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A SCENARIO ANALYSIS OF SOCIO-ECONOMIC AND CLIMATE RELATED CHANGES IN NUTRIENT LOAD AND RETENTION FOR THE PREGOLYA RIVER CATCHMENT (SOUTH-EASTERN BALTIC): THE VIEW AT THE BEGINNING OF 21ST CENTURY

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Abstract

The study analysed the transboundary Pregolya River Catchment, covering both the Polish and Russian parts, using the HYPE hydrological module and FyrisNP emission-retention model. The results revealed significant spatial variations in nutrient retention. The data assessment indicates that, at the start of the 21st century, the nutrient load from the Polish part of the catchment is significantly greater than that from the Russian part. Model simulations based on climatic projections for the years 2041–2060, but with current nutrient loads, showed a significant level of uncertainty in the changes of nutrient export to the Baltic Sea. The range for total nitrogen was –10 % to +27 %, and for total phosphorus it was –29 % to –10 %. Model simulations based on different socio-economic scenarios, but current climate conditions, showed that if present 5-year trends are maintained, nutrient export will only increase slightly (3 % for total nitrogen and total phosphorus). If the plans for socio-economic growth of Polish and Russian local governments are implemented, including the expansion of agriculture in Kaliningrad Oblast, there will be a significant increase in nutrient export (78 % for total nitrogen and 55 % for total phosphorus).

Keywords: nutrient load; catchment; scenario modelling, climate change, Pregolya River; Baltic Sea

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СЦЕНАРНЫЙ АНАЛИЗ СОЦИАЛЬНО-ЭКОНОМИЧЕСКИХ И КЛИМАТИЧЕСКИХ ИЗМЕНЕНИЙ НАГРУЗКИ И УДЕРЖАНИЯ БИОГЕННЫХ ВЕЩЕСТВ В ВОДОСБОРЕ РЕКИ ПРЕГОЛИ (ЮГО-ВОСТОЧНАЯ БАЛТИКА): ВЗГЛЯД НА НАЧАЛО XXI ВЕКА

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Аннотация

В ходе исследования был проанализирован трансграничный водосборный бассейн реки Преголи, охватывающий как польскую, так и российскую части, с использованием гидрологического модуля HYPE и модели расчета нагрузок и удержания биогенных веществ FyrisNP. Результаты выявили значительные пространственные различия в характеристиках удержания биогенных веществ. Оценка данных показывает, что в начале XXI века биогенная нагрузка из польской части водосбора значительно выше, чем из российской части. Моделирование, основанное на климатических прогнозах на 2041–2060 гг., но с учетом нынешней нагрузки по биогенным веществам, показало значительный уровень неопределенности в изменениях экспорта биогенных веществ в Балтийское море. Диапазон для общего азота составлял от –10 % до +27 %, а для общего фосфора — от –29 % до –10 %. Модельные расчёты, основанные на различных социально-экономических сценариях и текущих климатических условиях, показали, что при сохранении

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нынешних тенденций экспорт биогенных веществ увеличится лишь незначительно (3 % для общего азота и общего фосфора). Если планы социально-экономического роста польских и российских органов местного самоуправления будут реализованы, включая расширение сельского хозяйства в Калининградской области, произойдет значительный рост экспорта биогенных веществ (78 % для азота общего и 55 % для фосфора общего).

Ключевые слова: биогенная нагрузка, водосбор, моделирование сценариев, изменение климата, река Преголя, Балтийское море

1. Introduction

The Pregolya River catchment is part of the Baltic Sea drainage basin (Fig. 1, *a*). Domestic wastewater and agriculture are the main anthropogenic sources of nutrients [1]. Previously, there were several expert assessments of nutrient export to the Baltic Sea with the Pregolya River outflow: about 3,700–4,250 tons N/year and 490–740 tons P/year [2–7]. Only one of the assessments [5] was based on monitoring data in the Russian part of the catchment. Most

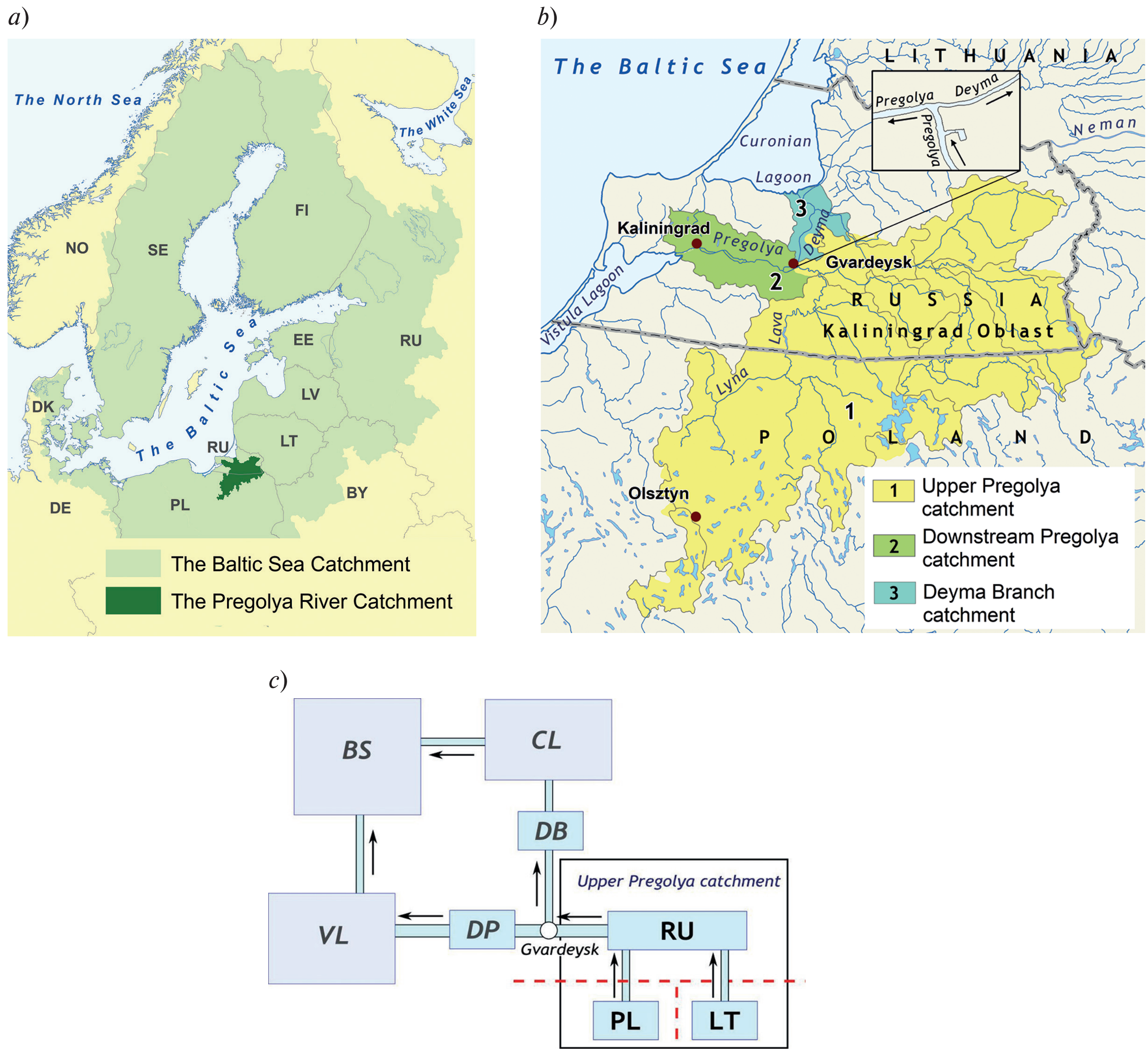

Fig. 1. The Pregolya River catchment (*a*), its transboundary location and sub-division into three segments (*b*): 1 — the Upper Pregolya catchment, 2 — the Downstream Pregolya catchment and 3 — the Deyma Branch catchment. The insert on fragment (*b*) shows the bifurcation point in Gvardeysk, where the Pregolya River forms two branches — the Downstream Pregolya (flowing to the Vistula Lagoon) and the Deyma Branch flowing to the Curonian Lagoon. The fragment (*c*) illustrates the structure of nutrient cascade of the Pregolya River catchment: PL, LT, RU — Polish, Lithuanian and Russian parts of the Upper Pregolya catchment, DP — Downstream Pregolya catchment (Russia), DB — Deyma Branch (Russia), CL — Curonian Lagoon, VL — Vistula Lagoon, BS — Baltic Sea

of the other assessments were based on modelling, but the models were developed only for the Russian part of the catchment [2–4, 7]. The whole Vistula Lagoon catchment, including the Polish and Russian parts, was considered in [6], but the paper only considered the load of inorganic nutrients — 5100 tons NO_3-N/year and 320 tons PO_4-P/year. Thus, a complete assessment of the whole Pregolya River catchment has not yet been carried out.

The Pregolya River catchment is shared by Poland and Russia, which have different national environmental legislation, management and decision-making systems [8]. Social and economic conditions vary both within and between the two national parts of the catchment [1].

Agriculture in the Kaliningrad Oblast has declined since the 1990s, with only 50 % of arable land currently in use [9]. In recent years, there has been a slight increase in agriculture in the Russian part of the catchment. From 2010 to 2014, the area of arable land increased by 5 % and livestock by 15 % [9]. Currently, agricultural development is a priority in the Kaliningrad Oblast policy. It is expected that there will be a 70 % increase in arable land, as well as a 350 % increase in cattle livestock and a 950 % increase in pigs by 2020, according to government strategies [9].

Changes in future climate may also impact nutrient emissions, as noted by [6, 10] conducted studies on the Vistula Lagoon catchment, which includes the Pregolya River, and found that climate change is likely to result in decreased nitrogen loads and slightly increased phosphorus loads. These findings are consistent with those of [11–13] present contrasting results for small Polish rivers and nutrient loads from land to the Baltic Sea. While [13] project an increase in nutrient loads, [12] show an increase in nitrate and phosphate loads with river discharge. The study suggests that further investigations are necessary, and [6] concluded that the impact of climate change should be extended to include the effects of land use and management on water quantity and quality in the Vistula Lagoon catchment.

The aim of the paper is to assess the nutrient emission and the retention for the Pregolya River catchment, as well as the load from it towards the Baltic Sea, under current and future climate and current and future socio-economic conditions.

The assessment of the nutrients load from the Pregolya River catchment made in the current paper is the most complete and comprehensive of existed ones [3, 6]. The study compared scenarios of changes in nutrient load from the catchment under different climatic and socio-economic conditions using the targeted installation of numerical models HYPE (flow model) for the Pregolya River catchment and the FyrisNP emission-retention model based on data from the beginning of the 21st century. The main goal of the scenario analysis was to compare the degree of impact of these different factors on the nutrient load.

2. Study area

Pregolya River is the largest river that flows into the Vistula Lagoon. Its basin comprises 65 % of the Lagoon's catchment area and its runoff is 44 % of the total runoff to the lagoon. The Pregolya River is bifurcated in two branches in the city of Gvardeysk (Fig. 1, *b*). Approximately 34 % of the Pregolya River runoff turns towards the Curonian Lagoon through the Deyma Branch [14]. This means that the nutrient export from the Pregolya River catchment are directed into the Baltic Sea via two buffer water bodies, namely, the Vistula and Curonian lagoons [15]. These lagoon ecosystems are characterized by a great content of nutrients which determine their high (eutrophic/hypereutrophic) level of biological productivity [16, 17].

The catchment area of the Pregolya River is shared almost equally between Russia and Poland, with 49 % and 51 % respectively (Fig. 1, *b*), and a small portion belonging to Lithuania (about 0.5 %). To illustrate the nutrient export cascade in the Pregolya catchment, a simplified scheme is presented in Figure 1c, where nutrients from the Polish and Lithuanian parts flow into the Russian part of the Upper Pregolya catchment. After the bifurcation point in Gvardeysk, nutrient fluxes are directed to the Baltic Sea through two pathways: 'Downstream Pregolya — Vistula Lagoon' and 'Deyma Branch — Curonian Lagoon'.

The Pregolya River catchment is home to 675,000 inhabitants in the Russian part and 460,000 inhabitants in the Polish part (Fig. 2, *a*). The majority of the Russian population resides in Kaliningrad city, with a population of 450,000 people. However, as the city's sewages are discharged directly to the Vistula Lagoon, bypassing the Pregolya River, the population of Kaliningrad was not considered in our scenario study. Table 1 shows the land use.

The Russian part of the catchment area considered 225,000 inhabitants (Table 2). In this area, 90 % of the urban population and 30 % of rural inhabitants are connected to the sewerage network [18]. In the Polish part, the corresponding numbers are 97 % and 43 %, respectively [19]. Almost all wastewaters (98 %) in the Polish part of the catchment area of the Pregolya River are treated. In the Russian part, three cities have biological treatment systems, while in the Polish part, ten cities and towns have such systems. Table 2 shows that there are more cattle and pigs, but fewer sheep and goats in the Polish part of the catchment area compared to the Russian part.

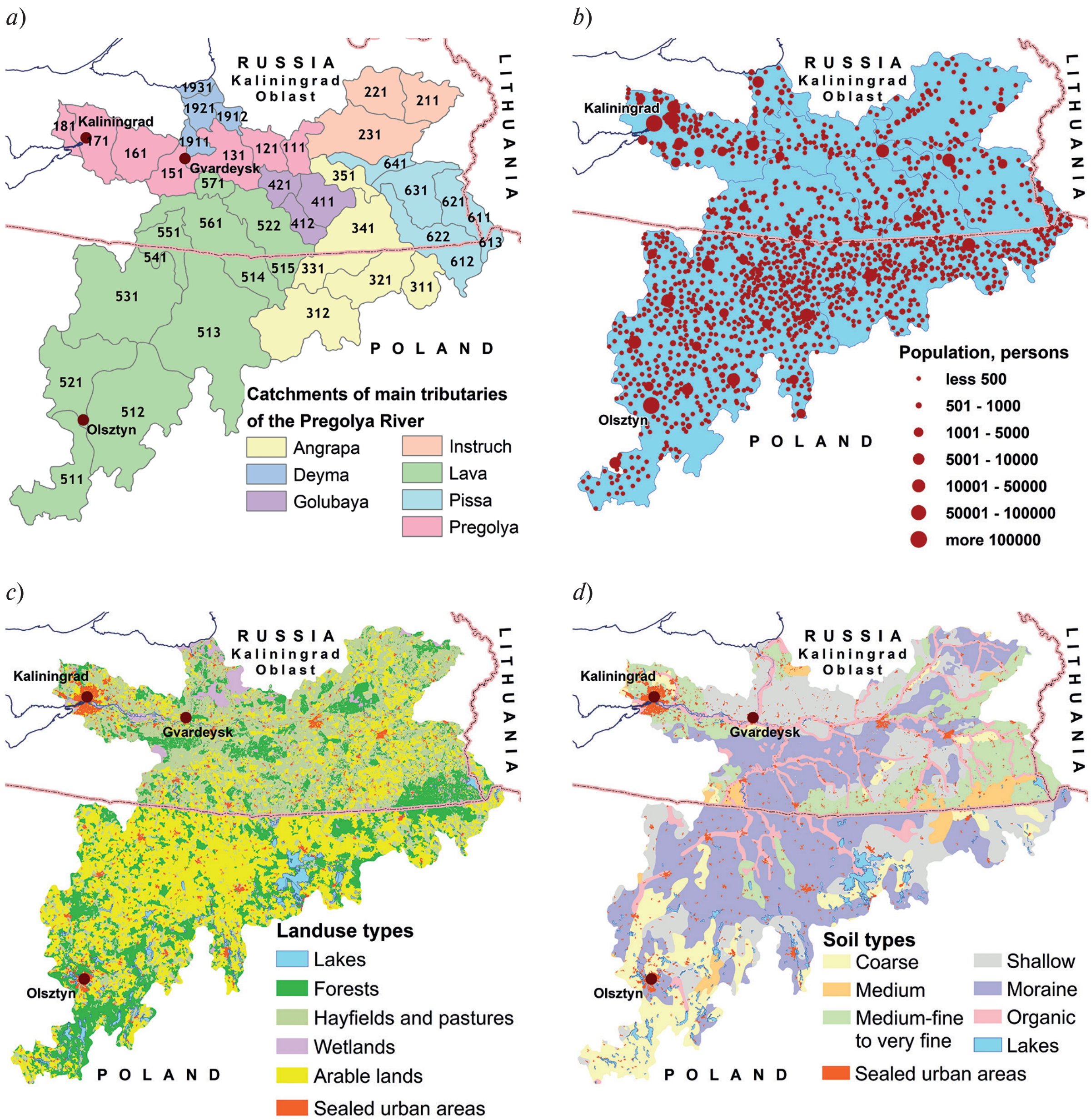

Fig. 2. The distribution of settlements (*a*), land use (*b*), and soil types in the Pregolya River catchment are shown. Fragment (*d*) displays the HYPE model set-up, which comprises 42 sub-catchments dedicated to 8 river streams (refer to the legend in (*d*))

Table 1

Land use in the Russian (RU) and Polish (PL) parts of the Pregolya River catchment

Land types	RU		PL		Total	
	Area [km^2]	% of RU area	Area [km^2]	% of PL area	Area [km^2]	% of total area
Agricultural land:						
– permanent crops	69	1.0	1	0.0	70	0.5
– rainfed	1451	21.6	4053	53.4	5504	38.5
Forest:						
– broad leaved forest	24	0.4	388	5.1	412	2.9
– mixed forest	1135	16.9	872	11.5	2007	14.0
– needle leaved forest	56	0.8	783	10.3	839	5.9
Open land:						
– with vegetation (meadows)	3436	51.2	921	12.2	4357	30.5

Fin table 1

Land types	RU		PL		Total	
	Area [km^2]	% of RU area	Area [km^2]	% of PL area	Area [km^2]	% of total area
– without vegetation	6	0.1	8	0.1	13	0.1
Lakes	37	0.6	337	4.5	374	2.5
Rivers	10	0.2	1	0.0	11	0.1
Wetland	204	3.0	38	0.5	242	1.7
Sealed urban area	285	4.2	183	2.4	468	3.3
Total	6714	100.0	7585	100.0	14298	100.0

Table 2

Main point sources of nutrients in the Russian (RU) and Polish (PL) portions of the Pregolya River catchment area: population (number of persons) connected to different types of sewage systems, livestock and poultry farming (number of heads)

Types of point sources of nutrients	RU (2014)	PL (2011–2014)
Population		
Urban Population [thousands]:	132	300
– connected to the sewerage network:	119	297
– mechanical treatment,	83	13
– mechanical + biological treatment,	35	109
– mechanical + biological + chemical treatment + nitrogen removal;	0	175
– do not connected to the sewerage network	13	4
Rural Population [thousands]:	93	159
– connected to the sewerage network:	28	68
– mechanical treatment	65	91
– do not connected to the sewerage network:		
Livestock and poultry farming		
Cattles [thousands]	56	144
Pigs [thousands]	128	166
Sheep and Goats, [thousands]	47	4
Poultry [thousands]	1991	1955

3. Materials and Methods

3.1. Models used

The hydrological model was set up using the HYPE model code [20, 21] for the Pregolya River catchment, which was extracted from the E-HYPE v3.1 [22]. The model was modified and calibrated using detailed local data for the catchment. The hydrographic structure of the Pregolya River catchment was divided into three parts for modelling purposes: the upstream catchment area of the Pregolya River (13,100 km^2) before the division into arms in Gvardeysk, and the catchment areas of the downstream Pregolya (1,100 km^2) and Deyma River (400 km^2) (see Fig. 1, *b*). Spatial data such as land use, population, and soil type distributions (Fig. 2, *b*, *c*) were used in the model.

The hydrological module of HYPE was calibrated by [23] for the period 1986–1996 in the catchment upstream of the hydrological gauging station in Gvardeysk (bifurcation point). Verification was performed for 2008–2009. The correlation coefficient and Nash Sutcliffe efficiency (NSE) [24] between measured and simulated discharges were 0.79 and 0.59 for the calibration period and 0.85 and 0.55 for the verification period, respectively. The annual average discharge of the Pregolya River in Gvardeysk (before bifurcation into two branches) was measured and simulated to be 90 m^3/s and 89 m^3/s, respectively. During the verification period, these values were 76 m^3/s and 78 m^3/s.

The FyrisNP model Version 3.1 was used to conduct source apportionment modelling of nutrient transport in the Pregolia River catchment. This model estimates the gross and net transport of nitrogen and phosphorus in rivers and lakes [25] based on runoff, point source discharges, land-use information, lake area, and river stream length and width, independent of time. The model for Instruch River, a tributary of the Pregolya River, had been previously set up and calibrated in other studies [26]. The FyrisNP model setup was verified using screening monitoring data

(2013–2015) for the outlet sections of the Upper Pregolya River in Gvardeysk, Downstream Pregolya River in Kaliningrad, and Deyma Branch in Polessk. The mean annual concentrations of total nitrogen showed a discrepancy of 6–14 % between the actual and model values, while for total phosphorus, the discrepancy was 6–7 %.

3.2. Nutrient load data

The data about anthropogenic sources of nutrients were taken from archives and electronic databases of the Territorial Authority of the Federal State Statistics Service in the Kaliningrad Oblast [27] and Statistical Office in Olsztyn [28] as well as from published literary sources [18, 19, 29–34].

To calculate nutrient emissions from the population, we compiled a complete list of inhabitants georeferenced to urban and rural areas. We used the rates of emission (13.5 g nitrogen/person per day and 2.1 g phosphorus/person per day) from [35] and technical parameters of water treatment facilities.

The annual emission of nitrogen and phosphorus from livestock was calculated based on the daily manure production per animal. For cattle, this was 50 kg, for pigs 5 kg, for goats and sheep 3 kg, and for chickens 0.16 kg. The calculation also took into account the nutrient content in the manure, as well as the number of livestock and poultry in the farms, enterprises, and households. The assumed weight percentage of nitrogen and phosphorus content in manure for different animals are as follows: cattle — 0.5 % and 0.2 %, pigs — 0.6 % and 0.2 %, goats and sheep — 0.8 % and 0.2 %, and chickens — 1.6 % and 1.3 % [36].

Nitrogen and phosphorus input were calculated for all livestock and poultry, including those on pasture breeding, considering the grazing period (April–October) and stabling period (November–March). The data collected for the Russian part of the catchment area was geo-referenced to settlements, while the data for the Polish part was aggregated at the voivodship level.

The FyrisNP model's diffuse load is mainly determined by the 'type specific concentration' parameter, which sets the nutrient runoff value for different land types such as forest, clear cuts, mires, urban areas, and others. Type-specific concentrations of data for arable lands in the Polish part of the catchment were estimated, taking into account the rate for South-Eastern Sweden (7.0 mgN/l, 1.5 mgP/l). For the Russian part, this value was reduced in accordance with the lower application of fertilizers (4.0 mgN/l, 0.3 mgP/l) [33].

3.3. Meteorological and water quality monitoring data

The poor availability of meteorological data within the Pregolya River catchment was noted earlier [6]: the data are not always accessible to the public, available measured data series contain gaps, and the spatial coverage of the station network is poor. Therefore, we used a bias-adjusted re-analysis dataset from the European Watch Project [37]. Forcing data in terms of daily precipitation and air temperature values from 15 grid points at a spatial resolution of 0.5 degree were obtained using RFData [38].

Supplementary screening monitoring was conducted in the Kaliningrad Oblast due to the lack of data on total nitrogen and phosphorus in the river streams of Pregolya River catchment. The monitoring covered all major tributaries of the Pregolya River within the Kaliningrad Oblast, consisting of 12 monitoring points. Laboratory analysis of organic nitrogen and phosphorus was performed. Samples were collected seasonally from 2013 to 2015 to estimate the levels of total nitrogen, nitrate nitrogen, nitrite nitrogen, ammonia nitrogen, total phosphorus, and phosphate phosphorus using standard methods [39–41].

3.4. Analyzed scenarios

The study compares the nutrient load from the Pregolya catchment during a baseline period with the load in two scenarios: baseline with climate change (2041–2060) and baseline with socio-economic changes (up to 2020).

Figure 3 provides a schematic outline of the scenarios. The baseline model run (Baseline Period) was conducted using the baseline climate (1991–2010) and baseline loading, which reflects current socio-economic conditions such as population, land use, and livestock for 2014.

The four model runs covered the future climate (2041–2060) according to four climate projections (CM5A-MR_WRF, CanESM2_RCA4, MPI-ESM–LR_CCLM, CNRM–CM5_RCA4) [42] and present socioeconomic conditions [9].

The two model runs for the socio-economic scenarios (BAU, DF) include changes in basic socio-economic drivers, namely land use structure, agriculture practice and intensity, and point sources and baseline climate (1991–2010) (Table 3). Scenario BAU (Business as usual) assumes preservation of the observed 5-year trends (2010–2014) in the development of agriculture and population, assuming that the spatial distribution of nutrient sources remains unchanged. Scenario DF is based on an analysis of official plans for socio-economic development issued by regional authorities in the Polish and Russian parts of the catchment [9].

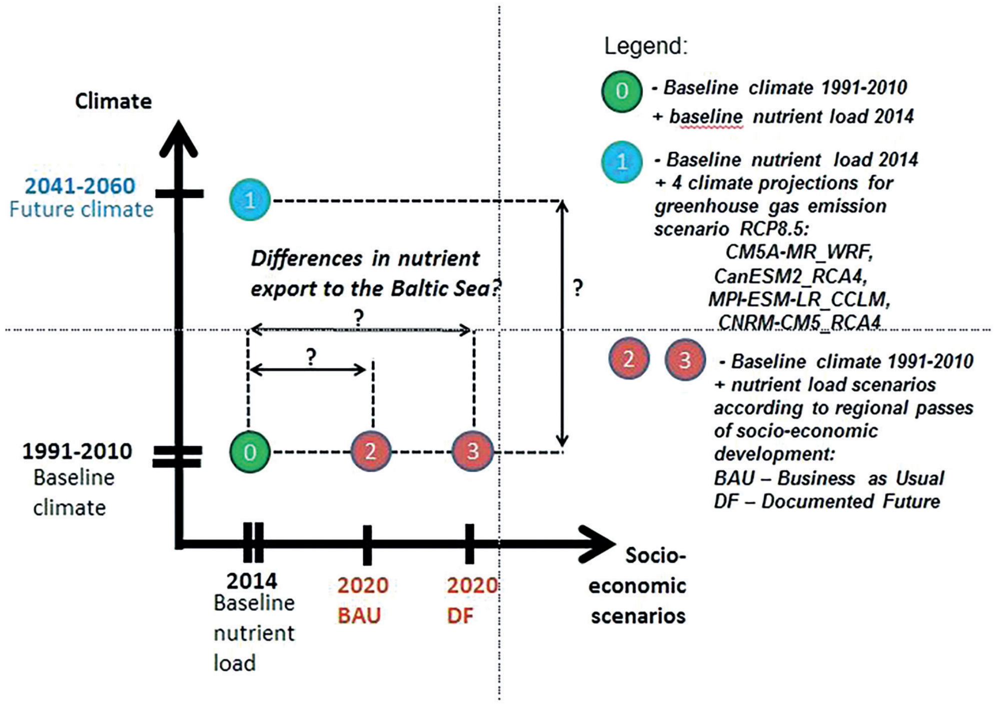

Fig. 3. Principle scheme of model runs of climate projections and socio-economic scenarios for the Pregolya River catchment: 0 — baseline climate and nutrient load, 1 — baseline nutrient load combined with 4 climate projections (1a, 1b, 1c, 1d respectively), 2 and 3 — BAU and DF scenarios combined with baseline climate

Tables 3 and 4 provide main characteristics of climate forcing and socio-economic state for used scenarios and their absolute and relative changes.

Table 3

Main characteristics of climate forcing (baseline 1991—2010 and climate projections 2041—2060) for the catchment area of the Pregolya River and their absolute (Δ) and relative (%) changes, which denote an increase (+) or decrease (–) of the average value of a parameter in relation to the baseline period (1991—2010)

Characteristics	Baseline scenario, 1991—2010	Min and max among climate projections (2041—2061)					
		Min			Max		
	Monthly mean	Value	Δ	%	Value	Δ	%
Precipitation, mm	795	854	+59	+7	1011	+216	+27
Temperature, °C	7.8	9.1	+1.3	–	9.8	+2	–

Table 4

Main characteristics of socio-economic state (baseline 2014 and Business as usual scenario (BAU) and Documented future scenario (DF)) for the catchment area of the Pregolya River and their absolute (Δ) and relative (%) changes, which denote an increase (+) or decrease (–) of the average value of a parameter in relation to the baseline period (2014)

Characteristics		Socio-economic scenarios					
		Baseline scenario, 2014		BAU (up to 2020)		DF (up to 2020)	
		RU	PL	RU	PL	RU	PL
Population, thousand people		225	460	+25 %	–6 %	+70 %	+3 %
Arable land, km^2		1450	4050	+5 %	0 %	+70 %	+3 %
Live-stock	Cattle, thousand head	56	144	+15 %	0 %	+850 %	+5 %
	Pigs, thousand head	128	166	+15 %	0 %	+250 %	+5 %
Poultry, thousand head		1990	1955	0 %	0 %	+100 %	+3 %

4. Results

4.1. Baseline Scenario

The total nutrient load from the Pregolya River catchment to the Curonian and Vistula lagoons, calculated for the baseline conditions (climate period 1991–2010 and the nutrient inputs of 2014), amounted to approximately 5.3 thousand tons of TN/year and 0.66 thousand tons of TP/year (Table 5, line 'Pregolya total'). The load from the Polish part of the Upper Pregolya catchment, according to the structure of the nutrient export cascade, is 3.8 thousand tons of N/year and 0.6 thousand tons of P/year on average.

The Pregolya River catchment retained 54 % of total nitrogen and 64 % of total phosphorus emitted from sources within the catchment. The highest retention values (up to 75 %) were observed in lake systems located in sub-basins 611, 613, 621 (Vistytis Lake), 312 (Mamry Lake), and other sub-basins in the Masurian Lakes District (511, 512, 513).

Table 5

Total nitrogen (TN) and total phosphorus (TP) emission, export and retention for the Pregolya catchment area and its individual parts for the Baseline scenario

Catchment area	Emission from internal sources		Nutrient export** from catchment		Specific nutrient export from catchment		Retention in catchment	
	TN	TP	TN	TP	TN	TP	TN	TP
	thousand tons (N or P) year^{-1}				ton (N or P) year^{-1} km^{-2}		%	%
Polish part	7.6	1.50	3.8	0.6	0.6	0.09	50	57
Lithuanian part	0.3	0.03	0.1	0.003	0.7	0.04	82	90
Russian part:	3.5	0.32	5.3	0.65	0.5	0.05	28	31
Upper Pregolya	2.8	0.25	4.8	0.64	0.5	0.04	27	27
Downstream Pregolya*	0.5	0.05	3.2	0.4	0.4	0.04	7	6
Deyma Branch	0.2	0.02	2.1	0.25	0.5	0.06	1	10
Pregolya Total*	11.4	1.85	5.3	0.65	0.6	0.06	54	64

Notes: * Kaliningrad city is not taken into account;
** it is originated by emission from sources in the catchment and load from the upper catchment minus retention within the catchment.

Source apportionment for nutrient load revealed that arable lands are the main sources of nitrogen and phosphorus input in the catchment of the Pregolya River upstream the bifurcation point in Gvardeysk, accounting for 58 % and 67 % respectively. Livestock wastes and municipal wastewater also contribute significantly, accounting for 21 % and 13 % of nitrogen input and 12 % and 15 % of phosphorus input respectively. For the catchment of the Downstream Pregolya the main sources are livestock wastes (29 and 31 %), municipal wastewater (18 and 28 %) and arable lands (27 and 21 %), and for the catchment of the Deyma Branch — municipal wastewater (44 and 64 %), arable lands (14 and 10 %) and livestock wastes (12 and 10 %).

4.2. Climate change impact on nutrient export

Table 5 summarizes the projected impacts of climate change on nutrient export from the Pregolia River catchment. The uncertainty ranges, produced by the ensemble of four climate models, are illustrated by the minimum and maximum values. The projected impact ranges for TN and TP are [–10 %; +27 %] and [–10 %; +29 %], respectively.

4.3. Response of nutrient export to socio-economic scenarios

Business as usual scenario (BAU)

Table 5 lists the changes in average annual export of TN and TP for the BAU scenario. The changes are moderate, showing an increase of about 3 % compared to the baseline scenario. However, there are significant differences between sub-catchments, with changes ranging from –0.7 to 27 % for TN and from –1.4 to 30 % for TP. The sub-catchments located in the Polish part show negative and low changes, with less than 2 % for nitrogen and 1 % for phosphorus. In contrast, the Russian sub-catchments exhibit significantly higher changes, ranging from 1–26 % for TN and 1–30 % for TP. The response above is based on the assumptions of the BAU scenario. It assumes a reduction in population size in Poland, while maintaining a stable agricultural sector. In contrast, the Russian part of the scenario assumes an increase in agricultural characteristics, such as livestock numbers and the use of arable land, alongside population growth. The source apportionment shares of TN and TP inputs remain unchanged in the BAU scenario.

Documented future scenario (DF)

The second socio-economic development scenario, DF, is characterised by a tremendous increase in population, agricultural areas, livestock, and poultry in the Russian part of the catchment (see Table 4). The impacts of DF on the entire catchment are major increases in the export of TN and TP, with a 79 % and 55 % increase respectively compared to the baseline scenario. At sub-catchment levels, the increases range from 3 % to 380 % for TN and from 3 % to 500 % for TP.

The majority of TN and TP exports come from arable lands (52 % TN; 55 % TP), livestock and poultry farming waste (31 % TN; 27 % TP), and sewage from the population (11 %; 15 %).

5. Discussion

5.1. Regionalisation of nutrient retention

There is a significant variation in the degree of nutrient load retention among individual sub-catchments. The ratio of the retained portion of the emission compared to the full emission within the catchment ranges from 0.5 % to 82 % for TN and from 0.7 % to 94 % for TP (refer to Fig. 4) under baseline conditions. The ratio of the retained portion of the emission compared to the full emission within the catchment ranges from 0.5 % to 82 % for TN and from 0.7 % to 94 % for TP (refer to Fig. 4) under baseline conditions.

The upper sub-catchments located in the lake region of the south-eastern part of the catchment area exhibit high levels of nutrient retention, including both nitrogen and phosphorus. This is due, at least in part, to the longer transition times of nutrients from these regions. Conversely, the lower reach sub-catchments exhibit the lowest degree of retention. The transition part of the catchment area has an average retention capacity.

The distribution of retention capacity is influenced by various factors. Retention is directly proportional to the extent of the river network and the number of lakes, and inversely proportional to the river runoff. The spatial distribution of retention capacity remained consistent across scenarios, even when the incoming river flow values changed in response to climatic changes or when the initial nutrient load from population and farming enterprises changed.

Although the retention for the entire catchment is believed to be accurate due to model calibration, the retentions simulated for individual sub-catchments are based on unverifiable model assumptions and are subject to considerable uncertainty. The discontinuities between neighbouring Polish and Russian subcatchments (Fig. 4) are a clear indication of this. It should be noted that the FyrisNP model only takes into account the retention in surface water systems and does not consider the removal of nitrate in groundwater, which is likely to be a significant factor [43].

a) *b*)

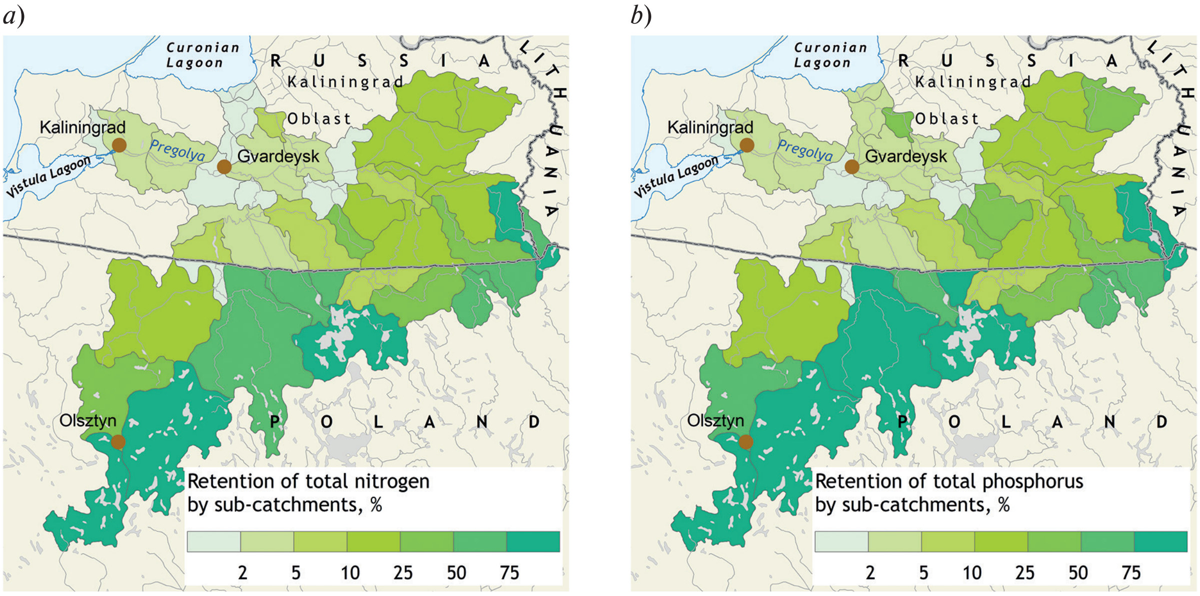

Fig. 4. Spatial distribution of the retention for total nitrogen (*a*) and total phosphorus (*b*) in the catchment of the Pregolya River for the baseline simulation

5.2. Synthesis of scenario analysis

The impact projections for climate change illustrate the significant uncertainty associated with climate models, with ranges of changes from –10 % to +27 %/+29 % for TN/TP export (Table 6). These results are consistent with those of [6, 42, 44] found similar uncertainty ranges at catchment scale as in the present study. They used the same climate model projections but different nutrient impact models for the Baltic Sea drainage basin (E-HYPE) and catchments in Denmark and southern Poland (NLES and DAISY), respectively.

The analysis of socio-economic scenarios, under the same basic climatic conditions (1991–2010), shows that the Business as Usual (BAU) scenario is likely to slightly increase nutrient export (by about 3 % for TN and TP). In the case of the Documented Future (DF) scenario, nutrient export is likely to increase substantially, by 79 % for TN and 55 % for TP (refer to Table 6). The main reason for this increase is agricultural development in the Russian part of the catchment.

Table 6

Mean annual nutrient export from the Pregolya River catchment for climate projections (2041–2060) and socio-economic scenarios, and their relative changes in absolute values (Δ) and percentage with signs (+)/(–), comparing to the baseline period

	Baseline period, 1991–2010	Climate projections, 2041–2061					
		Min			Max		
	Mean annual	Value	Δ	%	Value	Δ	%
TN, ton/year	5268	4762	–506	–10	6708	1440	27
TP, ton/year	657	594	–63	–10	848	191	29
Socio-economic scenarios							
	Baseline scenario, 2014	BAU (up to 2020)			DF (up to 2020)		
	Mean annual	Value	Δ	%	Value	Δ	%
TN, ton/year	5268	5452	184	3.5	9406	4138	79
TP, ton/year	657	675	18	2.7	1021	364	55

The socio-economic scenarios used in this study differ from those used by [42, 44], who employed the Shared Socio-economic Pathways (SSPs). Of the three SSPs used in their study, SSP5 (Fossil-fueled development) had the largest increase in nutrient load, but the increases in SSP5 were much less than the major increase in our DF scenario. This example demonstrates that even a scenario like SSP5, which is considered representative of a development leading to significant increases in nutrient exports, may be surpassed by a scenario based on actual government plans, such as the DF scenario. We consider the DF scenario a plausible development for the Russian part of the Baltic Sea drainage basin and possibly for Belarus, and therefore it should be taken into account in a HELCOM context. However, the DF scenario is less plausible in EU countries where agriculture is already highly intensive.

6. Conclusions

The paper presents for the first time a nutrient emission-retention-export study covering the whole transboundary Pregolya River Basin (Polish and Russian parts of it) including the two river branches (with their own catchments) at its lower reach, flowing to the Vistula Lagoon (Downsteram pregolya) and to the Curonian Lagoon (Deyma Branch). The catchment area of the transboundary Pregolya River showed significant spatial variations in characteristics of retention within its sub-catchments, which gives room for formulation of spatially differentiated strategies to reduce the load.

This study revealed a particular feature of the transboundary catchment area between an EU member country and Russia — the export from the Russian part of the catchment area is currently much smaller, but it will likely increase progressively as agricultural outputs recover to the level of 1970–1980th. Therefore, the introduction of modern farming methods that take into account minimal nutrient impacts are required to compensate for the increase in nutrient loads.

Model calculations were conducted to assess the impact of different climatic projections on nutrient export under the same nutrient load conditions as in 2014 (Fig. 5). The results showed a range of uncertainty for nutrient export, with a potential decline of 10 % and an increase of 27 % for TN, and a potential decline of 10 % and an increase of 29 % for TP. The Pregolya River catchment is situated on the boundary between sections of the Baltic Sea catchments that respond differently to climate changes. Further research is required to clarify this issue.

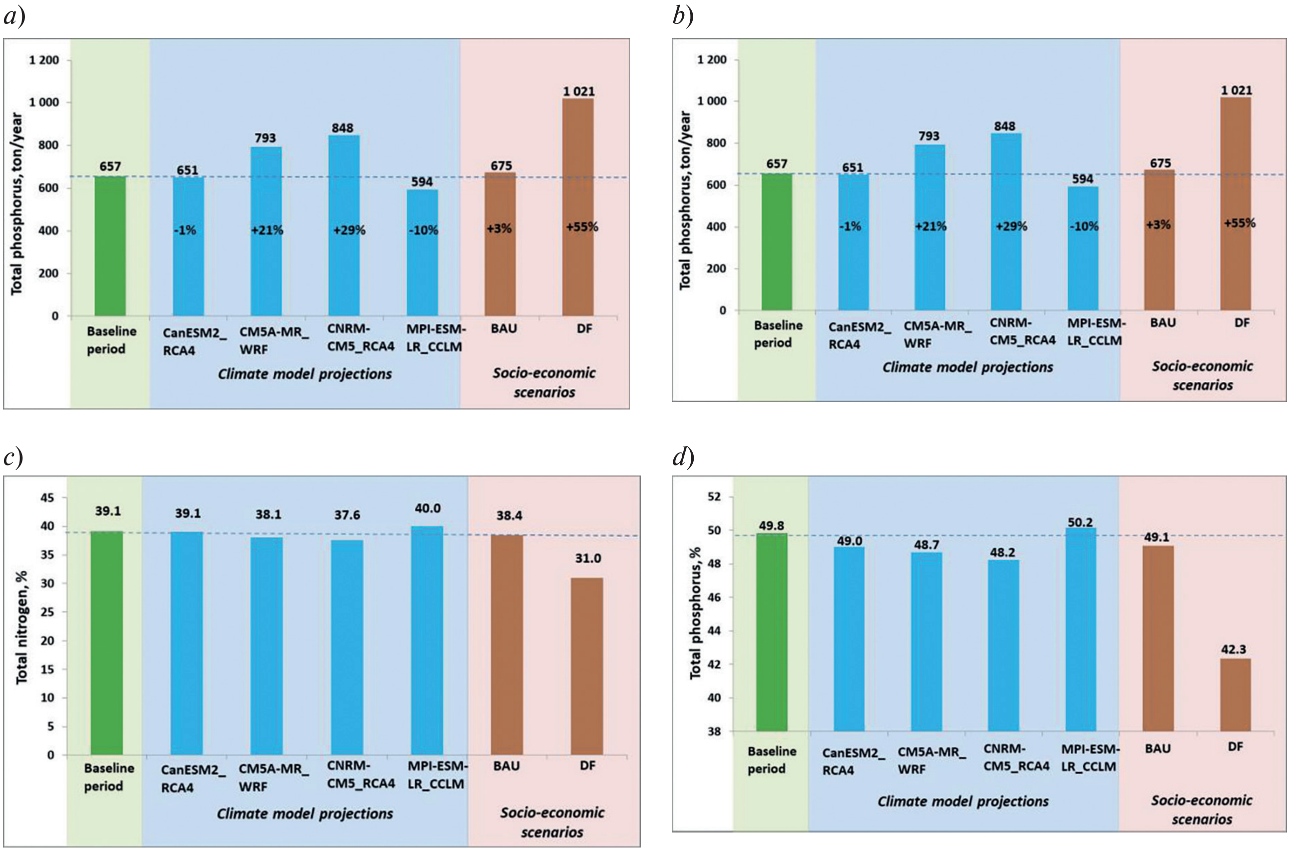

Fig. 5. The export of total nitrogen (*a*) and total phosphorus (*b*) from the catchment as well as retention of total nitrogen (*c*) and total phosphorus (*d*) in the Pregolya River catchment under different climate and socio-economic scenarios. Export from the Pregolya River catchment is shown in total to both of the recipient water bodies, the Vistula and Curonian Lagoons

A series of model simulations were conducted to explore the impact of different socio-economic scenarios on nutrient export under constant climate conditions (1991–2010) (Fig. 5). The results indicate that if current trends continue (Business as Usual scenario), there will only be a slight increase (3 %) in nutrient export for nitrogen and phosphorus. If the documented plans for socio-economic growth are implemented on both the Polish and Russian sides (DF scenario), nutrient export will increase significantly. Specifically, TN will increase by 78 % and TP by 55 % due to intensified agriculture in Kaliningrad Oblast, Russia.

The results indicate that changes in the local climate of the Baltic Sea region can affect the nutrient export characteristics, even when nutrient inputs to the catchment remain unchanged. When developing plans for socio-economic development, it is important to consider the climatic aspect, which is often overlooked in Russia. Uncontrolled growth of nutrient export can have adverse effects on the already low water quality of the Baltic Sea.

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