. Seasonal distribution of SSC in the water column (**A**) winter, (**B**) spring, (**C**) summer, (**D**) autumn.

4.3.2.3 Analysis of the bedload transport

The potential bedload transport in the model is calculated according to the shear velocities and the sediment grain sizes. However, the applied version of the sediment model cannot simulate the exact flux of sediment via bedload, as a result, only the potential seasonal bedload transport maps are presented in Figure 22. It is clear that the bedload is visible only in the delta region and the northern part of the lagoon, where the non-cohesive sediments are dominant. Comparing the bedload results with the suspended concentrations a specular distribution of the values is evident. The non-cohesive particles transported by the river are redistributed on the eastern part of the lagoon northward from the river mouth, while the suspended cohesive sediments can be easily transported to the western part of the lagoon reaching the spit. In winter season the SSC in the water column are low due to ice cover, while the bedload transport is intensive compared with the warmer seasons. One of the reasons is the increased water density due to lower water temperature.

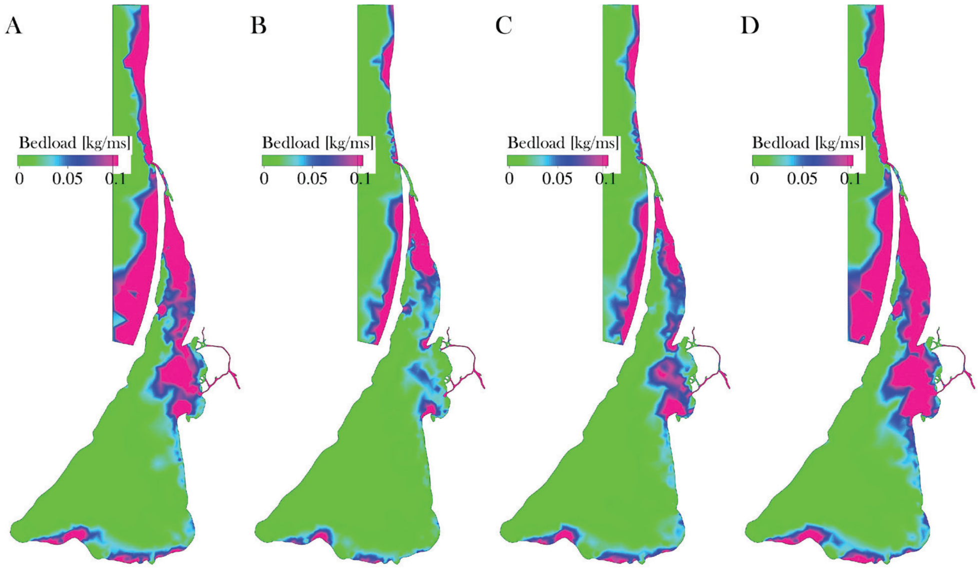

Figure 22. Seasonal maps of potential bedload: (**A**) winter, (**B**) spring, (**C**) summer, (**D**) autumn.

4.3.2.4 Erosion-accumulation zones

The analysis of the long-term simulation results let to the identification of the erosion-accumulation zones in the lagoon (Fig. 23). Only one map was produced to show the changes between the initial model bathymetry and the bathymetry of the last simulation time step.

Results showed that the lagoon functions as a sediment sink with accumulation zones in the southern and central part of the lagoon. It was calculated that, in average, after 12 years the southern and central parts became 6 mm shallower compared to the initial model bathymetry. Maximum changes found in the Nemunas Delta front were >+700 mm from the initial bathymetry as well as an accumulation zone in the southern part of the Klaipėda Strait. The erosion zones were in the northern part of the lagoon. The averaged erosion was 3 mm after the whole simulation period, with the maximum values on the very north, close to the southern part of to the Klaipėda Strait.

The averaged accumulation rate in the southern part was about 0.5 mm y^{-1}, the averaged erosion rate in the north was about 0.23 mm y^{-1}. Analysing results in smaller areas higher erosion and accumulation rates can be found, e.g., in the Nemunas Delta and Klaipeda Strait with accumulation rates of about 7 mm y^{-1}.

These results showed the absolute difference between two bathymetries, but the analysis of the single point showed that the erosion-accumulation areas in the lagoon are sensitive to physical processes and can differ yearly. As an example, two years with low river discharges and less sediments coming to the system, can show smaller and less intensive accumulation zones and rates in the Curonian Lagoon, comparing to years with high riverine sediment loads.

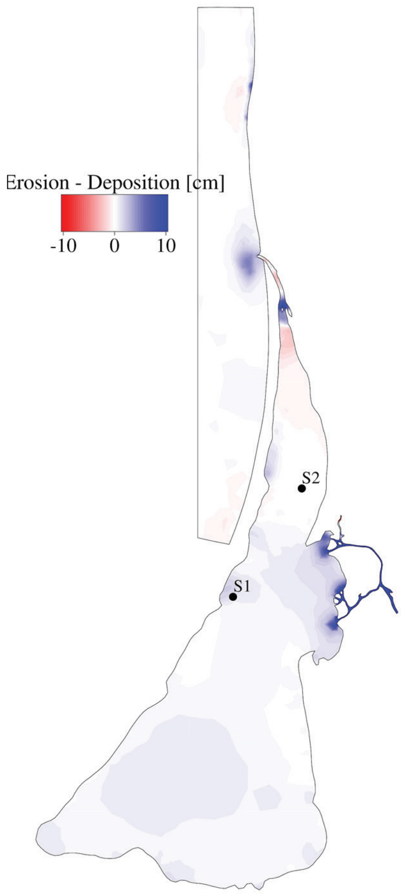

Figure 23. The erosion-accumulation zones in the Curonian Lagoon after 12 years.

4.3.2.5 Sediment budget in the lagoon

The sediment budget components and the possible amounts of sediments coming to the system or out of the system were calculated from the model results of suspended sediments. The sediment input to the system was assumed as a sum of all riverine sediment loads of the river mouths plus the loads coming through the Klaipeda harbour gates from the sea to the lagoon. The sections where the sediment fluxes were calculated are shown in the Figure 24.

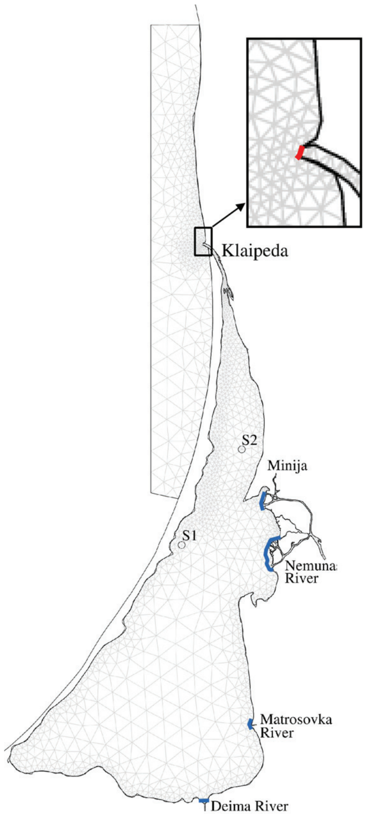

Figure 24. The sections for the flux calculation. Blue lines indicate the sections of the rivers (input) and red line indicates the flux section in the harbour (input and output).

The analysis of the sediment amounts entering the Curonian Lagoon showed that there was no trend. The Nemunas River discharge causes the great differences on the amount of input material seen for a given year (Fig. 25). The highest sediment input occurred in spring with the river flood period. The biggest calculated amount of riverine sediments was for the years 2010 and 2013 and was equal to $1192 \cdot 10^6$ kg and $1275 \cdot 10^6$ kg respectively. The average annual amount of sediment coming to the system was equal to $484.4 \cdot 10^6 \pm 378.0 \cdot 10^6$ kg y^{-1}. The computed outgoing sediment transport to the sea never exceeded the sediment input and had a strong correlation with the sediment input (R^2=0.77). The average annual amount of sediments flushed out of the system was equal to $185.8 \cdot 10^6 \pm 178.2 \cdot 10^6$ kg y^{-1}.

The cumulative curves in Figure 25 showed that the lagoon accumulates more sediments than transports to the sea. The accumulation was highest during the flood season. The analysis of all sediment input and output amounts showed that on average about 62% form the annual amounts of riverine sediments were trapped in the lagoon.

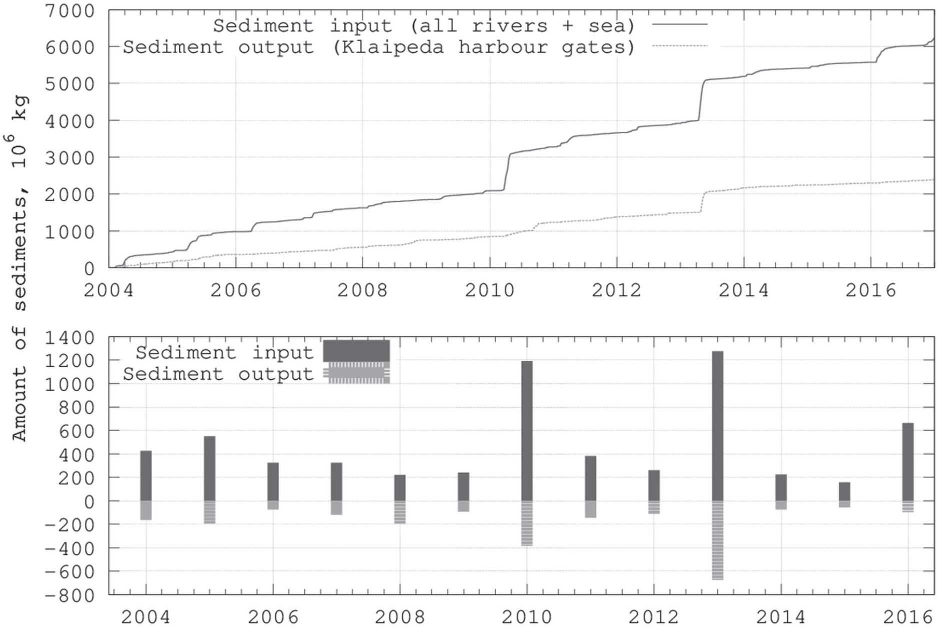

Figure 25. The cumulative amount of sediments coming into the system.

4.3.3 Analysis of the short term events for sediment transport

Additionally, the 3 years short-term simulations were used to investigate the impact of ice cover and strong winds to the sediment distribution and transport (simulations CAL and NoICE). The reproduction of ice cover by the model for the winter period reproduced the sheltering of the water from wind and changed the hydrodynamic conditions, described also by Chubarenko et al. (2019) that influenced the sediment transport in the whole lagoon and changed suspended sediment concentrations. The simulation where the ice cover was taken into account gave an averaged SSC value of

1.50±1.79 mg l^{-1} for all Curonian Lagoon. Without the ice cover SSC values increased until 2.8±2.7 mg l^{-1}. A significant increase (>10 mg l^{-1}) appeared when the strong wind events were present in the region. A one-day event with the south-easterly winds and wind speeds of more than 10 m s^{-1} is shown in Figure 26. The absence of ice cover produced much higher bed shear stress values that caused bigger suspended sediment concentrations in the water column.

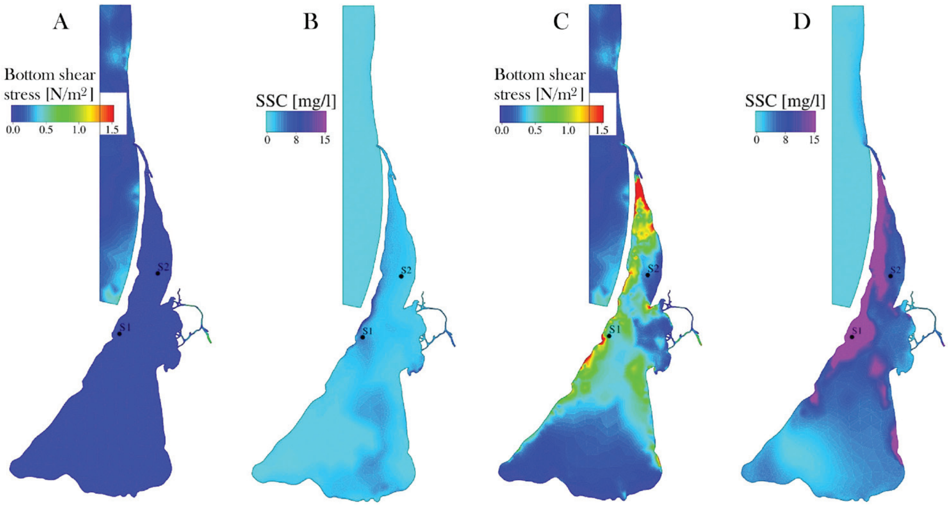

Figure 26. One day (1st February 2014) event of the influence of ice cover on the sediment transport simulation (wind speed 10 m s^{-1}, SE wind direction). (**A**) Bed shear stress with ice; (**B**) SSC with ice; (**C**) Bed shear stress without ice; (**D**) SSC without ice.

The time series of SSC in the water column for stations S1 and S2 with and without ice cover are presented in Figure 27. In the deeper muddy station S1 the influence of ice cover was visible only with wind speeds higher than 10 m s^{-1} and wind blowing from the east, south-east or south directions. The effect of the ice cover in the shallower station S2 with sandy sediments were visible with winds blowing from south-west to north-west and wind speeds of more than 6 m s^{-1}. There were no northerly winds in the analysed season.

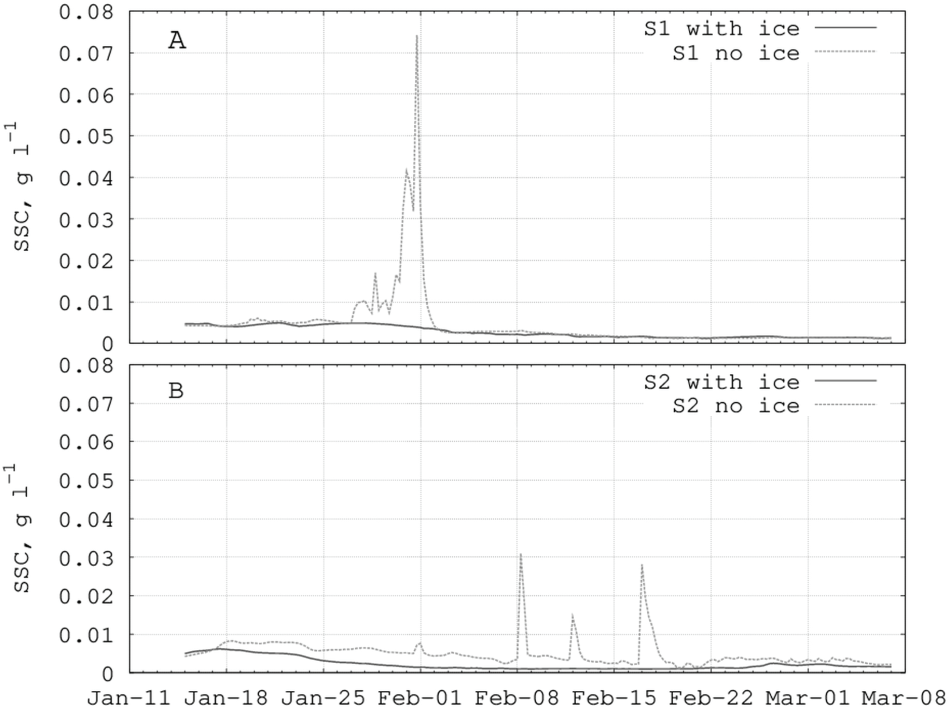

Figure 27. Simulated suspended sediment concentration with and without ice cover at monitoring station S1 (**A**) and S2 (**B**) during the first part of 2014.

A single storm event from the CAL simulation on 6th December 2013 with SW winds with speed higher than 20 m s^{-1} was analysed in more detail (Fig. 28). The results showed that in one or two days a great amount of sediments can be resuspended, and part of these sediments can be washed out of the system forming erosion zones in the lagoon (Fig. 29).

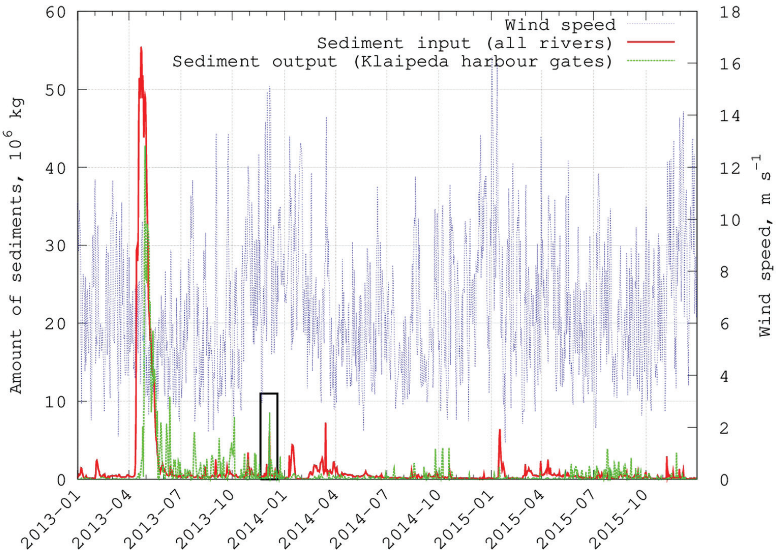

Figure 28. Time series of sediment input and output from the Curonian Lagoon to the sea. Black rectangular indicates the discussed storm event.

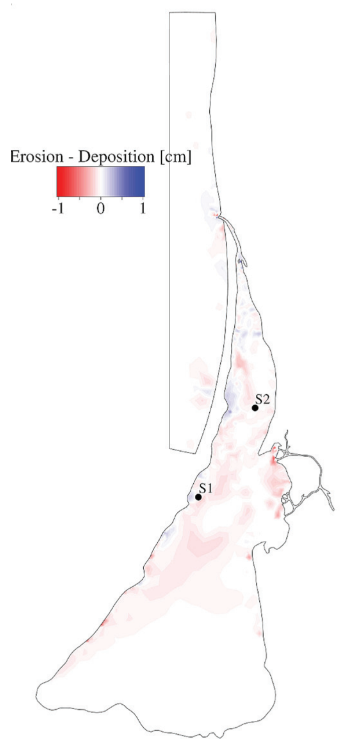

Figure 29. The erosion zones after a storm in 6th December 2013.

The model simulates the sediment fluxes through the given sections, thus it was possible to estimate the sediment input and output to the system (Fig. 24). An amount of $11.4 \cdot 10^6$ kg was transported outward through the harbour gates in two days (6th and 7th). Taking into account the sediment input on these days, after a storm a loss of $4.7 \cdot 10^6$ kg of sediments was calculated with erosion zones on the south-eastern side and central part of the lagoon. This was 8% of all sediment output and 3% of total input in 2015 but only 0.7% of the total output and 0.4% of input in 2013. 2015 and 2013 are the years with minimum and maximum input in the period of 2004-2016 respectively. Comparing these numbers with the average daily sediment riverine input (about $0.110 \cdot 10^6 \pm 0.086 \cdot 10^6$ kg d^{-1}) 42 days would be necessary to refill the basin.

4.3.4 Interactions of resuspension and ecology

Resuspension events are poorly studied in the shallow Baltic Lagoons and in the Curonian Lagoon as well. The main factors controlling the resuspension in the lagoon are waves induced by the wind energy (Chubarenko et al., 2002). The general scheme of the resuspension and the benthic flux measured with intact cores (see section 3.4.1.) is drawn in Figure 30.

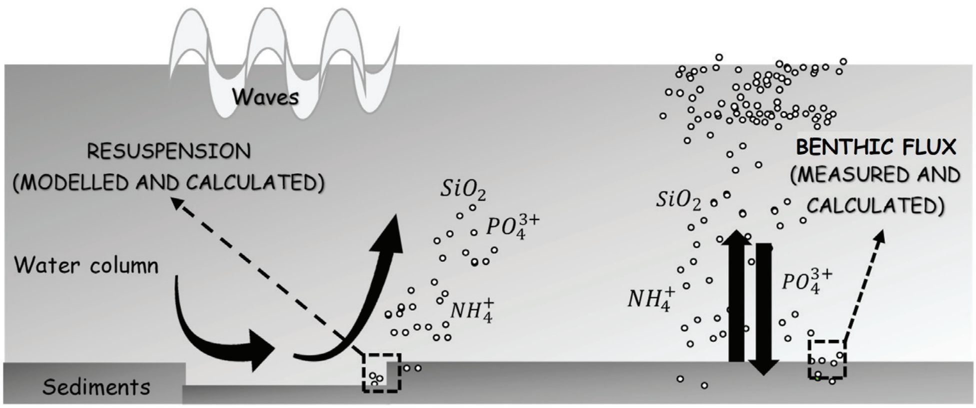

Figure 30. The general scheme of resuspension and advection processes for the nutrient flux.

One of the tasks of the study was to evaluate the resuspension events using numerical models. For this task the erosion-accumulation values for the S1 station was extracted from the long-term simulation (Fig. 31). Only the period 2008-2016 is presented in the graph for better visibility of the frequency of the resuspension events. Remember that the S1 station is covered by muddy sediments and the organic material was not taken into account by the sediment model, as a result, the real eroded depth may be higher.

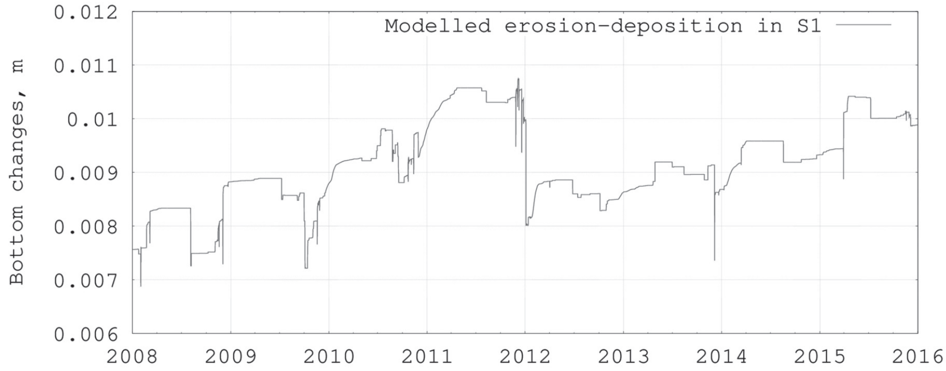

Figure 31. The modelled bottom changes in the S1 station

The dynamics of the bottom sediments indicated the resuspension events that were used to quantify the nutrient fluxes. This allowed estimation of the possible nutrient flux from the bottom sediments to the water column multiplying it by the eroded depth and the area (1 m^2).

Results showed that during stronger wind events when the wave height is >0.5 m (wind speed >11m s^{-1}) more than 1 mm of muddy sediments can be resuspended, which contains high amount of dissolved ammonia, silica and reactive phosphorus. The highest number of erosion events was found in autumn, while in spring accumulation occurred more often. The summer season is the most important for the ecological processes when the nutrients are limited (García-Robledo et al., 2013). Results showed that there are few resuspension events in summer.

Only the maximal seasonal values were analysed to understand the possible sediment contribution of the nutrients to the water column (Table 6). If erosion occurs, a positive nutrient flux takes place.

***Table 6.* The characteristics of the modelled nutrient flux from the sediments to the water column.**

Season	Maximum Erosion	Modelled Flux (mmol m^{-2} d^{-1})		
Name	**mm/day**	NH_4^+	PO_4^{3-}	SiO_2
Winter	1.96	0.08±0.00	0.003±0.000	0.04±0.04
Spring	0.58	0.03±0.00	0.001±0.000	0.04±0.01
Summer	1.10	0.03±0.01	0.005±0.001	0.13±0.07
Autumn	0.87	0.01±0.00	0.001±0.000	0.09±0.02

4.4 Climate change scenarios and predicted changes in sedimentation mechanisms

The last task of this study was to apply the climate change scenarios for the Curonian Lagoon and see the possible changes in the system. Only two climate change projections were studied from the SMHI models under the RCP4.5 and RCP8.5 (Collins, 2013) where the numbers represent the possible values of radiative forcing in 2100 compared with the pre-industrial level. The riverine sediment input was calculated using the sediment rating curve described in section 4.1 (Fig. 8) multiplied by the projected river discharges.

The climate change scenarios were run from the year 2007 until the end of 2033. The 2D SHYFEM model version was used to simulate the sediment transport in the Curonian Lagoon due to a very long computational time. The period of 2007-2015 was used for comparison of the present situation and the climate change scenario projections to investigate the performance of the climate change model reliability. From the hydrodynamic runs, it was found that the projection provided by the SMHI model for the Nemunas River discharge overestimated the observed river discharge data by about 30%. Therefore, it is possible that the sediment input to the lagoon may be overestimated as well.

The modelled SSC comparison from the present situation and the climate change scenarios are presented in Figure 32. The results showed that the SSC values retrieved from the LONG simulation revealed higher values in the middle of the simulation and lower values in the end of the simulation while the trends of the climate change scenarios are always increasing and are slightly overestimating the SSC values after 10 years. The main idea of this study was to see the possible changes and analyse the general trends. Therefore, the general model performance showed a reasonable agreement between present and projected values and can be used for further analysis. The comparison of the reference simulation (LONG) discharge and water temperatures in the monitoring stations are presented in Figure 33. For the period 2008-2013 from 35 to 55% of the LONG simulation and projected values fall into double relative discrepancy interval.

After 25 years of the simulations, results showed that the RCP8.5 climate change projection transported and accumulated much more sediments comparing to the RCP4.5 scenario (Fig. 34). The average accumulation was 1.3 mm y^{-1} for RCP4.5 and 2.6 mm y^{-1} for RCP8.5. The maximum accumulation rate of 250 mm y^{-1} was found in the river branches with the RCP8.5 projection. Two main accumulation zones can be identified from erosion-accumulation maps: one in the Nemunas River front, another in the southern part of the Klaipeda harbour.

Both scenarios showed much higher suspended sediment concentrations in S2, which is located along the way of the river flow. The projections after 25 years showed a significant increase of averaged SSC values compared to the long-term simulation results. In the S1 station, average concentrations have changed from 20.2 mg l^{-1} to

33.5 mg l^{-1} with RCP4.5 and 59.6 mg l^{-1} with RCP8.5. In the S2 station, the average concentrations changed from 13.9 mg l^{-1} to 65.1 mg l^{-1} with RCP4.5 and 104 mg l^{-1} with RCP8.5. While maximum values increased from 146 mg l^{-1} to 168 mg l^{-1} and 284 mg l^{-1} in station S1 and from 120 mg l^{-1} to 497 mg l^{-1} and 662 mg l^{-1} in station S2 with RCP4.5 and RCP8.5 respectively.

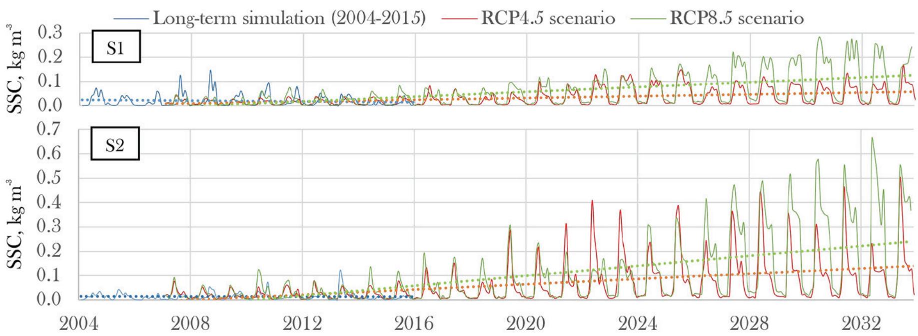

Figure 32. The suspended sediment concentration for the monitoring stations for three simulations LONG, RCP4.5 and RCP8.5

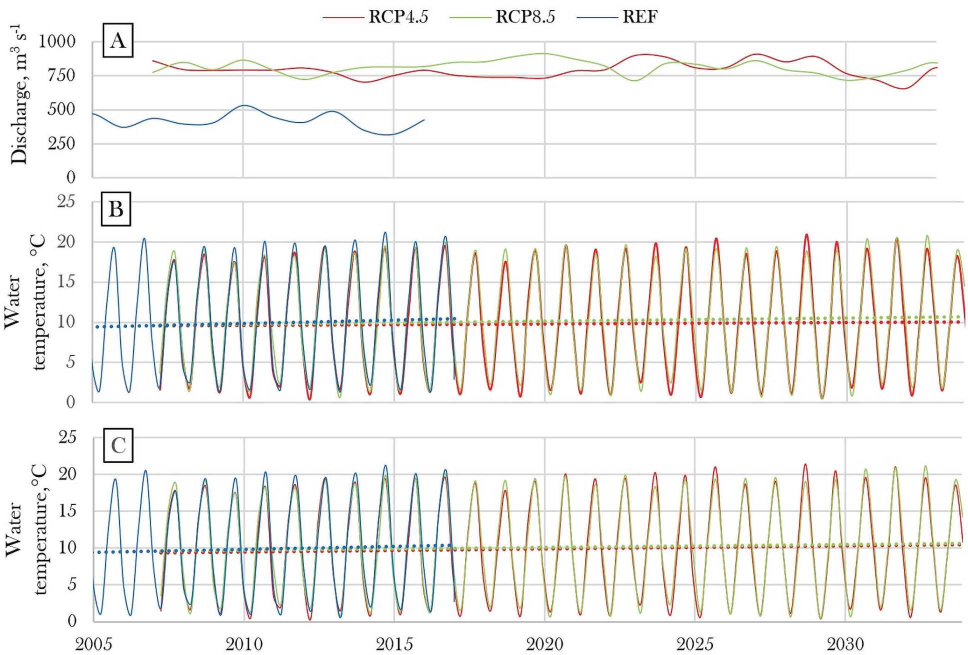

Figure 33. Forcing factors for the reference and climate change scenario. (A) river discharges; (B) water temperature in S1 station; and (C) water temperature in S2 station.

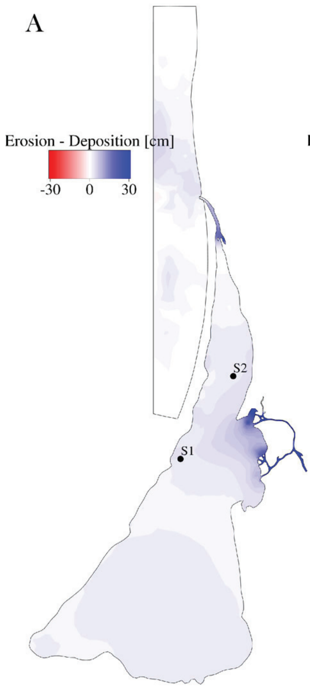

Figure 34. The modelled bottom changes after 25 years.
The results of RCP4.5 (left) and RCP8.5 (right) climate change scenarios.

5

Discussion

5.1 Importance of the sediment rating curve for the Nemunas River

The sediment transport model for the Curonian Lagoon cannot be set up without the suspended sediment input on the model river boundary for all simulation period. The closest permanent monitoring station in the Nemunas River (Smalininkai) was about 90 km from the model boundary, where only the TSS values were measured a few times per season. It is well known that the sediment rating curves are useful tools for predicting suspended sediment concentrations for the periods without samples (Asselman, 2000). These rating curves are based on the relationship between measured sediment concentrations and the river discharge and can be used to assess the patterns and trend in the rivers (Warrick, 2015). In applying the sediment rating curve for the river it is important to consider the rates of sediment supplies that can influence a sediment rating curve. The main factor controlling the suspended sediment supply is a wash load and its transport in the river (Asselman, 2000). The sediment supply strongly affects the increase or decrease of SSC values depending on the supply rates. Another important factor controlling the SSC values is the river discharge and its ability to erode and carry sediments in the flow and ability to dilute the suspended sediment concentration (Warrick, 2015).

In Bukaveckas et al. (2019) TSS values measured in the Smalininkai station were compared with the measured discharge values and no relationship was found between

TSS and river discharge in this station. These findings aimed at organizing one year field campaigns to get the sediment boundary condition data for the sediment transport model and the data for model calibration. Additional data was collected to get a broader view of the system and showed that the SSC trends in the river and lagoon are different. It is important to mention that the sampling campaigns in the lagoon were planned for the ice free season when the weather conditions were calm and did not show the possible highest concentrations due to higher wind waves that could have a strong influence for the resuspension and sediment redistribution and transport. Therefore, more observations are needed for better understanding of the system dynamics.

It was found that the highest riverine concentrations were in winter-spring season when the flood period started. In the lagoon the highest TSS (20-57 mg l^{-1}) and SSC values were found in the summer-autumn season together with the algal bloom or when the abundance of the cyanobacteria were more than 50% from all phytoplankton communities. In comparison with the other Curonian Lagoon studies (Kari et al., 2017; Bukaveckas et al., 2019), the similar TSS values were measured. The highest concentrations found in the literature were published by Remeikaite-Nikiene et al. (2012) with the maximum TSS of 304 mg l^{-1} (in the article called particulate matter) during the summer-autumn season. The reasons of very high concentrations were explained by high plankton concentrations in the water column.

Comparing the results with the other lagoons of the Baltic Sea, only concentrations of total suspended solids (TSS) were measured. Similar trends with lower values in winter (TSS=5-10 mg l^{-1}) and higher in summer (TSS=20-35 mg l^{-1}) were found in the closest Vistula and Szczecin lagoons (Leipe et al., 1998; Chubarenko et al., 2019). In comparison with the biggest lagoon in the world – the Patos Lagoon in Brazil – where the freshwater and wind are the main drivers, the TSS values varied from 50 to 150 mg l^{-1} (in the article called as Suspended Particulate Matter, g m^{-3}) with the recorded maximum of 1000 mg l^{-1} (Tavora et al., 2019). In the Patos Lagoon a strong interannual variability of TSS was found, with the highest concentrations in austral spring and summer and the lowest in autumn and winter.

For the developing of the sediment rating curve the Nemunas discharge on the model boundary and SSC measurements in Rusnė were used. The moderate relationship was found between the measured SSC and Nemunas River discharge using a power-law function. The SSC values predicted by the sediment rating curve during the flood period were underestimated compared with the measured values. With respect to the specific features of the Nemunas River, the lower SSC for the high river discharges can cause only minor uncertainties for the model results due to specific conditions in the delta region. Firstly, during the floods, especially large ones, in the delta region the flow velocities hardly decrease because of the water overflow to the valley (Rimkus and Vaikasas, 2012) and can carry less sediments in the water flow. Secondly, it is known that during the flood big amounts of sediments (about 35%

of the suspended sediment input) are deposited in the delta meadows due to favourable conditions for deposition and do not reach the Curonian Lagoon (Vaikasas and Rimkus, 2003). The applied sediment transport model does not take into account the flooded areas and sedimentation in the meadows, as a result, lower SSC values on the model river boundary should be in good agreement with the possible amounts of sediments that enter the Curonian Lagoon.

The developed sediment rating curve for 2015 was used for all the simulation period to estimate the Nemunas River suspended load and for the climate change scenarios as well. According to Warrick (2015) the sediment rating curves are useful tools for SSC prediction but they should be used with care since different years can have a different sediment supply rates depending on natural or human-caused changes in the watershed.

In this study there were no other measurements available for SSC, therefore the sediment rating curve based on one-year data was used for the longer simulation periods. All explanations in this chapter showed that even a moderate relationship between predicted and measured values will not affect the model results significantly.

5.2 The influence of cyanobacteria on settling velocity

The previously developed and well calibrated SEDTRANS05 module for the Venice lagoon (Ferrarin et al., 2008b; Neumeier et al., 2008) was applied to the domain of the Curonian Lagoon to understand the sediment transport mechanisms. At a first view, the Venice lagoon, a restricted, shallow, tidal-dominant lagoon with low river discharges and wind wave influence, seemed similar to the Curonian Lagoon. However, first simulations that have been carried out for the sediment model calibration showed that in a warm season the riverine sediment loads were not sufficient to reproduce the measured SSC values in the lagoon waters. It suggested that conditions in the Venice Lagoon and Curonian Lagoon are different.

According to Amos et al. (2004) the total suspended sediments in the Venice Lagoon had higher settling velocities in summer comparing with winter (water temperature ~5°C) that was associated with the formation of flocs due to bonding with organic material. However, the studies done for Curonian Lagoon showed the lowest settling velocities in summer ($3.5 \cdot 10^{5}$ m s^{-1}) compared with spring and autumn (Bukaveckas et al., 2019). This suggested that the biological components in such complex lagoons like the Curonian Lagoon and Venice Lagoon could be vital for the sediment dynamics and need to be analysed in more detail. The authors of Bukaveckas et al. (2019) showed that settling velocities for the total suspended sediments in the Curonian Lagoon are very low when positively buoyant cyanobacteria were present.

The comparison of primary producers and the origin of the organic matter is significantly different in the Venice Lagoon compared with the Curonian Lagoon. In the Venice Lagoon, the dominant primary producers are macroalgae *Ulva spp.* and a phytoplankton, mainly dominant by diatoms, plays a minor role in the lagoon (Bianchi et al., 2003; Facca et al., 2002). While in the Curonian Lagoon, the dominant primary producers are phytoplankton, with the cyanobacteria blooms in summer (Pilkaitytė and Razinkovas, 2006), mainly involving *Aphanizomenon flos-aquae* and *Microcystis aeruginosa* (Bresciani et al., 2014). *A. flos-aquae* contains microscopic vesicles that regulate their buoyancy and therefore they are accumulated on the water surface (Walsby, 1994).

The study by Pilkaitytė and Razinkovas (2006) showed a strong relationship between cyanobacteria biomass and water temperature while the authors of Aleksandrov et al. (2018) found a moderately strong relationship between Chl-*a* concentrations and water temperature. These studies were a starting point for the development of a new formula for settling velocity.

It is important to mention that the water temperature is not the only driver forcing cyanobacteria blooms and only a moderately strong relationship was found but there were no other parameters in the sediment transport model that could be used to compute settling velocities. An introduced formula for settling velocity is activated with the water temperature higher than 8ºC (Fig. 35). The Curonian Lagoon is known as a well mixed water body with almost no stratification in the water column. In Figure 35 the water temperatures are shown for three Curonian Lagoon stations from the north to the south and they do not indicate significant difference in the horizontal and vertical scale. The thermal stratification between the surface and the bottom layer can be visible in the winter season in areas deeper than 3 m, as well as in calm weather conditions in summer, and they can cause stratification between surface and bottom. According to Zilius et al. (2014) water temperatures measured on a surface and in 1 m deep differed by 2.4-3.4ºC in July 2011, when the cyanobacteria bloom was present.

The simulation results with the new formula for settling velocity showed a better agreement between the measured and modelled SSC values than before. In station S1 the sediment model performance quality increased from 12.5% to 40%, while in station S2 from 15% to 60%. The model results showed that the new formula for settling velocity was necessary to achieve the appropriate SSC values. However, more adequate observations on settling velocities, especially for the cyanobacterial blooms period in late summer and beginning of autumn, especial in the areas with cohesive sediments, where the developed model underestimates the measured values (Station S1), would be needed to see if the new formula is robust for the Curonian Lagoon environment. In addition, the organic material in suspensions is not the only factor that can affect the suspended sediment concentration and sediment dynamics in the system. For example, the benthic vegetation can influence the bed roughness and bottom sediment erodibility (Amos et al., 2004; Grabowski et al., 2011), which was not

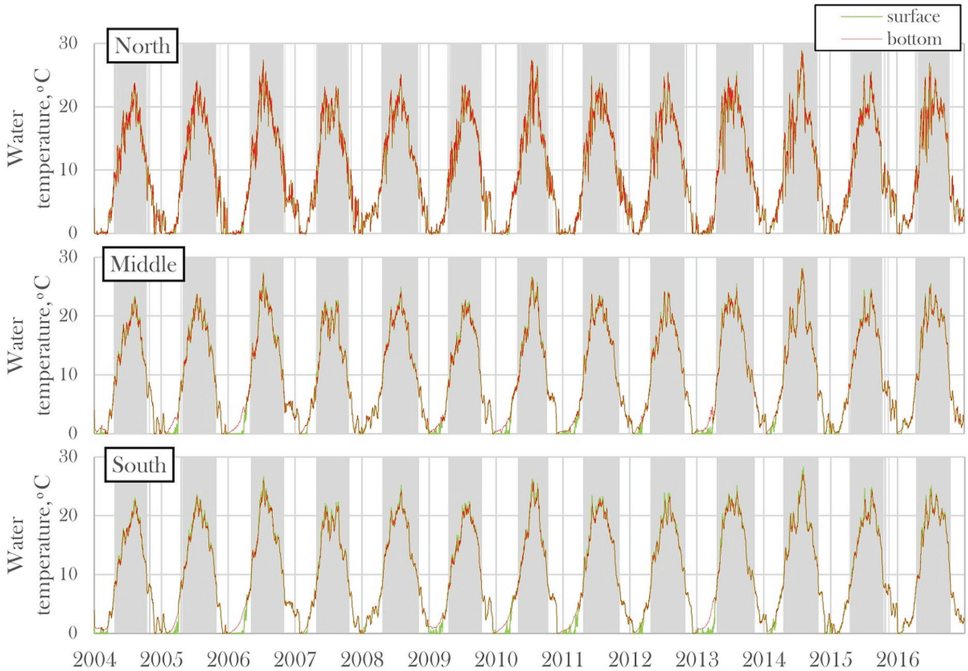

Figure 35. Comparison of water temperature along the three Curonian Lagoon stations: in the north (55.573414ºN; 21.157354ºE; depth 2.38m), in the middle (55.314449ºN; 21.123343ºE, depth 3.33m) and in the south (55.030495 ºN; 20.917892ºE, depth 4.17m). Grey area indicates the period when the new formula for settling velocity was activated.

considered by this study due to the lack of data. However, it should be clear that the final goal will be to include cyanobacteria, either as a state variable, or as a forcing value, into the code in order to increase the reliability of the new equation, which can then be based directly on the real mass of cyanobacteria.

5.3 Evaluation of model calibration and validation results

The sediment transport model is coupled with the hydrodynamic model. Therefore, in the beginning of the study the hydrodynamic part of the model was tested using water levels, temperature, salinity and wave data. Statistical analysis results reported strong correlation values for all parameters in all stations inside the Curonian Lagoon, except the salinity in Juodkrantė station where only a moderate relationship was found. In the previous study done by Zemlys et al. (2013) with a much finer computational grid and better representation of two flow structures in the Klaipėda harbour also the moderate relationship for salinity in this station was reported. The main reason is the ability of the model to reproduce fast brackish water intrusions to the lagoon without a lag. The worst model performance was found in winter. In Zemlys et al. (2013) the same tendency was indicated mainly due to the absence of ice data in the model. For this study, the satellite ice data was introduced to the model, but possibly due to the lower model resolution, it overestimated the number of the sea water intrusions, as a result, further investigations are needed to get better model validation results.

The wave model validation results should be analysed with care. The visual observation data from Ventė monitoring station was used which is grouped to wave height bands and does not show the real variation. Still it was found that the wave model underestimates the highest measured waves that could be caused due to the coarse model resolution.

The comparison of the results with the previous studies (Table 5) revealed that the higher resolution model describes the variations of parameters better. Nevertheless, taking into account all the other parameters validated for this study, the model performance can be considered satisfactory and can be applied for further tasks.

The calibration of the sediment transport model for the Curonian Lagoon with the new settling velocity showed lower than 50% model performance quality in the S1 station that can be explained with the wider knowledge of the entire system. According to the seasonal maps of the water currents (Fig 15), the S1 station has minor influence of the Nemunas River indicating that other source of the input material should be taken into account. Stronger currents were formed on the western coasts of the lagoon possibly causing coastline erosion and increases in SSC. The SHYFEM model does not simulate a coastline change, and as a result the eroded material is not added to the system. The Curonian Spit is covered with sandy dunes open to the aeolian processes where part of the sand can be blown to the lagoon waters (Trimonis et al., 2003). According to Galkus and Jokšas (1997), 37% of the total sediment input (lithogenous income material) can enter the Curonian Lagoon from the other sources such as precipitation, shore erosion, aeolian processes, waste waters or others. All these processes are not extensively studied in this region and cannot be taken into account by the sediment transport model, as a result, it may cause model discrepancies.

However, the applied sediment transport model showed correct SSC fluctuations in station S1 according to different hydrodynamic conditions with the higher SSC values during the flood period, summer-autumn season when the possible cyanobacteria bloom is present and when higher waves are dominant. The model performance showed a correct behaviour of the SSC values that is the main property of the models in the sediment transport research. There is a variety of sediment modelling studies where values lower than 50% were accepted during the model calibration or validation processes because of the complexity of the study area and observation errors (Davies et al., 2002; Ferrarin et al., 2010a; Escobar and Velásquez-Montoya, 2018).

Despite the uncertainties in the S1 station, the model calibration results in S2 station and validation results showed satisfactory agreement between modelled and measured values, where 60% and 72% of the measured values respectively fall into the double relative discrepancy interval. The station S2 is exactly located on the way of the river water flow, while validation stations were spread in the northern site of the lagoon with different sedimentation properties.

5.4 Hydrodynamics of the Curonian Lagoon

The analysis of the hydrodynamic model results was performed by the investigation of the seasonal patterns of salinity, currents and waves. The Curonian Lagoon is a well mixed water body where the outflow from the lagoon is dominant (Ferrarin et al., 2008a; Zemlys et al., 2013). Previous studies for the lagoon hydrodynamics were designed for the short periods (usually one year) that do not show the long-term fluctuations and the evaluation of the results can be applicable only for that particular year. Also, the model results for the short period can miss important events such as strong floods or low discharges of the rivers that influence the average dynamic of all parameters. As it can be seen from Figure 4, the flood periods significantly differ from year to year, causing changes in the current structures in the delta region.

The Nemunas River enters the lagoon in the central part and divides the system into two parts. In Ferrarin et al. (2008a) the water circulation simulated for the idealized wind forcing showed mostly anti-clockwise circulation in the southern part of the lagoon and northward currents with the outflow from the lagoon due to the Nemunas River. The results of this study showed the cyclonic and anticyclonic circulation in the southern part. In the shallower northern part, the residual currents were directed northward and the speed between the surface and bottom currents did not differ significantly. The model simulation results in the deeper bottom areas showed shifted directions of currents comparing with the surface currents.

The seasonal maps of the average salinity distribution simulated for the period 2004-2016 and period 2004-2015 (Umgiesser et al., 2016) showed slightly different salinity variations with the strongest salinity gradients in winter and higher concentrations in spring in the northern part of the lagoon close to the Klaipėda Strait. The differences between the model set up of this study and the study published in 2016 are the ice cover data and the small changes in the computational grid. The reader could refer to Umgiesser et al. (2016) article for more details of the simulation set up and results. However, these data are not the main factors causing the alterations in the results. The frequency and amounts of the sea water intrusions and the river discharges significantly differs each year and can cause different results for the region. There was no analysis done for the bottom and surface salinity due to the study from Zemlys et al. (2013) indicating that the difference between the surface and bottom salinity is negligible.

The analysis of the maximum salinity showed that in all seasons the salinity value of 5 can reach the central part of the lagoon. Comparing the average maximum salinity results from the simulation for the year 2009 (Zemlys et al., 2013), similar water intrusions were found reaching the central part of the lagoon. The maximum brackish water intrusions were found in autumn when the river discharges were low. The main factor controlling the exchange between lagoon and the sea is the wind driven barotropic pressure gradient. The strong northerly and northwesterly winds cause a barotropic inflow from the sea to the lagoon, while the absence of wind or mild wind forms two-layer flow in the Klaipėda harbour (Zemlys et al., 2013).

The wave model evaluated the averaged wave heights for the Curonian Lagoon, indicating that the highest waves are formed in autumn because of the stronger winds comparing with spring and summer. The wind forcing is shown in Figure 4. The simple parametric wind wave model underestimated the highest wave values that can influence sediment resuspension. Therefore, for the future studies on the sediment transport mechanisms more complex spectral wave models should be included.

Additional case study was performed for the Baltic Sea coastal area near Palanga. The reader can refer to Mėžinė et al. (2013) for more details. In that study, the coastline change model GENESIS was coupled with RCPWAVE wave model for the assessment of coastline changes. The RCPWAVE model uses the same CERC method to model wave properties according to wind speed and fetch. The results of that study revealed that the parametric wave model does not represent the real wave climate in the Baltic Sea well and can be used only for feasibility studies.

5.5 Factors controlling SSC

In spring, the influence of rivers was evident and rivers were the main factors causing high concentrations on the river mouths due to big amount of sediments transported during the flood period. The northern part is strongly influenced by the river sediment loads in spring as well, where the sediment transport was mainly directed seaward due to the higher water levels in the lagoon and had higher SSC comparing with the more stagnant southern part. In the southern part, the sediment transport depends on the meteorological forcing (Ferrarin et al, 2008a; Umgiesser et al., 2016) and can have considerably varying concentration values depending on the wind speed and direction within different years. Average concentrations in the water column from about 5 mg l^{-1} in the years 2011, 2015 until 25-35 mg l^{-1} in 2009, 2010 were estimated.

In summer, the suspended sediment concentration gradient was formed from east to west due to the water circulation and low river discharges. For this season, the main factor influencing water column mixing and exchange between the southern and the northern part of the lagoon was wind (Umgiesser et al., 2016). The autumn season showed the biggest part of the lagoon with concentrations >25 mg l^{-1}due to the highest waves and strongest currents that were present in autumn, as a result the highest bed shear stress values that cause resuspension were found. The high water temperature in September is the main factor that causes more sediments in suspension due to the introduced formula for the settling velocity that imitates the sediment trapping during the cyanobacteria bloom through the water temperature.

The seasonal maps of the suspended sediments showed a general situation in the lagoon environment through the 12 year simulation results. However, the short-term events are much more important due to the fast changes in the lagoon that can have a crucial impact for the ecological processes or even irreversible consequences for the entire system. The short-term simulation results are analysed in the section below and are grouped as factors that influence the sediment dynamics in the system.

5.5.1 The role of the ice cover

The sediment transport processes in the Curonian Lagoon are not fully understood due to the fact that almost no measurements under ice exist. Numerical models are some of the tools for the evaluation of these processes, and, as a result, the impact of ice cover was investigated through the additional analysis of the results from the CAL and NoICE simulations described in the section 3.3. The two simulations were carried out running the model with and without ice cover data with the same meteorological forcing and boundary conditions. The period when the lagoon was frozen extracted from the simulations was from 15th of January 2014 until 7th of March 2014.

The results demonstrated that ice cover plays a crucial role for the sediment dynamics (Fig. 26). The study done by Umgiesser et al. (2016) had already showed that the incorporation of ice coverage data into the model gives much better results in terms of salinity and water renewal time. The use of satellite ice cover data gave a possibility to analyse the performance of the system on a longer time window and with higher details. Ice cover sheltered wind forcing over the lagoon surface and stopped the sediment resuspension due to waves induced by the strong winds that are very common in winter period (Fig 4C, D). The ice cover decreased the water exchange between north and south of the lagoon and less fresh water from the Nemunas went to the south. These factors reduced the suspended sediment concentration in the water column in winter compared to the concentrations simulated without ice cover. The ice thickness was not taken into account by the model. This could change the results in the shallow areas and the delta region, where the thick ice cover can change the hydrodynamic conditions. The ice jams formed in the river mouths can influence the river discharges, also the cross section of the water body can be reduced due to the ice presence reduction that can increase the current velocity.

Most of the studies analysing the influence of the ice cover are done for rivers (Hirshfield and Sui, 2011; Turcotte et al., 2011) and are based on field observations. The *in situ* measurements of the total suspended sediment concentration in the Vistula Lagoon with ice and ice free conditions showed about 2-3 times lower concentrations when the lagoon was ice-covered (Chubarenko et al., 2019). The water exchange with the sea and the river discharges were the main forcing factors in the Vistula Lagoon under ice cover.

5.5.2 Impact of stormy wind

The effect of the strong wind events on sediment erosion in coastal lagoons received a lot of research attention in the past years (e.g., Forsberg et al., 2018 and reference therein), possibly due to climate change forecast on increasing storminess (IPPC, 2014). High wind speeds lead to increased bed shear stress values as a function of waves and currents that causes resuspension.

The wind effect on the sediment dynamics in the lagoon was investigated using the CAL simulation results (3 years). The results showed that the strong storm events are important factors influencing the distribution of the suspended sediments and can have a strong influence for the sediment budget calculation or analysis of erosion-accumulation zones in the region. The main outcome is that strong storm events showed big amounts of resuspended sediments that can be washed out of the system in a short period and the time to recover is from a few days to seasons. Taking into account the projections of climate change, sediments can be washed out of the system more often and lagoon could start losing sediments due to the increased storminess.

The stormy winds are also important for the coastal erosion processes and dunes sand propagation that can influence the suspended sediment concentration in the water column and their transport to the deeper lagoon areas. For future studies the coastline change model GENESIS (already applied for the Baltic Sea coastal area, see Mėžinė et al., 2013) could be coupled with the SHYFEM model for better understanding of the amounts of costal erosion and their consequences for the Curonian Lagoon.

5.6 Erosion-accumulation zones in the Curonian Lagoon

The long term simulation results allowed the investigation of the erosion accumulation zones other 12 years. The erosion accumulation zones were in good agreement with Ferrarin et al. (2008a), where the southern part with a resident time of more than 120 days was classified as an accumulation zone. The northern part characterized by strong riverine influence was limited for accumulation of suspended matter and acted as a transitional zone. According to Chubarenko et al. (2002) the wind wave impact in the lagoon counteracts the accumulation of suspended material transported by the Nemunas River in the north, which thereby maintains the deeper regions in this lagoon.

The measured accumulation rates by Pustelnikovas (2008), in five points (four points on the western site and one close to Matrosovka River, located at the south eastern coasts of the lagoon) showed the accumulation of 3.2 mm y^{-1} on the west coasts and 3.4 mm y^{-1} in the deeper areas. The measurements were done in the areas where muddy sediments, rich in organics, are dominant. The developed model did not include organic particles, and as a result, the estimated sedimentation rates for total suspended material in the southern part should be higher than the ones modelled for inorganic particles only.

The results of this study agree with the accumulation rates calculated for the Curonian Lagoon close to the Nemunas branches (Mažeika, 2018; personal communication). The sample core was taken where the riverine sediments were dominant. According to the radiocarbon dating, the average deposition rates for the last 60-80 years were 3.75-5 mm y^{-1} while for the five year period the calculated deposition rates were ~7.5 mm y^{-1}.

The general scheme of the accumulation zones for the lagoon was drawn by Gulbinskas (1995), where the southern part and western area around Nida (western coast, in front of the Nemunas delta) together with small areas in the Nemunas delta front were defined as accumulation zones, while other areas were presented as transitional zones. The zonation was controlled by the bottom sediment grain sizes and water depth. The accumulation zones refer to finer sediments while the transition zone refers to the coarser particles. The results from the sediment transport model gave a possibility to identify the erosion-accumulation processes more accurately. The areas of the accumulation was found in the southern and central part of the lagoon with transitional zones (white colour in Fig. 23) on the eastern and western parts where strong currents were formed. The northern part of the lagoon can be called the transitional zone as well with respect to two factors. Firstly, very low erosion values are simulated by the model. Secondly, it is known that the shallow eastern coasts in the northern part are covered by the macrophytes (Bučas et al., 2019) that are hindering erosion. However, these processes could not be taken into account by the model.

The sediment budget calculations revealed that the lagoon is accumulating sediments with an average of 0.5 mm y^{-1}. At this rate about 8000 years will be needed to fill the Curonian Lagoon with sediments if we assume the same accumulation rate in the future. However, this is only the theoretical number that will be influenced by a large variety of factors in the future. Firstly, it was already shown that the lagoon accumulates sediments mostly in three main zones: delta region, southern part of the lagoon and the Klaipeda Strait. The depth changes in these regions will cause different current structure in the lagoon. Furthermore, the bottom sediment composition, the erosion thresholds, wave climate and other parameters will act differently due to morphological changes in the basin and possibly will affect accumulation rates. The climate change and biological activity in the water column will influence the accumulation in the Curonian Lagoon as well.

5.7 Sediment budget calculation using the model results

The sediment budget for the Curonian Lagoon was calculated by taking the difference between incoming and outgoing sediments. The estimated averaged annual sediment input to the system, which consisted of riverine input and the input from the sea, was $484.4 \cdot 10^6 \pm 379.0 \cdot 10^6$ kg y^{-1}. The annual output to the sea was $185.8 \cdot 10^6 \pm 178.2 \cdot 10^6$ kg y^{-1} and $298.6 \cdot 10^6 \pm 238.1 \cdot 10^6$ kg y^{-1} stayed in the lagoon in the form of suspensions or on the bottom. It is clear that the Curonian Lagoon acts as a sink for the sediments and differs from similar lagoons in the Baltic area, where Vistula lagoon is losing sediments (Chubarenko and Chubarenko, 2001) and Szczecin lagoon is transporting sediments to the sea (Leipe et al., 1998). The sediment budget for the Curonian Lagoon calculated by other studies was in the range of our study. The total budget calculated by Pustelnikovas (1998) was $\pm 454.2 \cdot 10^6$ kg y^{-1} and by Galkus and Jokšas (1997) $\pm 450.8 \cdot 10^6$ kg y^{-1}. The biggest disagreement in these studies was between the amounts of sediments that exit to the sea and are accumulated in the lagoon. In Pustelnikovas (1998) it was calculated that the lagoon accumulates $337.2 \cdot 10^6$ kg y^{-1} and in Galkus and Jokšas (1997) an accumulation of $132.8 \cdot 10^6$ kg y^{-1} was found. The modelled sediment budget for different years can vary by more than 5 times and the period for which the budget is calculated should be taken with care. Therefore, big differences between the calculated amounts of accumulated sediments can be found by different studies. Moreover, a strong correlation between incoming and outgoing annual amounts of sediments was found.

The Curonian Lagoon transports big amounts of riverine sediments in comparison with the Vistula Lagoon, a lagoon in the Baltic area close to the Curonian Lagoon, but with low river discharges. The average riverine sediment load in Vistula Lagoon is about $88 \cdot 10^6$ kg y^{-1} and additional input from the Baltic Sea is about $34 \cdot 10^6$ kg y^{-1} (Chubarenko and Margoński, 2008). To compare, the modelled input from the sea to the Curonian Lagoon was $14.0 \cdot 10^6 \pm 5.8 \cdot 10^6$ kg y^{-1}. However, in the shallow Vistula Lagoon (average depth 2.7 m) intensive resuspension acts due to waves and a sediment loss of $322 \cdot 10^6$ kg y^{-1} to the Baltic Sea was found (Chubarenko and Margoński, 2008). This concludes that the Vistula Lagoon is losing sediments, while the Curonian Lagoon with high riverine loads accumulates sediments inside the lagoon.

It is important to mention that in the model at the open sea boundary the suspended sediment concentration was set to 0 because of the absence of data. It is known that the sediment budget could be sensitive to this value. However, the model simulations that were carried out cannot answer the question how sensitive the sediment budget is according to the SSC in the Baltic Sea. Nevertheless, comparing the modelled sediment loads from the sea to the lagoon ($14.0 \cdot 10^6 \pm 5.8 \cdot 10^6$ kg y^{-1}) with the measured loads by Pustenikovas ($7.2 \cdot 10^6$ kg y^{-1}) (1998) and Galkus and Jokšas ($15.6 \cdot 10^6$ kg y^{-1}) (1997), it was assumed that the modelled values are appropriate and can be used for the sediment budget calculation. Some of the possible reasons why the concentration value of 0 on the sea boundary did not affect the incoming sediment loads are: (i) the lagoon is a non-tidal water body; (ii) the outflow of the lagoon is dominant (see Fig 4A) and (iii) after a one-year simulation run, the concentrations in the sea close to the Klaipeda Strait are in the reasonable range, as a result, the computed flux is in a good agreement with the values found in literature.

These uncertainties in the Baltic Sea leads to possible future studies focused on the sediment transport mechanisms in the sea and their influence for the Curonian Lagoon environment. The numerical model for the analysis of the sediment transport mechanisms could be a valuable tool for optimizing the dredging activities in the Klaipeda Strait, and the harbour area. For such specific tasks, the numerical model could be applied with higher resolution in order to reproduce, within the use of the unstructured mesh, both the sediment transport in the lagoon and the small-scale dynamics around the artificial structures of the harbour area.

5.8 Evaluation of resuspension events

In this study the sediment transport model was applied for the evaluation of the resuspension events in the Curonian Lagoon. The question was raised after Zilius et al. (2016) study where the future studies were addressed for the relevance of the resuspension in the Curonian Lagoon that can cause nutrients release from the bottom sediments to the water column and affect the cyanobacteria bloom. In freshwater systems, phosphorus concentrations are often low and limit algal growth (Ji, 2008). It is known that in summer during basic riverine flow, the bottom sediments become a relevant source of nutrient to the overlaying water column.

There are two main types of the models that are used to simulate the sediment resuspension. The first is a sediment transport model together with the hydrodynamic model (Liu and Huang, 2009), that simulates changes in TSS concentration, water turbidity, morphological changes and does not model nutrients or over biological material. The second type is a biogeochemistry (or ecological) model coupled with the hydrodynamic model that can answer the questions about the nutrient cycles and other parameters as well (Capet et al., 2016; Smits et al., 2013). It simulates benthic-pelagic interactions that represent the pathways of organic matter and resolves multiple element cycles between the bottom and water column.

The 2D ecological model for the Curonian Lagoon was presented by Zemlys et al. (2008). However, the processes between the bottom and water column were not evaluated due to the lack of measurements. This study aimed to combine the results of the sediment transport model with the measured nutrient concentrations in the pore water to calculate the possible nutrient flux due to resuspension. Resuspension events were analysed using the modelled daily values of the bottom changes (erosion-accumulation rates). The nine year data in S1 station showed a minor variation of the bottom depths (Fig. 31). Therefore, only the maximum seasonal values were analysed to calculate the nutrient supply flux (Table 6). The results presented a positive summer phosphate flux of 0.005±0.001 mmol m^{-2} d^{-1}, while the bottom fluxes measured by intact core incubation showed a negative phosphate flux in summer (Petkuviene et al., 2016; Zilius et al., 2018). The scheme of the intact core incubation fluxes are presented as a benthic flux in Figure 30. In general, the resuspension increased more phosphate concentration than ammonia or silica compared with the measured benthic flux data presented by Petkuviene et al. (2016) and Zilius et al. (2018). Despite the fact that the sediment resuspension was limited in time, it could be an important mechanism maintaining phytoplankton when nutrients are limited.

However, the SEDTRANS05 model itself cannot model the nutrient cycle. This method can be used only in the areas where the nutrient concentrations in pore water were measured. The combination of the model and the measurements can be a valuable tool for the small scale studies. However, future studies should be focussed on (i) short-term bathymetry changes (1 hour or less) and (ii) the influence of organic material and benthic fauna for particle resuspension that should be taken into account. Another possibility for the future studies could be the application of the 3D SHYFEM ecological model AQUABC, which is under development, or EUTRO (Zemlys et al., 2008, Umgiesser et al., 2003).

5.9 Future trends for the sedimentation in the lagoon

This study aims to evaluate the future trends for the Curonian Lagoon in terms of sedimentation changes under climate change. Usually climate change is associated with global warming, and atmospheric and ocean circulation changes. The most important factors analysing the possible consequences for the systems are changes in wind, waves, storm regimes and ice and flooding periods.

The increased storminess is expected according to the increase of mean sea level and variations of the wind speed (Gräwe and Burchard, 2012). The sediment transport model results showed the Curonian Lagoon is vulnerable to stormy winds that increase the sediment suspension in the lagoon. The higher probability of resuspension events is expected due to increased storminess that can increase erosion zones in the region and the supply of increased amounts of nutrients from the bottom sediments. Equally, the storms are the main components influencing coastline erosion. A case study done for the Lithuanian Baltic Sea coastal area about 20 km to the north from the Klaipeda harbour showed the coastal erosion rates due to waves (see Mėžinė et al., 2013). Results agreed with the fact stated by Łabuz (2015) that Lithuanian and Latvian coasts are vulnerable to erosion. The more detailed studies with the climate change scenarios could be done by coupling SHYFEM with the coastline change model.

The analysis of 13 years of ice cover data did not show a clear trend for the ice cover presence in the lagoon (Fig. 4B). Nevertheless taking into account the climate change scenarios that predict the decreasing number of days with ice cover in the future (BACC II Author Team, 2015), the higher SSC values in winter could be expected due to the wind wave action on resuspension. Therefore, it is expected that the Curonian Lagoon will decrease its capacity to retain sediments in the future. However, it also has to be considered that an increase of the Nemunas sediment load for winter is forecasted in a climate change perspective (emission scenarios RCP4.5 and RCP8.5 (Čerkasova, 2019)), with a probably associated enhancement of the winter sediment load into the lagoon. The ice jams were not taken into account in this study. It is possible that the ice free winter will shorten the flood period and less sediments in early spring will be transported to the lagoon.

Two climate change scenarios were studied: RCP4.5 and RCP8.5. The LONG simulation results were used as a reference simulation for the analysis of the set up of the climate change scenarios and comparison of the model results. The analysis of the hydrodynamic runs showed that the boundary conditions on the Nemunas River overestimated the observed river discharge data by about 30%, as a result the sediment input to the lagoon was overestimated as well (Fig. 33A). For the climate change scenarios, only the Nemunas discharges were used for riverine forcing. The sediment rating curve was used to calculate the input sediment loads for the projected discharges. Comparing the projected riverine sediment input loads with the reference simulations, it was found that the projected loads were overestimated by about 1.5 times.

The SSC values from the long-term simulation (LONG) were averaged over the water column in stations S1 and S2 to see the performance of the climate change models. In the beginning of the simulation the modelled SSC values in monitoring stations were underestimated while after 5 years the rapid increase of the SSC in the water column was visible (Fig. 32). After 25 years of simulation the averaged SSC values compared with the reference simulation increased by more than 1.6 (S1) and 4.7 (S2) times with the scenario RCP4.5 and by more that 2.9 (S1) and 7.4 (S2) times with the scenario RCP8.5. In both projections, the main driver for these changes was much higher river discharges on the boundary that formed stronger currents in the river. As a result, the erosion in the river was much higher compared to the reference simulation and even more sediments were transported to the system. This caused a higher accumulation rates in the delta front and a strong SSC increase in the lagoon, especially in the S2 station, which is located along the way of the river water flow.

The sediment transport model with the new formula for settling velocity is sensitive to the changes in the water temperature. Both projections showed a significant increase of the water temperature until 2100 that will decrease the sediment settling velocity. However, the climate change scenarios were simulated until 2033 and on the end of the simulation the mean annual water temperature increased only by 0.3°C for RCP4.5 and 0.5°C for RCP8.5 scenario in comparison with the reference simulation. It is important that the increase of water temperature induced more days with the water temperatures higher than 8°C that activates the new formula for settling velocity. In the reference simulation, the average number of days with the water temperature higher than 8°C was 187, while from 2016 in RCP4.5 the number increased to 214 days $year^{-1}$ and in RCP8.5 to 217 days $year^{-1}$. This will lead to lower setting velocities and more sediments in the suspension. Therefore, the developed formula for the settling velocity should be used with care in the climate change scenarios. In addition, more scenarios for the cyanobacteria blooms should be studied together with the sediment transport mechanisms. The increased water temperature could favour cyanobacteria blooms (Bartoli et al., 2018), and, as a result, more sediments can be trapped in the water column.

The analysis of the erosion-accumulation zones revealed that the lagoon acts as a sediment sink and after a long period no erosion zones are formed in the lagoon. The climate change scenarios have shown that three main accumulation zones can be distinguished: (i) Nemunas delta front, (ii) southern part of the lagoon and (iii) the southern part of the Klaipėda Strait. Results showed that the lagoon accumulates sediments much faster with scenario RCP8.5. The fast accumulation in the river branches did not allow carrying out the long simulations runs (until 2100). This will be done in the near future.

These climate change results should be used with care because of many uncertainties in the climate change projections. Nevertheless, the general future trends can be drawn from these findings. Both scenarios showed an increase of the riverine sediment loads that follows the accumulation patterns of the present situation. Without paying attention to the changes due to the overestimated input of the sediments, most changes are likely to occur during the winter due to the decreasing number of days with ice cover and increase storminess or summer-autumn due to the increased water temperature and possibly increased water turbidity.

5.10 Sediment transport model: advantages and limitations

A large variety of hydrodynamic and sediment transport numerical models are available for the scientific community (Umgiesser et al., 2004; Neumeier et al., 2008; Moharir et al., 2014; Lesser et al., 2004) and can be applied for a big variety of studies in different temporal and spatial scales. An open source models, such as SHYFEM and SEDTRANS05 (Umgiesser et al., 2004; Neumeier et al., 2008) always are more advanced than the commercial due to the price and possibilities to adapt the model for the specific conditions of the study site. The sediment transport models coupled with the hydrodynamic model are powerful tools for the hindcasting and forecasting the sedimentation patterns in the aquatic environments and their impacts on the coastal erosion or ecological processes.

However, the high-resolution model needs a high computational power. The long-term simulations take a long computational time. The set-up of the numerical models needs a good meteorological and physical data that usually are obtained from the other more general models. The most essential steps are the model calibration and validation. These processes require big datasets of *in situ* measurements that show the quality of model performance. There are many sediment transport studies where the lack or insufficient *in situ* measurements were found (Teeter et al., 2001; Ferrarin et al., 2010a; Elias and Hanses, 2013).

The sediment transport model was a prevailing tool in this study. The big datasets for the model set up were collected from meteorological and hydrodynamic models. The field campaigns were organised for calibration and validation data sampling. A super computer with 64 processors was used for the model runs. The absence of measured physical processes for the sediment dynamics in the Curonian Lagoon did not allow achieving better model results.

SEDTRANS05 cannot be used for the analysis of the coastline changes due to a simple parametric wave model that does not calculate the energy of braking waves. For the deeper understanding of the resuspension events, the sediment model should be coupled with a real wave module, and should also take into account the organic material in the bottom sediments.

5.11 Gaps and future perspectives

The work done during the doctorate studies revealed the sedimentation pattern in the biggest lagoon in Europe. The representation of physical processes in the SHYFEM model can contribute to a better understanding of sediment dynamics in the Curonian Lagoon and help to find the best management solutions and minor future stresses due to changing climate. However, still good morphometric maps of the

Curonian Lagoon are missing for the evaluation of the model results for the erosion-accumulation zones in the system. A more detailed study for the developed sediment rating curve is necessary in order not to underestimate the sediment loads during the flood period. Therefore, more frequent *in situ* measurement campaigns and laboratory experiments in near future should be organized. More reliable data to validate the model during extreme events is needed.

The analysis of the parametric wave model calibration results showed the underestimated maximum wave heights, as a result, next steps planned for the near future is to use the spectral wave model for better representation of waves in the lagoon. The coupling with the nearshore numerical model could be a valuable tool for the evaluation of the costal hazards and analysis of future perspectives and mitigations of negative consequences in the region. The model applications for the evaluation of the resuspension or other biological or ecological factors combined with the sediment transport in the future will be evaluated by applying a biogeochemical model such as SHYFEM/EUTRO (Umgiesser et al., 2003 and references therein) or SHYFEM/AQUABC (still under development), coupled with the sediment transport.

Regarding the climate change scenarios, the long term simulations (up to 100 years) will be carried out in the future. The ensembles of the climate change models will be used to evaluate the variation of results according to different climate and ocean models.

6

Conclusions

1. The unique sediment dynamics analysis in the complex lagoon system with high river discharge and uneven sediment loading (Curonian Lagoon) was performed using a 3D hydrodynamic and sediment transport model. The sediment rating curve was developed from *in situ* measurements, necessary for the calculation of the Nemunas River sediment loads on the model boundary. Also a new formula was incorporated to the sediment transport model taking into account cyanobacteria blooms impact on the sediment settling velocity in summer and early autumn. The reliable results of the sediment transport model calibration and validation (40-72% fell into double relative discrepancy interval) allowed carrying out the simulation runs for the investigation of accumulation and erosion zones, sediment budget, ice impact, extreme storm events and climate change (RCP4.5 and RCP8.5 projections) impact on the sediment transport.

2. Long-term simulation (13 years) enabled to reveal three main accumulation zones in the lagoon: (i) the Nemunas Delta front, (ii) southern part of the lagoon and (ii) southern part of the Klaipėda Strait. The averaged accumulation rate of 0.5 mm y^{-1} was obtained for the entire lagoon and the maximum 7 mm y^{-1} accumulation was found in the delta front. Study results are in line with the accumulation rates calculated by Mažeika (2018, personal communication) for the delta area, but were lower comparing with the results of Pustelnikovas (2008) for the deep southern lagoon areas due to organic material that was not taken into account by the sediment transport model.

3. Components of the sediment budget showed that lagoon acts as a sediment sink and that 62% of total annual input of riverine sediments are trapped inside the lagoon. The average annual amount of sediment coming to the system is $484.4 \cdot 10^6 \pm 378.0 \cdot 10^6$ kg y^{-1} and the output is $185.8 \cdot 10^6 \pm 178.2 \cdot 10^6$ kg y^{-1}. The results revealed that a lagoon without ice cover would have significantly higher SSC (>10 mg l^{-1}) in winter with the wind speed >10 m s^{-1} in deeper station with cohesive sediments and wind speed >6 m s^{-1} in shallower station with non-cohesive sediments. The analysis of the storm on 6th December 2013 showed a total loss of $4.7 \cdot 10^6$ kg of sediments with the need of 42 days to refill the sediment loss.

4. The results obtained by sediment transport model showed that during stronger wind events (>11 m s^{-1}) more than 1 mm of nutrients rich muddy sediments can be resuspended. In comparison to benthic fluxes measured in intact cores in other studies, resuspension has stronger effects on phosphate release to the water column than dissolved ammonia or silica. However, in order to answer the peculiarities of resuspension in the lagoon better, the analysis of (i) the influence of organic material and benthic fauna for particle resuspension and (ii) short-term bathymetry changes (1 hour or less) are necessary.

5. Scenarios for different climate change projections had overestimated riverine sediment loads. However, it followed the accumulation patterns of the present situation with 2.5 fold and 5 fold higher accumulation rates with RCP4.5 and RCP8.5 respectively. The most changes are likely to occur during the winter due to decreasing days with ice cover and increase storminess or in summer-autumn due to increased water temperature and possibly more intense cyanobacteria blooms that will increase the SSC and water turbidity.

6. The study enabled to develop a valuable model that was able to answer questions of sediment transport mechanisms in the biggest lagoon in Europe without necessity of direct measurement for all the lagoon. In future, this model will be coupled with a coastline change model and ecological model to be used as a tool for more detailed analysis of the coastal Baltic Sea and the transitional zone. Furthermore, the additional *in situ* measurements and laboratory experiments are necessary for better understanding of the physical processes in the system that should be done in the future.

7

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Summary in Lithuanian

ĮVADAS

Temos aktualumas

Hidrodinamika, bangos ir jūros dugno bei vandens storymės sąveika sukelia nuosėdų pernašą. Nuosėdos į vandens stulpą patenka iš įvairių šaltinių, o jų elgsena priklauso nuo nuosėdų erozijos, pernašos ir nusėdimo procesų (Ji, 2008). Šiame darbe nuosėdomis vadiname tik litogeninės kilmės daleles. Sedimantacijos procesai gali turėti įtakos uostų ir navigacijos kanalų užnešimui nuosėdomis, apriboti vandens augalų augimą dėl nepakankamo saulės šviesos prasiskverbimo ar sumažinti augmenijos tankį dėl sumažėjusio vandens skaidrumo, sukelti teršalų pernašą, pakitimus bentoso organizmų buveinėse ir kt. Sedimentacijos procesų suvokimas gali padėti išspręsti tokias aplinkos problemas kaip eutrofikacija, teršalų perneša, dugno ar krantų erozija, užnešimo nuosėdomis ir nuotekų valymo problemas. Tačiau tai labai sudėtinga užduotis, reikalaujanti didelių duomenų rinkinių apie tiriamą sistemą. Matematinis modeliavimas yra vienas iš metodų, galinčių aprašyti vandens, nuosėdų pernašos mechanizmus ir morfologinius pasikeitimus.

Pastaraisiais dešimtmečiais matematinis modeliavimas labai išpopuliarėjo ir šiuo metu yra plačiai taikomas daugelyje mokslinių tyrimų, susijusių su hidrodinaminių savybių tyrimais, nuosėdų pernaša, meteorologija, ekologija ir klimato kaita (García-Oliva ir kt., 2019; Friedland ir kt., 2019, Saraiva ir kt., 2019). Pagrindinis modelių pranašumas yra tai, kad sukalibruoti ir patikrinti matematiniai modeliai gali realiai atspindėti vandens telkinį ir būti lengvai pritaikomi sudėtingiems tyrimams, sujungiantiems kelis modelius ir siekiantiems nustatyti galimus sistemos pokyčius, pasekmes ir jų raidą. Gerai sukalibruoti modeliai gali tapti puikia priemone sprendimų priėmimams.

Šis tyrimas skirtas nuosėdų pernašos mechanizmų tyrimams Baltijos jūros pietrytinės pakrantės dalyje, daugiausiai dėmesio skiriant Kuršių marioms. Tyrimas atliekamas taikant matematinius modelius. Pernešamų suspenduotų dalelių kiekiai ir kryptis Kuršių mariose vis dar menkai išanalizuoti, todėl nuosėdų pernašos modelis galėtų būti puiki priemonė, gebanti analizuoti nuosėdų kryptis upės–marių–jūros sistemoje. Iki šiol nuosėdų pernašos procesai mariose buvo nagrinėjami, remiantis eksperimentiniais metodais, kurie parodė apibendrintą nuosėdų dinamikos vaizdą sistemoje ir jos įtaką ekologiniams procesams (Pustelnikovas, 1994; Galkus ir Jokšas, 1997; Galkus, 2003a, b). Pirmą kartą SHYFEM nuosėdų pernašos modelis Kuršių marių tyrimams buvo pritaikytas 2007 m. (Ferrarin, 2007). Dvimatis hidrodinaminis modelis kartu su spektrinių bangų modeliu buvo taikomas, norint ištirti srovių ir bangų įtaką dugno šlyties įtempimui ir jo kaitą. Vienerių metų scenarijaus skaičiavimui buvo naudojami realūs kraštinių sąlygų, meteorologiniai ir hidrologiniai duomenys. Detalesnės nuosėdų pernašos studijos buvo atliktos Klaipėdos sąsiauryje, uosto teritorijoje, jungiančioje Kuršių marias su Baltijos jūra. Tyrimui naudotas DHI (Danijos hidrometrorologijos instituto) dvimatis matematinis modelis MIKE-2 (Kriaučiūnienė ir kt., 2006 m.; Kriaučiūnienė ir Gailiušis, 2004 m.). Nepaisant to, šie tyrimai nėra pakankami, norint įvertinti daugiamečius nuosėdų dinamikos ir morfologinius pokyčius Kuršių mariose.

Šio tyrimo metu siekiama išsamiai atsakyti į anksčiau nenagrinėtus klausimus apie nuosėdų pernašos mechanizmus Kuršių mariose, išanalizuoti resuspensijos poveikį marių ekologinei būklei, naudojant matematinį modeliavimą, prognozuoti pernašos mechanizmų pasikeitimus dėl klimato kaitos, išnagrinėti biologinės medžiagos įtaką nuosėdų sulaikymui vandens stulpe ir ledo dangos įtaką nešmenų pasiskirstymui.

Tyrimo tikslas ir pagrindiniai uždaviniai

Tyrimo tikslas – remiantis matematinio modelio rezultatais, ištirti nuosėdų pernašos mechanizmus lagūnoje, pasižyminčioje stipriu upės poveikiu ir didele nuosėdinės medžiagos prietaka.

Pagrindiniai uždaviniai:

1. Susisteminti turimus aplinkos bei hidrodinaminius duomenis ir sukurti tinkamai sukalibruotą nuosėdų pernašos modelį, galintį sumodeliuoti skirtingus Kuršių marių scenarijus.

2. Išanalizuoti erozijos–akumuliacijos vietų pasiskirstymą ir apskaičiuoti nuosėdų biudžetą.
3. Įvertinti resuspensijos įtaką Kuršių marių aplinkai.
4. Prognozuoti sedimentacijos procesų pokyčius, remiantis RCP4.5 ir RCP8.5 klimato kaitos scenarijais.

Darbo naujumas

Yra daugybė tyrimų, kuriuose matematiniai modeliai buvo taikomi nuosėdų dinamikos tyrimams upių žiotyse, lagūnose ir jūrose (Maicu ir kt., 2019; Ferrarin ir kt., 2008b ir 2010; Lesser ir kt., 2004). Šiame tyrime matematinis modelis buvo pritaikytas nuosėdų pernašos mechanizmų tyrimams didžiausioje Europos lagūnoje, Kuršių mariose. Taikytas SEDTRANS05 modelis yra sukalibruotas Venecijos lagūnai ir plačiai taikomas Viduržemio jūros regiono tyrimuose (Ferrarin ir kt., 2010a,b; Neumeier ir kt., 2008; Ferrarin ir kt., 2008b). Tačiau hidrodinamika ir sedimentacinai procesai Kuršių mariose ir Venecijos lagūnoje yra kitokie.

Tai originalus tyrimas, kurio metu matematinis modelis SEDTRANS05 taikomas lagūnoje, kurioje reikšmingą įtaką nuosėdų pernašai turi organinės medžiagos kiekis vandens storymėje. Siekiant išanalizuoti nuosėdų pernašos mechanizmus, buvo sukurta nauja dalelių nusėdimo formulė. Ši formulė yra paremta Bukavecko ir kt. (2019) studijos rezultatais, kur žemi dalelių nusėdimo greičiai buvo išmatuoti dėl stipraus melsvabakterių „žydėjimo“ vasarą ir rudenį. Vandens temperatūra yra vienas iš faktorių, veikiančių melsvabakterių „žydėjimą“, todėl nauja formulė buvo sukurta kaip dalelių nusėdimo greičių funkcija, priklausanti nuo vandens temperatūros.

Nauji aspektai, kurie yra nagrinėjami šiame darbe, yra: 1) erozijos ir akumuliacijos zonų išskyrimas, remiantis matematiniu modeliu; 2) ledo dangos ir audrų įtakos nuosėdų pernašai įvertinimas; 3) resuspensijos analizė, tiriant sumodeliuotus morfologinius dugno pokyčius; 4) klimato kaitos scenarijų modeliavimas, siekiant išsiaiškinti galimus sedimentacijos pokyčius Kuršių mariose.

Rezultatų mokslinė ir praktinė reikšmė

Sukurta dalelių nusėdimo greičio formulė leido pritaikyti nuosėdų pernašos modelį Kuršių marioms ir sukurti vertingą įrankį tolimesnei nuosėdų dinamikos analizei Kuršių mariose, Baltijos jūros pietrytinėje dalyje ir kitose panašiose aplinkose. Šio tyrimo rezultatai pateikia išsamią marių hidrodinaminių ir nuosėdų pernašos mechanizmų apžvalgą laike ir erdvėje. Modelio rezultatai parodė svarbų Nemuno upės vaidmenį ir ledo dangos įtaką sedimentacijos procesams. Nustatyta, kad organinė medžiaga vaidina svarbų vaidmenį Kuršių marių sistemoje, ko nebuvo pastebėta Venecijos lagūnoje.

Nuosėdų pernašos modelyje nagrinėjamos tiek lipnios (dalelių dydis <63 µm), tiek birios nuosėdos (dalelių dydis >63 µm). Modelis gali būti pritaikomas įvairiems tyrimams: išanalizuoti resuspensijos dažnumą, įvertinti dugnu pernešamų dalelių dalį, apskaičiuoti vandens drumstumą, kuris gali padėti markofitų tyrimams ar atlikti dalelių pernašos modeliavimą, galintį prisidėti prie mikrobiologinės taršos tyrimų. Klimato kaitos scenarijai gali būti naudojami rengiant plėtros planus marių regione, tačiau norint modelį pritaikyti Klaipėdos uosto tyrimams, reiktų atlikti papildomą modelio kalibravimą ir patikrą, naudojant smulkesnę modelio gardelę, galinčią detaliau aprašyti procesus sistemoje, susiduriančioje su gamtine ir antropogenine apkrova.

Rezultatų aprobavimas

Šio darbo rezultatai buvo pristatyti 7 tarptautinėse ir 4 nacionalinėse konferencijose:

8-oji mokslinė-praktinė konferencija „Jūros tyrimai bei technologijos – 2014“, Klaipėda, Lietuva, 2014 m. balandis;

12-oji tarptautinė konferencija „Littoral 2014“, Klaipėda, Lietuva, 2014 m. rugsėjis;

10-asis Baltijos jūros mokslų kongresas, Ryga, Latvija, 2015 m. birželis;

9-oji mokslinė-praktinė konferencija „Jūros ir krantų tyrimai – 2016“, Klaipėda, Lietuva, 2016 m. balandis;

10-oji mokslinė-praktinė konferencija „Jūros ir krantų tyrimai – 2017“, Klaipėda, Lietuva, 2017 m. balandis;

8-asis „EuroLag“ Europos pakrančių lagūnų simpoziumas, Atėnai, Graikija, 2018 m. kovas;

11-oji mokslinė-praktinė konferencija „Jūros ir krantų tyrimai – 2018“, Klaipėda, Lietuva, 2018 m. gegužė;

7-asis IEEE/OES Baltijos šalių švarios ir saugios Baltijos jūros simpoziumas ir energetinis saugumas Baltijos šalims, Klaipėda, Lietuva, 2018 m. birželis;

11-oji tarptautinė „SedNet“ konferencija, Dubrovnikas, Kroatija, 2019 m. balandis;

12-asis Baltijos jūros mokslo kongresas Stokholme, Švedijoje, 2019 m. rugpjūtis;

15-oji tarptautinė konferencija apie lipnių nuosėdų transportavimo procesus „INTERCOH“, Stambulas, Turkija, 2019 m. spalis.

Šios disertacijos rezultatai buvo paskelbti mokslinėse publikacijose:

Mėžinė, J., Zemlys, P., Gulbinskas S., 2013. A coupled model of wave-driven erosion for the Palanga Beach, Lithuania. *Baltica*, 26 (2) 169-176. Vilnius. ISSN 0067–3064. doi:10.5200/baltica.2013.26.17

Umgiesser, G., Zemlys, P., Erturk, A., Razinkovas-Baziukas, A., **Mėžinė, J.,** and Ferrarin, C. 2016. Seasonal renewal time variability in the Curonian Lagoon caused by atmospheric and hydrographical forcing. *Ocean Science*, 12, 2043–2072. doi:10.5194/os-12-391-2016

Mėžinė, J., Ferrarin, C., Vaičiūtė, D., Idzelytė, R., Zemlys, P. and Umgiesser, G. 2019. Sediment transport mechanisms in a lagoon with high river discharge and sediment loading. Water, 10(11), 1970. doi: 10.3390/w11101970

Disertacijos struktūra

Disertaciją sudaro šie skyriai: Įvadas, Literatūros apžvalga, Medžiaga ir metodai, Rezultatai, Diskusija, Išvados, Literatūros sąrašas. Disertacijos apimtis – 83 puslapiai. Disertacijoje panaudoti 144 literatūros šaltiniai. Disertacija parašyta anglų kalba. Joje yra 6 lentelės ir 35 paveikslai.

Padėka

Padėkos žodį norėčiau pradėti nuo didelio ačiū Sergejui Oleninui, kuris patikėjo manim ir atvedė į institutą, kuris supažindino mane su Petru Zemliu ir davė pradžią mano ilgam keliui Klaipėdos universitete nuo bakalauro baigiamojo darbo iki daktaro disertacijos.

Mano pati didžiausia padėka yra skirta mano vadovui Georgui Umgiesseriui. Aš vis dar negaliu patikėti, kad ši disertacija pabaigta. Sunku žodžiais apsakyti, kaip aš esu dėkinga už palaikymą, motyvaciją, pagalbą, greitus atsakymus ir naktis, praleistas narpliojant mano problemas ar skaitant mano rašinius. Ačiū už tai, kad tikėjote manim ir parodėte modeliavimo grožį. Norčiau labai padėkoti savo konsultantui Christianui Ferrarinui už neįkainojamą pagalbą. Ačiū už skirtą laiką ir pagalbą, kai buvau pasiklydus modeliavimo labirintuose, už visus profesionalius ir turiningus atsakymus į milžinišką kiekį mano turėtų klausimų. Noriu jums abiem padėkoti už šiltą ir malonų priėmimą Venecijoje.

Savo padėką noriu išreikšti a.a. Sauliui Gulbinskui už pagalbą, palaikymą ir pasidalinimą savo ekspertinėmis žiniomis.

Labai ačiū Petrui Zemliui, kad skyrėte man laiko ir pasidalinote vertingais patarimais tiek profesinėje, tiek asmeninėje srityje. Ačiū už jūsų kantrybę ir nukreipimus reikiama linkme. Taip pat noriu padėkoti Ali, ypač už motyvaciją ir palaikymą praėjusiais metais, kai to labiausiai reikėjo.

Noriu išreikšti gražiausius žodžius geriausiems recenzentams, kuriuos galėjau turėti. Didžiausia padėka skirta Carl Amos už didžiulį darbą, vertingą kritiką ir komentarus, leidusius disertaciją pakelti į aukštesnį lygį. Dar didesnis ačiū Nerijui Blažauskui, kuris leido patikėti, kad disertacija parašyta puikiai.

Noriu padėkoti visiems doktorantūros komiteto nariams už visas pastabas ir patarimus doktorantūros studijų metu. Mano išskirtinė padėka Eglutei už ypač malonią pagalbą ir ramybę.

Ypač esu dėkinga Mindaugui Žiliui, Jolitai Petkuvienei ir Irmai Vybernaitei-Lubienei už pagalbą renkant mėginius ir atliekant laboratorinius darbus. Nuoširdus ačiū mano „doktorantūros sesei“ Nataljai už visas mokslines įžvalgas, visus juokelius ir pamąstymus.

Mano mergytės, Irmute, Jolita, Marija, Dinute ir Aušryte, esu be galo dėkinga už jūsų palaikymą, už visus gražius jūsų pasakytus žodžius, už visą laiką, kurį praleidome kartu, už visas mokslines ir nebūtinai mokslines diskusijas, už visas idėjas ir visus patarimus, kuriuos man davėte. Ačiū už jūsų laiką, tai neįkainojama.

Taip pat esu dėkinga kolegoms Rasai Morkūnei, Sergėjui Suzdalevui, Nerijui Nikai, Viačeslavui Jurkinui, Arūnui Balčiūnui, Jūratei Lesutienei, Evelinai Grinienei ir Juliui Morkūnui už jūsų draugystę ir pasiūlymus problemų sprendimams. Taip pat norėčiau padėkoti doktorantams Donaldai, Tomai, Tobia, Soukainai ir Karolinai už šypsenas ir draugystę.

Nesu tas žmogus, kuriam labai patinka rašyti, tačiau norėčiau pasinaudoti proga ir padėkoti visiems instituto žmonėms, kurie palaikė mane ir niekada neatsisakė padėti ruošiant šį baigiamąjį darbą.

Mano paskutiniai padėkos žodžiai skirti šeimai. Šilčiausi žodžiai ir ypatinga padėka vyrui Tadui ir dukrytei Godai. Dėkoju už jūsų kantrybę, už galimybę įgyvendinti savo svajonę ir palaikymą sunkiausiomis akimirkomis. Esu ypač dėkinga savo tėvams, kurie apgaubė mane meile ir rūpesčiu. Be jūsų aš niekada nebūčiau įveikusi šio kelio.

Šis tyrimas – Klaipėdos universiteto Ekologijos ir aplinkos mokslų doktorantūros studijų programos dalis. Dalis tyrimo buvo finansuojama iš Europos socialinio fondo pagal Visuotinės dotacijos priemonę (CISOCUR projektas VP1-3.1-ŠMM-07-K-02-086) ir („EcoServe“ projektas Nr. 09.3.3-LMT-K-712-01-0178). pagal dotacijos sutartį su Lietuvos mokslo taryba (LMTLT). Šis tyrimas iš dalies finansuotas Lietuvos Aplinkos Apsaugos Agentūros projekto metu (Nr. 28TP-2015-19SUT-15P-13) ir Pietų Baltijos programos ECODUMP projekto.

TYRIMŲ MEDŽIAGA IR METODAI

Tyrimų rajonas

Kuršių marios yra didžiausia Europos lagūna (1584 km^2), pasižyminti sudėtinga vandens masių cirkuliacija, veikiama Nemuno upės nuotėkio, vėjo ir jūrinio vandens pritekėjimo iš Baltijos jūros (Pav. 1). Tai gana sekli sistema, kurioje vidutinis gylis yra 3,8 m (Žaromskis, 1996). Kuršių marių hidrologinis režimas stipriai priklauso nuo upėmis atnešamo vandens kiekio. Pagrindinės į marias įtekančios upės yra Nemunas, Minija, Deima ir Danė. Dažniausiai marių vandens lygis yra aukštesnis nei Baltijos jūros, todėl vyrauja vandens ištekėjimas iš marių (Zemlys ir kt., 2013). Remiantis

Trimonio ir kt. (2003) studija, Kuršių marių šiaurinėje dalyje pagrindinę dugno paviršiaus dalį užima vidutinio smulkumo (0,5–0,25 mm), smulkus smėlis(0,25–0,1 mm), stambus aleuritas (0,1–0,05 mm) ir smulkus aleuritas (0,05–0,01 mm), o pietinėje dalyje vyrauja aleuritingos ir dumblingos nuosėdos (Gelumbauskaite ir kt., 1999). Tačiau patys nuosėdų pernašos mechanizmai mariose yra mažai nagrinėti.

Matematinis modelis SHYFEM

Tyrime buvo naudojama modeliavimo sistema SHYFEM (http://www.ismar.cnr.it/shyfem), kurią sudaro baigtinių elementų trimatis hidrodinaminis, pernašos ir difuzijos, parametrinis bangų, nuosėdų pernašos ir dugno modeliai. Hidrodinaminių lygčių skaitiniam sprendimui yra naudojamas baigtinių elementų metodas, kuris leidžia naudoti teritoriškai kintamos raiškos gardeles. Detalesnį modelio aprašymą galima rasti (Umgiesser et al. 2004) bei (Zemlys et al. 2013).

Nuosėdų pernašos modelis skaičiuoja srovių arba bangų sukeltą nuosėdų pernašą tiek lipnioms (angl. *cohesive*), tiek birioms (angl. *non-cohesive*) nuosėdoms. Svarbu paminėti, kad modeliuojamos yra tik neorganinės nuosėdos (smėlis, aleuritas, molis). Modelio branduolį sudaro SHYFEM adaptuotas nuosėdų pernašos modelis SEDTRANS05 (Neumeier ir kt., 2008). SEDTRANS05 turi penkias dugnu pernešamų dalelių skaičiavimo formules, kurias galima pasirinkti. Šiam tyrimui buvo pasirinkta van Rijn'o (1993) dugno nuosėdų pernašos formulė.

Tyrimui buvo naudojama trimatė modelio versija. Modelio skaičiavimo gardelę sudarė 3269 elementai ir 2021 mazgai, vertikaliai išskirti 5 sigma sluoksniai (3 pav.). Gardelės rezoliucija kito nuo 250 m Klaipėdos sąsiauryje iki 3 km Baltijos jūroje ir pietinėje Kuršių marių dalyje. Tai palyginti stambi gardelė su smulkesniais elementais hidrodinamiškai aktyviose vietose.

Duomenys

Modelio sudarymui buvo naudoti šie duomenys:

1. Atviros jūros kraštinių sąlygų duomenys (druskingumo, temperatūros ir vandens lygio) buvo gauti iš MIKE21 (DHI) hidrodinaminio modelio (laikotarpiui 2004–2006 m.), operacinio Baltijos jūros modelio HIROMB (SMHI) (2007–2009 m.), Vokietijos Leibnico Baltijos jūros tyrimų instituto, Varnemundėje modelio MOM (2010–2015 m.).
2. Meteorologiniai duomenys (kritulių, saulės radiacijos, oro temperatūros, drėgnumo, debesuotumo, vėjo greičio ir atmosferos slėgio) gauti iš ECMWF modelio (2004–2008 ir 2011–2013 m.) ir HIRLAM modelio (2009–2010 m.).

3. Upių nuotėkio duomenys gauti iš Lietuvos hidrometeorologinės tarnybos. Nemuno upės debitai modelio kraštinei sąlygai buvo perskaičiuojami prie Smalininkų poste matuotų debitų pridedant matuotus Šešupės, Jūros, Šešuvio upių debitus ir atimant Gilijos upės debitą (29% nuo Nemuno debito) (Jakimavičius, 2012). Laikas buvo perskaičiuojamas pagal Maningo (angl. Manning) formulę (Chen, 1992).
4. Satelitiniai ledo duomenys gauti iš sintetinės apertūros radaro matavimų iš trijų žemės stebėjimo misijų (Idzelytė ir kt., 2019).
5. Dugno nuosėdų duomenys surinkti iš Gelumbauskaitės ir kt. (1999) ir Gulbinsko ir Žaromskio (2002) žemėlapių.
6. Buvo pasirinkti du klimato kaitos scenarijai: RCP4.5 ir RCP8.5 (Collins, 2013). Meteorologiniai klimato kaitos duomenys pasirinktiems scenarijams surinkti iš sumažinto ICHEC modelio, kuris remiasi globaliu EC-Earth klimato modeliu. Kraštinių sąlygų duomenys scenarijams gauti iš SMHI modelių.

Maistingųjų medžiagų koncentracijų dugno nuosėdose duomenys surinkti iš KU biogeochemijos grupės atliktų analizių.

Nuosėdų pernašos modelio kalibravimui buvo naudojami 2014–2015 metų nešmenų koncentracijų duomenys, surinkti šio tyrimo metu pagal metodiką, pristatytą 5 paveiksle, ir iš papildomų šaltinių, besiremiančių ta pačia metodika. Taip pat papildomai surinkti 2016 metų nešmenų koncentracijų duomenys modelio patikrai.

Modelio kalibravimo ir patikros metodai

Kalibruojant nuosėdų pernašos modelį ir atliekant jo patikrą, buvo apskaičiuotas santykinis sumodeliuotų (M) reikšmių nuokrypis nuo išmatuotų reikšmių (I). Jeigu daugiau nei pusė (50%) santykinio nuokrypio (angl. *discrepancies ratio*) reikšmių patenka į intervalą $0,5 < M/I < 2$, yra laikoma, kad modelis gerai aprašo nuosėdų pernašos procesus. Santykis $M/I=1$ rodo idealų sumodeliuotų ir išmatuotų reikšmių atitikimą.

Hidrodinaminio modelio patikros metu sumodeliuotos reikšmės buvo lyginamos su išmatuotomis. Modelio kokybei nustatyti buvo apskaičiuoti koreliacijos koeficientai (R), determinacijos koeficientai (R^2) ir vidutinė kvadratinė vidurkio paklaida (RMSE).

Modelis buvo kalibruojamas dviejose stotyse: gilesnė S1 stotis netoli Nidos, kur vyrauja dumblingos, lipnios nuosėdos, ir seklesnė S2 stotis šiaurinėje centrinėje marių dalyje su vyraujančiomis smėlingomis, biriomis nuosėdomis (1 pav., 4 lentelė)

REZULTATAI

Rezultatai pristatyti 4 skyriuose: 1) Surinktų suspenduotos medžiagos duomenų analizė; 2) Modelių kalibravimas ir patikra; 3) Esamos situacijos skaičiavimai (2004–2016) ir 4) Klimato kaitos scenarijai ir sedimentacijos mechanizmų pokyčių prognozės.

Pirmame skyriuje pateikti *in situ* matavimų rezultatai Nemuno upėje (Rusnėje) ir dviejose Kuršių marių stotyse. Remiantis Nemuno upėje išmatuotomis nešmenų koncentracijomis buvo sukurta Nemuno upės nešmenų įverčio kreivė (Pav. 8), pritaikyta kiekvienos dienos atnešamų dalelių koncentracijų apskaičiavimui, reikalingų modelio upės kraštinei sąlygai sudaryti. Nešmenų įverčio kreivė leidžia apskaičiuoti nešmenų koncentraciją priklausomai nuo upės debito. Gautas tvirtas ryšys tarp Nemuno upės debito ir nešmenų koncentracijų (R^2=0,67). Taip pat buvo analizuojamos Kuršių marių nešmenų koncentracijos dviejose modelio kalibravimo stotyse (S1 ir S2). Nustatyta, kad vasaros sezono metu dalelių koncentracija mariose yra didesnė nei šaltuoju sezonu.

Antrame skyriuje pristatomi hidrodinaminio modelio patikros ir nuosėdų modelio kalibravimo ir patikros rezultatai. Hidrodinaminio modelio patikros metu buvo tikrinamos keliose tyrimų stotyse (Pav. 3C) išmatuotos ir sumodeliuotos druskingumo, vandens temperatūros, vandens lygio ir bangų aukščio reikšmės. Koreliacijų koeficientai ir vidutinės kvadratinės vidurio paklaidos yra pristatytos 5 lentelėje.

Nuosėdų pernašos modelio kalibravimo metu buvo tikslinamos modelio parametrų reikšmės. Pagal nutylėjimą nuosėdų pernašos modelis naudoja parametrų reikšmes, kurios buvo sukalibruotos Venecijos lagūnai. Taikant modelį Kuršių marioms buvo pakeista pradinė kritinio dugno įtempimo reikšmė, apskaičiuota remiantis Amos ir kt. (2004) pateikta kritinio dugno įtempimo reikšmių skaičiavimo formule pagal išmatuotą dugno nuosėdų tankį. Parinkta reikšmė ir nustatytas 775 kg m^{-3} naujai nusėdusių nuosėdų tankis.

Nuosėdų pernašos modelio kalibravimo metu nustatyta, kad Venecijos lagūnoje ir Kuršių mariose skiriasi nešmenų nusėdimo principai. Bukavecko ir kt. (2019) studijoje pateikti kur kas mažesni dalelių nusėdimo greičiai intensyvių melsvabakterių „žydėjimų" vasaros sezono metu nei buvo sumodeliuoti, todėl į modelį buvo inkorporuota nauja nešmenų nusėdimo formulė, sumažinanti dalelių nusėdimo greitį esant vandens temperatūrai, aukštesnei nei 8°C. Tai siejama su galimu neorganinių dalelių užlaikymu vandens paviršiuje esant dideliam melsvabakterių kiekiui. Modelis neturi galimybės modeliuoti organinės medžiagos ciklų, todėl priklausomybė buvo išvesta atsižvelgiant į vandens temperatūrą, prieš tai išanalizavus Chl-*a* koncentracijų pokyčius kintant temperatūrai.

Modelio kalibravimas (2014–2015 m.) ir patikra (2016 m.) buvo atlikti lyginant sumodeliuotas ir išmatuotas suspenduotų neorganinių dalelių koncentracijas (kg m^{-3}) dviejose skirtingų sedimentacinių sąlygų stotyse – S1 ir S2. Rezultatai parodė, kad nuosėdų pernašos modelis šie tiek sumažina suspenduotų dalelių koncentracijas, tačiau didesnė dalis patenka į dvigubo santykinio pasikliovimo intervalą, todėl yra laikoma, kad nuosėdų pernašos modelis yra gerai sukalibruotas ir gali būti taikomas Kuršių marių nuosėdų dinamikos tyrimams.

Trečiame skyriuje pristatomi hidrodinaminio ir nuosėdų pernašos modelio rezultatai. Išnagrinėti sezoniniai srovių, druskingumo, vandens temperatūros ir bangų aukščių dėsningumai. Remiantis ilgalaikiais modelio skaičiavimo rezultatais (2004–2016), nustatyta, kad daugiausia druskėto vandens įsiveržimų būna rudens sezonu, o maksimalių druskingumo reikšmių analizė parodė, kad druskėtas Baltijos jūros vanduo gali patekti net iki centrinės Kuršių marių dalies nepriklausomai nuo sezono. Kuršių marių vidutinė vandens temperatūra žiemos sezonu yra 1,7±0,6°C, pavasario – 7,4±1,4°C, vasaros – 19,5±1,8°C ir rudens sezonu – 10,8±0,8°C. Sumodeliuotų bangų aukščių analizė parodė, kad rudens sezonu bangų aukščiai yra didžiausi.

Nagrinėjant nuosėdų pernašos modelio rezultatus buvo sudaryti sezoniniai nešmenų koncentracijų, dugnu pernešamų dalelių ir dugno šlyties įtempimo žemėlapiai. Dugno šlyties įtempimo žemėlapiai aiškiai rodo aukštesnes reikšmes hidrodinamiškai aktyviose vietose. Didžiausios reikšmės matomos rudens sezono metu dėl srovių ir bangų poveikio. Apskaičiuotos vidutinės nešmenų koncentracijos parodė aukštas koncentracijas vasaros ir rudens sezonais (atitinkamai 19±18 mg l^{-1} ir 19±15 mg l^{-1}) ir gerokai mažesnes žiemos ir pavasario sezonais (3±1 mg l^{-1} ir 6±6 mg l^{-1}). Viena pagrindinių priežasčių, lemiančių aukštas nuosėdų koncentracijas vandens storymėje šiltuoju sezonu yra dalelių nusėdimo greičio sumažėjimas dėl melsvabakterių „žydėjimo“. Pavasario sezono metu nešmenų koncentracijos Kuršių mariose yra labai netolygiai pasiskirsčiusios. Didžiausios koncentracijos buvo Nemuno deltoje (23±10 mg l^{-1}), o vyraujanti nuosėdų pernašos kryptis iš Nemuno upės link Baltijos jūros nulėmė dvigubai didesnę nei vidutinė koncentraciją šiaurinėje marių dalyje (12±6 mg l^{-1}).

Nuosėdų pernašos modelis leidžia aprašyti zonas, kuriose dalelių transportas vyksta dugnu. Tai svarbu analizuojant smėlio dalelių pernašą. Aiškiai matoma, kad pernaša dugnu vyksta tik Nemuno avandeltoje ir šiaurinėje marių dalyje, kur vyrauja smėlingos nuosėdos. Sezoniniai žemėlapiai parodė, kad dugnu velkamų nuosėdų zonos yra didžiausios žiemos ir rudens sezonais.

Erozijos akumuliacijos greičių analizė parodė vidutinį 0,5 mm per metus akumuliacijos greitį. Didžiausi akumuliacijos greičiai buvo apskaičiuoti Klaipėdos sąsiaurio pietinėje dalyje ir Nemuno avandeltoje (7 mm per metus). Buvo išskirtos trys pagrindinės akumuliacijos zonos: Nemuno avandeltoje, pietinėje Kuršių marių ir pietinėje Klaipėdos sąsiaurio dalyse (Pav. 23).

Taip pat buvo apskaičiuotas nuosėdų balansas. Teigiamas balanso dalis sudarė suma nuosėdų, atnešamų upėmis ir patenkančių iš jūros į marias. Neigiama balanso komponentė nukreipta iš marių į jūrą. Apskaičiuota, kad vidutiniškai per metus iš upių ir jūros atnešama $484{,}4 \cdot 10^6 \pm 378{,}0 \cdot 10^6$ kg suspenduotos medžiagos, o išnešamą į jūrą $185{,}8 \cdot 10^6 \pm 178{,}2 \cdot 10^6$ kg. Nustatyta, kad vidutiniškai Kuršių mariose yra sulaikoma apie 62% upėmis atneštų nuosėdų.

Trečiame skyriuje analizuojami ir trumpalaikių (2013–2015) modelio skaičiavimų rezultatai. Pristatoma ledo įtaka nuosėdų dinamikai Kuršių mariose (Pav. 26). Tyrimo metu buvo lyginami du scenarijai. Pirmasis – esamos situacijos su realiais duomenis, o antrasis atkartoja pirmąjį, tik nėra įvedama ledo dangos duomenų. Scenarijaus be ledo dangos rezultatai parodė, kad suspenduotų dalelių koncentracija reikšmingai padidėja (>10 mg l^{-1}) pučiant stipresniam nei 10 m s^{-1} vėjui S1 stotyje ir stipresniam nei 6 m s^{-1} S2 stotyje. Trumpalaikio skaičiavimo rezultatai taip pat buvo panaudoti išanalizuoti audrų įtaką Kuršių marių nuosėdų dinamikai. Nagrinėti 2013 m. gruodžio 6 dienos audros padariniai, parodė, kad per trumpą laiką gali būti išplauti dideli nuosėdų kiekiai ($4{,}7\cdot10^6$ kg). Apskaičiavus dienos vidutinį nuosėdų kiekį, patenkantį į sistemą ($0{,}110\cdot10^6 \pm 0{,}086\cdot10^6$ kg per dieną), nustatyta, kad apytiksliai reikia 42 dienų, kad atnešama medžiaga padengtų audros sukeltą nuosėdų nuostolį.

Kitas šio tyrimo uždavinys buvo įvertinti resuspensijos įtaką ekologiniams procesams, remiantis matematinio modelio rezultatais. Šiam tikslui pasiekti buvo nagrinėjami sumodeliuoti 2008–2016 metų dugno morfologiniai pokyčiai S1 stotyje (Pav. 31). Buvo analizuojamos tik sezono maksimalios paros erozijos reikšmės. Apskaičiuoti maistingųjų medžiagų sezoniniai srautai pristatyti 6 lentelėje.

Nuosėdų pernašos mechanizmų pokyčiai dėl klimato kaitos buvo modeliuojami remiantis RCP4.5 ir RCP8.5 klimato kaitos scenarijais (Collins, 2013). Klimato kaitos scenarijų skaičiavimai apėmė laikotarpį nuo 2007 iki 2033 metų. 2007–2015 m. laikotarpis buvo skirtas palyginti pradinio (esamos situacijos) modelio scenarijaus rezultatus su klimato kaitos scenarijaus rezultatais. Nustatyta, kad SMHI sugeneruoti klimato kaitos scenarijų Nemuno upės debitai yra reikšmingai didesni nei realūs išmatuoti duomenys 2007–2015 m., todėl būtina turėti omenyje, kad klimato kaitos scenarijai perviršija atnešamos medžiagos kiekius.

Remiantis klimato kaitos scenarijais galima išskirti pagrindines ateities tendencijas. Pagal RCP4.5 scenarijų Kuršių mariose vidutinis akumuliacijos greitis butų 1,3 mm per metus, o vidutinės metinės koncentracijos padidėtų nuo 20,2 mg l^{-1} iki 33,5 mg l^{-1}. Pagal RCP8.5 scenarijų Kuršių mariose vidutinis akumuliacijos greitis butų 2,6 mm per metus, o vidutinės metinės koncentracijos padidėtų iki 5,6 mg l^{-1}.

DISKUSIJA

Diskusiją sudaro vienuolika skyrių: 1) Nemuno upės nešmenų įverčio kreivės svarba; 2) Melsvabakterių įtaka nusėdimo greičiams; 3) Modelio kalibravimo ir patikros rezultatų įvertinimas; 4) Kuršių marių hidrodinamika; 5) Faktoriai kontroliuojantys suspenduotos medžiagos koncentraciją; 6) Erozijos–akumuliacijos zonos Kuršių mariose; 7) Nuosėdų balanso skaičiavimai, remiantis modelio rezultatais; 8) Resuspensijos įtaka marių ekologijai 9) Sedimentacijos mariose ateities trendai; 10) Nuosėdų pernašos modelis: privalumai ir apribojimai ir 11) Spragos ir ateities perspektyvos.

Pirmame skyriuje aptariama nešmenų įverčio kreivės sudarymo metodika ir jos svarba modelio kraštinėms sąlygoms. Nešmenų įverčio kreivė sudaryta remiantis 2015 m. matavimo duomenimis, apimančiais visus sezonus ir potvynio laikotarpį. Kadangi matuotų duomenų yra mažai, tai buvo vienintelė priemonė, kuri leido sugeneruoti atnešamos medžiagos koncentracijas visam modeliavimo laikotarpiui.

Antrame skyriuje aptariama organinės medžiagos įtaka nuosėdų procesams Kuršių mariose. Remiantis Bukavecko ir kt. (2019) studija, teigiama, kad dideli organinės medžiagos kiekiai vasaros sezono metu, turi didelę įtaką nešmenų nusėdimo greičiams, todėl į jau sukurtą nuosėdų pernašos modelį buvo būtina įtraukti naują dalelių nusėdimo formulę, sumažinančią nešmenų nusėdimo greičius didėjant vandens temperatūrai. Įvedus naują formulę, reikšmingai pasikeitė sumodeliuotų ir išmatuotų reikšmių santykiai. Po pataisymų į dvigubo santykinio pasikliovimo intervalą pateko 40% S1 stotyje (prieš tai pateko 12,5%) ir 60% (15%) S2 stotyje sumodeliuotų reikšmių. Tai pagrindinis rodiklis, kuris aprašė naujos formulės svarbą ir poreikį. Tęsiant tyrimus ateityje, būtina atlikti detalesnius tyrimus, galinčius įvertinti organinės medžiagos, ypač melsvabakterių, įtaką nešmenų nusėdimui Kuršių mariose. Tai leistų išsikelti naują tikslą: tobulinant matematinį modelį, įtraukti melsvabakteres į modelį kaip faktorių, kontroliuojantį nešmenų nusėdimą.

Trečiame skyriuje aptariami nuosėdų pernašos modelio kalibravimo ir patikros rezultatai. S1 stotyje modelis gerai aprašė tik 40% išmatuotų reikšmių, tačiau S2 stotyje ir modelio patikros metu daugiau nei 50% reikšmių pakliuvo į dvigubo santykinio pasikliovimo intervalą, todėl teigiama, kad modelis sukalibruotas tinkamai. Taip pat paaiškinama, kad neatitikimus S1 stotyje gali lemti nuosėdos, į sistemą patenkančios dėl eolinių procesų, į kuriuos modelis šiuo metu neturi galimybės atsižvelgti.

Ketvirtame ir penktame skyriuose yra aptariami faktoriai, kontroliuojantys nešmenų mechanizmus. Analizuojami tokie faktoriai kaip srovės, vandens temperatūra, bangos, Nemuno upės įtaka, ledo dangos ir audrų įtaka. Ilgalaikių skaičiavimų duomenys parodė, kad pagrindinis veiksnys, kontroliuojantis nuosėdų pernašos kryptis mariose, yra Nemuno upė, kai tuo tarpu nešmenų koncentracija vandens storymėje kontroliuoja ir vandens temperatūra. Vasaros sezono metu daugiau medžiagos yra sulaikoma vandenyje dėl aukštų vandens temperatūrų ir sulėtėjusio nešmenų nusėdimo.

Trumpalaikių skaičiavimų rezultatai parodė, kad ledo danga yra labai reikšminga nuosėdų pernašai žiemos sezonu. Ledo dangos įtraukimas į modelį leidžia išvengi labai aukštų koncentracijų žiemos metu, sukeliamų stipraus vėjo, todėl sumodeliuotos suspenduotų neorganinių dalelių koncentracijų reikšmės yra artimesnės išmatuotoms. Scenarijus be ledo dangos tai patvirtino ir parodė reikšmingai aukštesnes koncentracijas žiemos metu, kurias lemia vyraujantys stiprūs vėjai. Svarbu atkreipti dėmesį, kad klimato kaitos scenarijuose yra prognozuojamas dienų su ledo danga sumažėjimas arba išvis ledo dangos išnykimas dėl šylančio klimato (IPPC, 2014), todėl galima daryti prielaidą, kad ateityje Kuršių mariose nešmenų koncentracijos vandens storymėje didės. Analizuojant 2013 m. gruodžio 6 d. audros padarinius buvo apskaičiuoti dideli išplautų nuosėdų kiekiai. Klimato kaitos scenarijuose prognozuojamas didėjantis audrų skaičius per metus, todėl galima daryti prielaidą, kad ateityje didesnis kiekis nuosėdų bus išplautas, o sistemai nespėjus atstatyti nuosėdų nuostolio, šiuo metu vyraujančią akumuliaciją gali pakeisti nuosėdų erozijos procesai.

Šeštame skyriuje analizuojama nuosėdų erozijos ir akumuliacijos schema. Šio tyrimo rezultatai sutampa su ankščiau atliktų tyrimų rezultatais, kurie pietinę Kuršių marių dalį aprašo kaip akumuliacinę zoną (Ferrarin ir kt., 2008a, Gulbinskas, 1995). Analizuojant modelio apskaičiuotus vidutinius akumuliacijos greičius, pastebėta, kad jie apie 6 kartus mažesni nei išmatuoti Pustelnikovo (2008) studijoje. Tai galima pagrįsti tuo, kad ankstesnėje studijoje matavimai buvo atlikti dumblingose vietose netoli kranto, kuriose nemažą dalį nuosėdų sudaro organinė medžiaga. Tuo tarpu matematinis nuosėdų pernašos modelis gali apskaičiuoti tiktai litogeninės kilmės nuosėdų akumuliacijąs, todėl gautos reikšmės yra mažesnės nei išmatuotos. Tačiau modelio apskaičiuoti akumuliacijos greičiai Nemuno avandeltoje sutampa su Mažeikos (2018, nepublikuoti duomenys) studija, kurioje vidutinis paskutinių penkerių metų akumuliacijos greitis yra apie 7,5 mm per metus.

Remiantis modelio apskaičiuotu vidutiniu akumuliacijos greičiu, prireiktų apie 8000 metų Kuršių marias užpildyti nuosėdomis. Tačiau reikia pabrėžti, kad tai tik teorinis skaičius, kuris keisis priklausomai nuo gamtinių ir antropogeninių faktorių. Visų pirma įtakos turės nevienodas akumuliacinių zonų pasiskirstymas, kuris lems srovių krypčių ir greičių pasikeitimus, paveiks nuosėdų sudėtį, atitinkamai gali pakeisti dugno šlyties įtempimo reikšmes ir kitus parametrus. Klimato kaita turės įtakos atnešamos medžiagos kiekiui, audrų pasikartojimui, ledo susidarymui ir kitiems procesams, kurie ateityje gali iš esmės pakeisti nuosėdų pernašos procesus Kuršių mariose.

Septintame skyriuje aptariamos nuosėdų balanso komponentės. Buvo nustatyta, kad Kuršių marios yra linkusios kaupti nuosėdas, tuo tarpu kitos Baltijos jūros lagūnos netenka nuosėdų (Aistmarių (Vistulos) lagūna) arba tiesiog jas perneša (Oderio lagūna) (Chubarenko ir Chubarenko, 2001; Leipe ir kt., 1998). Modeliu apskaičiuoti daugiamečiai atnešamos ir išnešamos medžiagos vidurkiniai kiekiai sutinka su ankstesnėmis Pustelnikovo (1998) bei Galkaus ir Jokšo (1997) studijomis. Priklausomai nuo upėmis atnešamos medžiagos kiekio, metinis balansas skyrėsi 5 kartus, lyginant vandeningus ir sausus metus.

Svarbu paminėti, kad nuosėdų pernašos modelyje kraštinė nešmenų koncentracijos sąlyga Baltijos jūroje buvo lygi 0 mg l^{-1}, tačiau tai neturėjo reikšmingos įtakos modelio skaičiavimų rezultatams. Sumodeliuoti vidutiniai metiniai iš jūros atnešamos medžiagos kiekiai ($14{,}0 \cdot 10^6 \pm 5{,}8 \cdot 10^6$ kg per metus) buvo panašūs į Pustenikovo ($7{,}2 \cdot 10^6$ kg per metus) (1998) bei Galkaus ir Jokšo ($15{,}6 \cdot 10^6$ kg per metus) (1997) išmatuotus kiekius.

Aštuntame skyriuje analizuojamas resuspensijos vaidmuo Kuršių marių ekosistemai. Remiantis kitų mokslininkų tyrimais, galima išskirti du pagrindinius modelių tipus resuspensijos įtakai tirti. Pirmasis yra panašus į šiame tyrime naudojamą modelį, tai hidrodinaminis modelis kartu su organinių ir neorganinių nuosėdų pernašos modeliu (Liu ir Huang, 2009), taikomas pakeltiems nuosėdų kiekiams apskaičiuoti. Antrasis – hidrodinaminis modelis kartu su ekologiniu modeliu (Capet ir kt., 2016; Smits ir kt., 2013). Antrasis modelių tipas pranašesnis, nes gali modeliuoti net tik pakeltų dalelių kiekį, bet ir biogeocheminius procesus.

Šiuo metu SHYFEM ekologinis modelis dar yra kuriamas, todėl vienas iš tyrimo uždavinių buvo pritaikyti SEDTRANS05 modelį resuspensijos įvertinimui. Šis metodas gali būti pritaikytas tik tose tyrimų vietose, kur maistingųjų medžiagų koncentracijos dugno nuosėdose yra žinomos ar išmatuotos. Taip pat reikia atlikti tarpinius skaičiavimus. Tyrimo metu yra analizuojami sumodeliuoti dugno pokyčiai ir esant erozijai, išplautas nuosėdų tūris yra padauginamas iš išmatuotos maistingųjų medžiagų koncentracijos poriniame vandenyje. Resuspensijos metu išsiskiriančių maistingųjų medžiagų srautai buvo palyginti su išmatuotais srautas dugno nuosėdų kolonėlėse (Žilius ir kt., 2018; Petkuvienė ir kt., 2016). Nustatyta, kad resuspensijos metu į vandens stulpą patenka daugiau fosfatų nei ištirpusio amonio ar silicio lyginant su maistingųjų medžiagų srautais, apskaičiuotais dugno nuosėdų kolonėlėje.

Devintame skyriuje aptariami nuosėdų pernašos mechanizmų pokyčiai dėl klimato kaitos. Atsirandantiems skirtumams nustatyti du klimato kaitos scenarijai (RCP4.5 ir RCP8.5) buvo lyginami su esamos situacijos (ilgalaikiai modelio skaičiavimai su ledo danga) rezultatais. Analizuojant nešmenų koncentracijas vandens storymėje S1 ir S2 stotyse, buvo nustatyta, kad vidutinės koncentracijos padidėja daugiau nei 1,6 kartus S1 stotyje ir 4,7 kartus S2 stotyje pagal RCP4.5 scenarijų. Pagal RCP8.5 scenarijų koncentracijos padidėja daugiau nei 2,9 kartus S1 ir 7,4 kartus S2 stotyse. Tokius didelius pokyčius lemia Nemuno upės kraštinės sąlygos, kurios buvo apskaičiuotos remiantis SMHI pateiktomis upių nuotėkio prognozėmis, o nuosėdų kiekis buvo apskaičiuotas pritaikius nešmenų įverčio kreivę, pristatytą pirmame rezultatų skyriuje. Abiejų scenarijų atnešamų nuosėdų kiekis buvo daugiau nei 30% didesnis nei esamos situacijos skaičiavimuose.

Didesnis upės debitas lėmė didesnius srovių greičius upės vagoje ir sukėlė didesnę eroziją. Dėl to dar daugiau nuosėdų buvo atnešta į Kuršių marių sistemą, kurios ir lėmė aukštas nešmenų koncentracijas tyrimo stotyse. Ypač S2 stotyje, kuri tiesiogiai priklausoma nuo Nemuno upe atnešto medžiagos kiekio. Kitas faktorius, turintis įtakos nešmenų užsilaikymui vandens storymėje, yra vandens temperatūra. Svarbu priminti, kad klimato kaitos scenarijai buvo skaičiuojami iki 2033 m., todėl nagrinėjant vandens temperatūros pokyčius didelių skirtumų tarp esamos ir būsimos situacijos nepastebima. Ilgalaikiai esamos situacijos skaičiavimai parodė, kad vidutiniškai buvo 187 dienos, kai marių temperatūra buvo aukštesnė nei 8°C. Nagrinėjant klimato kaitos scenarijų 2016–2033 m. periodą, pastebima, kad dienų skaičius, kai marių vandens temperatūra aukštesnė nei 8°C, didėja: 214 dienų pagal RCP4.5 ir 217 dienų pagal RCP8.5. 8°C yra riba, kai modelyje yra aktyvuojama nauja nešmenų nusėdimo formulė, todėl padidėjęs dienų skaičius taip pat turi įtakos aukštesnėms nešmenų koncentracijoms vandens storymėje. Ateityje ši formulė turėtų būti taikoma atsižvelgiant į klimato kaitos scenarijų poveikį melsvabakterių „žydėjimui“.

Tiek RCP4.5, tiek RCP8.5 scenarijai identifikavo tas pačias pagrindines akumuliacijos zonas Nemuno avandeltoje, pietinėje Kuršių marių ir pietinėje Klaipėdos sąsiaurio dalyse, kurios buvo išskirtos esamos situacijos skaičiavimuose. Vis dėlto, klimato kaitos scenarijai įveda labai daug neapibrėžtumų, todėl sumodeliuotos prognozės turi būti analizuojamos ir taikomos atsargiai.

Dešimtame skyriuje aptariami SEDTRANS05 modelio privalumai ir trūkumai. Vienas pagrindinių taikyto matematinio modelio privalumų yra tai, kad SHYFEM yra atviro kodo programa, prieinama kiekvienam. Kita, nuosėdų pernašos modelis kartu su hidrodinaminiu modeliu yra vertingas įrankis tiek buvusios, tiek esamos, tiek būsimos situacijos analizei ir vertinimui. Tačiau reikia atsižvelgti ir į tai, kad aukštos rezoliucijos modeliai reikalauja didelių skaičiavimo resursų ir didelių duomenų masyvų, kuriuos ne visada įmanoma gauti. Modelio kalibravimo ir patikros žingsniai yra labai jautrūs ir reikalauja patikimo *in situ* matavimų skaičiaus.

Vienuoliktame skyriuje sudėti akcentai ateities planams. Papildomi nuosėdų ir nešmenų tyrimai Kuršių mariose, Nemuno upėje ir laboratoriniai eksperimentai turi būti atlikti, siekiant praplėsti žinias apie dalelių elgseną vandenyje ir dugne. Ateityje spektrinių bangų modelis turėtų būti naudojamas bangų energijai modeliuoti. Taip pat norint efektyviau įvertinti resuspensijos įtaką marių ekologijai, reiktų naudoti SHYFEM/EUTRO (Umgiesser ir kt., 2003) arba SHYFEM/AQUABC (dar kuriamas) ekologinius modelius, galinčius aprašyti biogeocheminius procesus.

Artimiausiu metu yra planuojama atlikti ilgalaikius klimato kaitos scenarijų skaičiavimus iki 2100 metų, naudojant klimato kaitos modelių ansamblius.

IŠVADOS

1. Unikaliam nuosėdų dinamikos tyrimui Kuršių mariose buvo pritaikytas trimatis hidrodinaminis ir nuosėdų pernašos modelis. Remiantis *in situ* matavimais buvo sukurta nuosėdų įverčio kreivė, būtina apskaičiuoti nuosėdų prietaką iš Nemuno, kuri buvo naudojama kaip upės kraštinė sąlyga modelyje. Į nuosėdų pernašos modelį buvo inkorporuota nauja formulė, siejama su nuosėdų nusėdimo greičio sumažėjimu dėl melsvabakterių „žydėjimo“ vasaros ir rudens sezonais. Patikimi nuosėdų pernašos modelio kalibravimo ir patikros rezultatai (40–72% sumodeliuotų reikšmių pateko į dvigubo santykinio pasikliovimo intervalą) leido atlikti modelio skaičiavimus, siekiant ištirti erozijos–akumuliacijos zonas, nuosėdų biudžetą, ledo dangos įtaką nuosėdoms, audrų poveikį ir klimato kaitos poveikį nuosėdų transportui mariose (pagal RCP4.5 ir RCP8.5 scenarijus).

2. Ilgalaikiai modelio skaičiavimai (13 metų) parodė tris pagrindines akumuliacines zonas: 1) Nemuno avandeltoje, 2) pietinėje Kuršių marių dalyje ir 3) pietinėje Klaipėdos sąsiaurio dalyje. Apskaičiuotas vidutinis akumuliacijos greitis Kuršių mariose yra 0,5 mm per metus. Didžiausias akumuliacijos greitis buvo Nemuno avandeltoje (7 mm per metus), sutapantis su Mažeikos (2018, nepublikuoti duomenys) studijos rezultatais Nemuno avandeltoje. Apskaičiuotas vidutinis akumuliacijos greitis mariose buvo mažesnis nei paskelbtoje Pustelnikovo (2008) studijoje. Šiems skirtumams įtakos gali turėti tai, kad nuosėdų modelis neatsižvelgia į organinės medžiagos kiekį ir buvimą nuosėdose.
3. Nuosėdų balanso dedamųjų skaičiavimas parodė, kad Kuršių marios sulaiko apie 62% upėmis atneštos nuosėdinės medžiagos. Nemunas yra pagrindinis veiksnys, kontroliuojantis nuosėdų įnešimą ir išnešimą iš sistemos. Vidutiniškai per metus iš upių ir jūros atneša $484,4 \cdot 10^6 \pm 378,0 \cdot 10^6$ kg suspenduotos medžiagos, išnešama į jūrą $185,8 \cdot 10^6 \pm 178,2 \cdot 10^6$ kg. Scenarijaus be ledo dangos rezultatai parodė, kad suspenduotų dalelių koncentracija reikšmingai padidėja (>10 mg l^{-1}) pučiant stipresniam nei >10 m s^{-1} vėjui S1 stotyje ir >6 m s^{-1} S2 stotyje. 2013 m. gruodžio 6 d. audros padarinių analizė parodė, kad per labai trumpą laiką gali būti išnešta apie $4,7 \cdot 10^6$ kg nuosėdų, o tai pareikalautų vidutiniškai 42 dienų, kad upėmis atneštų nuosėdų kiekis atstatytų nuosėdų nuostolį.
4. Nuosėdų pernašos modelio rezultatai parodė, kad esant stipriam vėjui (>11 m s^{-1}) gali būti resuspenduota daugiau nei 1 mm dumblingų nuosėdų. Vienoje tyrimų stotyje (šalia Nidos) nustatyta, kad dėl resuspensijos į vandens stulpą išsiskiria daugiau fosfatų nei ištirpusio amonio ar silicio lyginant su maistingųjų medžiagų srautais, apskaičiuotais dugno nuosėdų kolonėlėje. Tačiau, norint detaliau išnagrinėti resuspensijos ypatybes, reikia išanalizuoti organinės medžiagos ir bentoso įtaką resuspensijai bei išnagrinėti trumpalaikius dugno pokyčius (1 val. ar trumpesnius).
5. Dviejų klimato kaitos scenarijų projekcijos turėjo padidėjusius upėmis atnešamų suspenduotų medžiagų kiekius, tačiau jie atkartojo esamas akumuliacines zonas su 2,5 karto pagal RCP4.5 scenarijų ir 5 kartais didesnėmis reikšmėmis pagal RCP8.5. Tikėtina, kad didžiausi pokyčiai atsiras žiemos sezono metu dėl sumažėjusio dienų skaičiaus su ledo danga ir dažnesnių audrų, taip pat dėl kylančios vandens temperatūros, kuri gali turėti įtakos melsvabakterių „žydėjimo“ intensyvumui ir padidinti suspenduotų dalelių kiekį ir vandens drumstumą.
6. Šio tyrimo metu sukurtas vertingas įrankis, gebantis atsakyti į klausimus apie nuosėdų pernašos mechanizmus Kuršių mariose neatliekant matavimų visame baseine. Ateityje numatoma sujungti esamą nuosėdų pernašos modelį su kranto linijos kaitos modeliu ar ekologiniu modeliu, siekiant sukurti įrankį detaliems Baltijos jūros ir tranzitinių sistemų tyrimams. Ateityje taip pat būtina atlikti papildomus *in situ* matavimus ir laboratorinius tyrimus, siekiant geriau suvokti fizinius procesus sistemoje.

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