Spatial and Temporal Changes in Nutrient Source Contribution in a Lowland Catchment within the Baltic Sea Region under Climate Change Scenarios.

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Key Points:

- Spatio-temporal trends of nutrient loads from various sources have been tracked in the subcatchment scale under climate change scenarios
- Climate change will result in the load increase from the whole catchment by 34% for total nitrogen and 85% for total phosphorus
- Outputs from individual nutrient sources could grow up even by 187% for total nitrogen and 302% for total phosphorus

Abstract

Currently, climate change is considered as an important factor affecting nutrient loads introduced through riverine systems into the Baltic Sea. Although the prospect of a large increase in pollution has long seemed very real, it still does not translate into planning of effective remedial actions. One of the factors limiting the development of such activities is the scale of simulations, focusing generally on catchment outlet profiles. To fill this gap and enable a step forward in understanding responses towards future predictions in a higher resolution scale (subcatchment), we assessed nutrient load contribution using calculation profiles localised along a main watercourse and its tributaries. To track spatial and seasonal changes of total nitrogen and phosphorus under short- and long-term (RCP4.5 and RCP8.5) climate change scenarios we used the digital platform Macromodel DNS/SWAT. Having at our disposal a catchment model with a good performance we could follow not only total load changes in particular subcatchments, but also track localisation of the pollution sources and their direct impact on load estimations. Our results showed an increase of the loads, especially from the agricultural land use type, up to 34% for TN and 85% for TP in the most extreme scenario. Moreover, forest areas have been noted as highly reactive to the climate changes, and through their localisation able to distinctly alter nutrient outflow. Finally, the contribution of urban areas should be further investigated since the dynamics of nitrogen and phosphorus release from impervious surfaces is noticeably different here than from the other diffuse sources.

Plain Language Summary

This paper describes how climate change will affect the amount of nutrients in a small river catchment in the Baltic Sea region. While it is known that climate change can increase nutrient loads, effective actions to prevent them are still lacking. Big picture based on whole catchment is still poor in the terms of finding nutrient “Hot Spots”. In this research, we looked at a more detailed scale to see where the nutrients are coming from and how they're changing over time. We used computer modelling to show that the amount of nutrients coming from agriculture, forests and city areas will increase due to climate change. Overall, the amount of nitrogen can raise by 34% and the amount of phosphorus by 85%. Our results can be the basis for making decisions regarding actions aimed at improving the condition of surface waters and counteracting climate change effects.

1. Introduction

The problem of nutrient outflows from the HELCOM member countries remains unresolved (Capell et al., 2021; Preisner et al., 2020; Räike et al., 2020). In addition, pressure on local, regional and national surface waters within the Baltic Sea catchment area is constantly increasing (Thorsøe et al., 2022). There are particular concerns about the future of nutrient loads discharged into this water body from Polish rivers, as they remain major contributors to its eutrophication (Gustafsson et al., 2012). Although numerous actions have been taken to improve this situation, their effects should be considered very limited, and definitely, insufficient. So far, simulation studies have focused on the scale of entire catchments without focusing on the sources of these problems concentrated in individual sub-basins. However, they allowed to indicate the projected climate change as another factor influencing non-point sources of pollution, and consequently causing a significant increase in the loads of nutrients introduced into rivers.

Moreover, they also indicate that particularly at risk are small- and medium-sized catchments or its parts (subcatchments), intensively used for agriculture, from where qualitative information is missing, or estimated just from the main watercourse data. In such cases, different modelling tools have been proven to be especially a handful, and exploited in various spatial and time scales (Andersen et al., 2006; Bai et al., 2019; Fu et al., 2019; Marcinkowski et al., 2017; Sharps et al., 2017; Sperotto et al., 2019) Through the use of Geographical Information System data (GIS) these tools allow for the prioritisation of specific subcatchments (Bhattacharya et al., 2020), and identification areas and sources having a pronounced share in the total load from the discussed catchment, and require dedicated remediation actions (Bojanowski et al., 2022). However, results of analyses focused on the impact of future temperature and precipitation changes on nutrient loads, and in the subcatchment scale, are still difficult to find. Therefore, the current study is motivated by the willingness to improve the understanding of causes and the extent of these changes by simulations performed on a more precise scale.

The goal of this study is the first comprehensive evaluation of total nitrogen and phosphorus loads released from different sources (point sources, agriculture, urban runoff, and forestry) under climate change. The simulations with use of the digital platform – Macromodel DNS/SWAT (Discharge–Nutrient–Sea/Soil & Water Assessment Tool) (Orlińska-Woźniak, 2020; Wilk et al., 2017; Wilk et al., 2018) were performed for the middle-sized lowland catchment of the Wełna River (part of the Odra River basin) in central Poland, which was divided into seven subcatchments reflecting the local hydrological network and terrain features. Therefore, the temporal and spatial changes of nutrient loads have been tracked on the subcatchment level enabling detection of current and future trends in specific source contribution into the total catchment loads. Our approach also enabled identification of the most responsive sources, i.e., vulnerable areas (Hot Spots), and pressures on the quality of the riverine environment. Since the applied modelling tool proved to be fully scalable, therefore, it offers a broad range of instruments for decision makers.

2. Methods

2.1 Analysed area

The Wełna River catchment is located in the belt of central European lowlands and covers an area of 2 621 km^2. The river flows 118 km from the lake located 10 km north-east of the town of Gniezno and discharges into the Warta River (Odra River basin) near the town of Oborniki. The whole catchment is covered mostly by agriculture (72%), while forested and urban areas constitute 22% and 4%, respectively (Table 1). For the purpose of the following analyses, the Wełna River catchment has been divided into 7 subcatchments (Figure 1) with two covering the direct catchment of the main river (1 and 7), and five representing subcatchments of the Wełna River tributaries (2, 3, 4, 5, and 6). Although agriculture remains the dominant land use form for each of the subcatchments, their share varies from 56%–86%. A similar range of variability applies to forested areas with the lowest share in subcatchment 2 (6%), and the highest in 6 (43%). Urban areas constitute generally between 2 and 5% of each subcatchment total area, with the highest share reflecting the area occupied by the town of Gniezno (1). While water areas (0–4%) represent the share of the land covered generally by lakes.

In the analysed area polar-sea air masses prevail, which make summers cooler and winters milder than in the eastern more continental parts of the country. The average annual temperature is around 8.2°C, and the annual rainfall is between 500–550 mm. Snow cover occurs for a maximum of about 51–57 days. Although the growing season here is one of the longest in Poland, beginning at the end of March and lasting about 220 days, it is also one of the driest regions in Poland, where droughts caused by a deficit of precipitation occur with increasing frequency.

Table 1. Characteristics of the Wełna River subcatchments.

Subcatchment	Agricultural area		Forested area		Urban area		Water area		Total subcatchment area
	km^2	%	km^2	%	km^2	%	km^2	%	km^2
1	496	73%	135	20%	35	5%	16	2%	682
2	141	86%	10	6%	7	4%	5	3%	164
3	181	84%	21	10%	6	3%	8	4%	215
4	144	70%	54	26%	3	2%	5	2%	206
5	512	74%	139	20%	22	3%	15	2%	688
6	192	56%	147	43%	6	2%	0	0%	345
7	221	69%	83	26%	14	4%	2	1%	321
Total	1 888	72%	589	22%	93	4%	51	2%	2 621

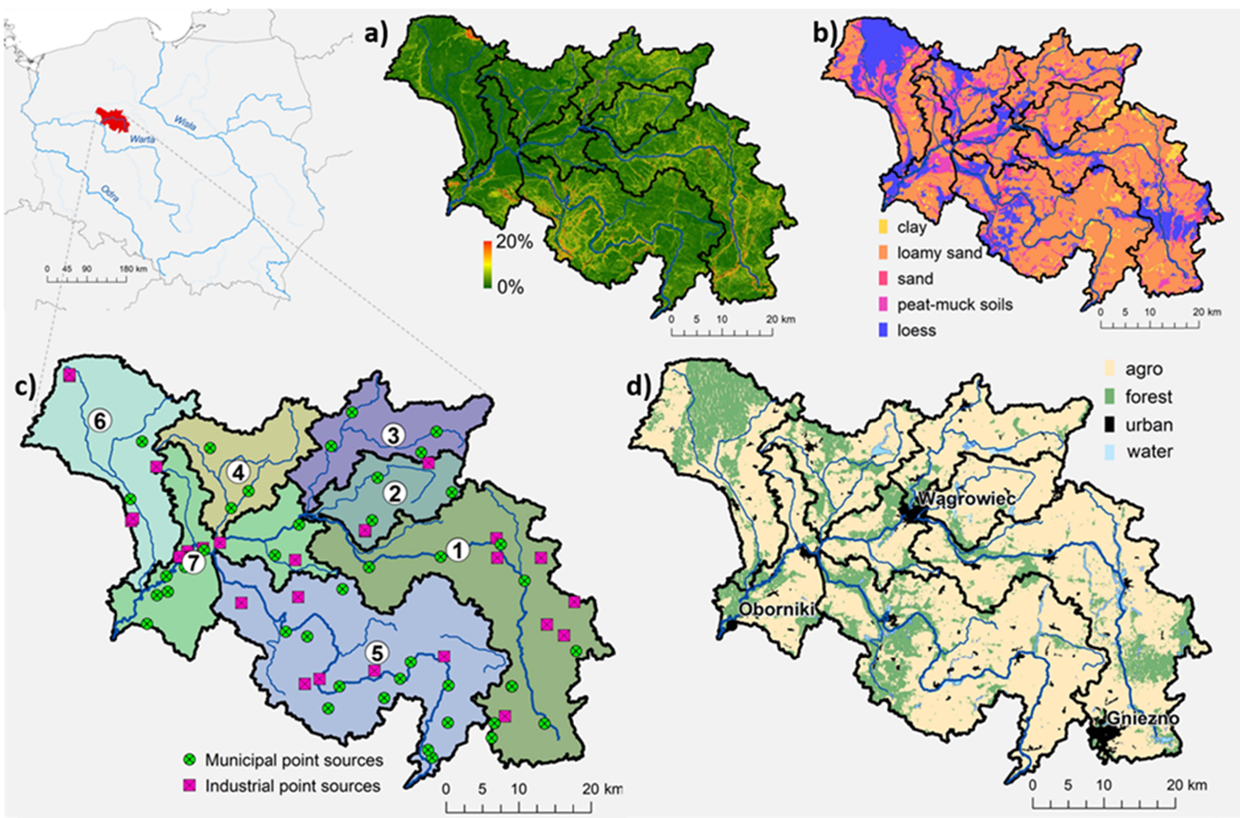

Figure. 1 Localisation of the Wełna River catchment with catchment elevations (a), soil distribution (b), point source locations (c), and land use (d).

2.2 Input Data and Base Scenario

Basic information on the Wełna River, i.e., daily flow rates and nutrient concentrations in the closing profile of the catchment (Oborniki), has been obtained from the state monitoring services (Institute of Meteorology and Water Management – National Research Institute – IMGW–PIB), and State Environmental Monitoring – SEM) (Table S1). Other data, such as maps of elevation, river network and soil maps, as well as meteorological data, necessary for the development of an accurate representation of the studied catchment area on the digital platform – Macromodel DNS/SWAT, were also obtained from the state repositories. Data on land use has been sources from the Corine Land Cover, while detailed information on emissions from point sources have been obtained mostly from the Local Data Bank of statistical information (Table S1). The year 2017 was selected for the analyses, which was characterised by the maximum amount of monitoring data for both flows (365 measurements) (IMGW–PIB), and total nitrogen (TN) and total phosphorus (TP) (12 measurements – SEM). The average air temperature in 2017 in Poland was 1.5°C higher than the long-term average (1971–2000), and was over 10°C, which resulted from the warm autumn at the end of the year. The time of snow cover presence was shorter than the long-term data, and the rest of the year was classified as thermally normal.

The study used the digital platform – Macromodel DNS with the SWAT module, described in detail in (Orlińska-Woźniak et al., 2020; Szalińska et al., 2021; Wilk, 2022). This advanced dynamic tool tracks nitrogen and phosphorus migration paths in a river basin taking into account their spatial and temporal variability. Apart from a very extensive input database depicting catchment specificity, natural and anthropogenic processes affecting transport and transformation of nutrients have also been included in this platform. The SWAT module (version 2012) is a tool which operates in the geographic information system (GIS) and is fully integrated with it and uses data on land use (forests, agriculture, and urban areas), and soil types (31 classes). Based on this data a total of 2,824 hydrological response units (HRUs), homogeneous in terms of vegetation, soil, and topography, have been identified for the studied Wełna River. Using a digital terrain model (DEM) these HRUs have been finally aggregated into the seven subcatchments used for this study. Simulation, transport, and transformation of nutrients required for the quantitative component of the model have been based on the water balance equation. It is worth mentioning that this tool also takes into account organic and inorganic forms of nitrogen and phosphorus. In this study, the results of the model are presented as loads of TN and TP. To verify that the model properly predicts loads of nutrients, results are calibrated with the TN and TP values resulting from SEM. Moreover, the model was calibrated not only on the TN and TP, but also on its particular forms (nitrate, ammonium, and organic nitrogen and phosphates) (SWH–PW, 2020).

Diffuse sources of nutrients from the different types of land use (agricultural, forest, and urban) in the SWAT model were simulated in the land phase of the catchment. In this phase, the model simulates both the infiltration of nutrients into the soil (fertilisation, plant biomass, and precipitation), and their removal from it (volatilization, denitrification, erosion, and surface runoff). Additionally, changes in the distribution of nutrients in the soil (uptake by plants) and the low mobility of phosphorus itself are also taken into account. Moreover, it is assumed that pollutants from the municipal and industrial point sources are introduced directly into the riverbed phase. The load of nutrients from atmospheric deposition affects both the land and river phases due to the presence of two deposition mechanisms in the SWAT module, i.e., wet and dry deposition. The model also allows for the determination of nutrient loads generated as a result of natural processes of nitrogen and phosphorus transformation, and transport in the soil, with the omission of all anthropogenic pressure.

In this study, the SUFI-2 algorithm (Khalid et al., 2016) was used to investigate SWAT module sensitivity and uncertainty. Sensitivity analysis performed with the Latin Hypercube One-factor-at-a-Time (LH-OAT) sampling approach (Ahn et al., 2023) was used to identify the most influential model parameters for simulating the observed data. It gives two types of results, the value of statistics "t", and the level of significance "p". The smaller the value of "p", the more sensitive the parameter. In turn, the value of "t" indicates the intensity and direction of change of a given parameter (positive values mean its increase and negative values a decrease) (Tables S3-S6).

The SWAT module for the Wełna River has been calibrated, verified, and validated using the SWAT–CUP software (Abbaspour, 2013) which was described in detail in Bojanowski et al., 2022. Flow data for the 18-year period (2001–2018) came from the water gauge stations on the Wełna River (Pruśce and Kowanówko), and its tributary (Flinta River – Ryczywół). The nitrogen and phosphorus concentration in the catchment was gathered from the SEM stations localised at the Wełna River (Oborniki and Rogoźno), and covered a period of 13 years (2005–2018). Three statistical measures, coefficient of determination (R^2), percent bias (PBIAS), and Kling-Gupta efficiency (KGE), have been used to indicate the Wełna River model performance. For flow, the calibration and verification coefficients R^2, KGE, and PBIAS classified the model performance generally as good and very good for the main river (Wełna), and satisfactory and good for its tributary (Flinta). During the validation procedure, all coefficient values rated the model performance for daily flow simulations as very good. For nitrogen and phosphorus, the model performance for TN simulations can be considered as very good or good, according to the all-applied coefficients. Lower model performance, mostly satisfactory, was observed for TP mainly due to the variability of phosphorus temporal distribution patterns.

The final simulation of the model, which has undergone calibration, verification, and validation procedures, has been used in the current study as a baseline scenario (BL) to provide data series for TN and TP loads from 5 described above emission sources (AGRO, FOREST, URBAN, POINT, and BACKGROUND) at the closure of 7 subcatchments with a monthly time step. Loads assigned into the individual subcatchments of the Wełna River tributaries (2, 3, 4, and 5) resulted from loads originating from the given subcatchment as simulated by the SWAT model. For the subcatchments representing the main river (1 and 7) they were obtained by subtraction of loads from upstream subcatchments from the loads resulting in the closure of the subcatchment located downstream. Therefore, the sum of all assigned loads is equal to the loads estimated at the Wełna River River closure.

2.3 Climate Scenarios

The climate scenarios have been developed using the UAP (Urban Adaptation Plans) project predictions (UAP, 2023), based on the data from the Euro-CORDEX, Regional climate models (RCM) (Dosio, 2016; Rummukainen, 2016), and the Global Climate Models (GCM) (Yang et al., 2019). Data from the Poznań – Ławica synoptic station (52.416885, 16.834444) has been used, and is located 25 km away from the Oborniki calculation profile. The statistical postprocessing (downscaling) (Eum et al., 2017; Iturbide et al., 2019) was performed using the tools available in the R environment (R, 2023). The climate condition analysis in the UAP project covered the moderate (RCP4.5) and extrapolative (RCP8.5) scenarios, and two future time horizons: short-term perspective (average of 2026–2035), and long-term perspective (average of 2046–2055) (Dobler et al., 2018). Therefore, four climate variant scenarios, with a monthly time step, were prepared to combine the RCP predictions and adopted time horizons: RCP4.5 (2026–2035) – V1, RCP4.5 (2046–2055) – V2, RCP8.5 (2026–2035) – V3, and RCP8.5 (2046–2055) – V4 (Figure 2).

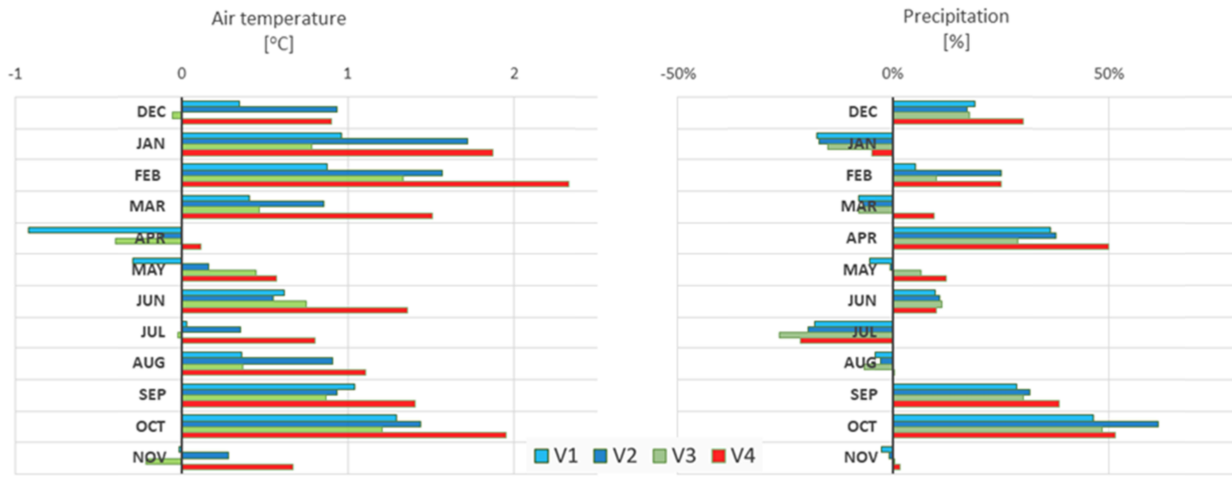

Figure 2. Changes in average monthly temperature and precipitation values for the RCP4.5 and 8.5 climate scenarios under short- and long-term horizons (Poznań station).

Significant changes in temperature and precipitation are expected in both the short- and long-term perspective. In the case of both extrapolation scenarios V3 and V4, the greatest changes should be expected in the autumn and winter months (even by 2.0–2.3 °C in October and February, respectively). In turn, the largest average decrease in temperature should be expected both in the short- and long-term perspective in April (even by 0.9°C for V2). A similar pattern of change can also be expected in the case of the moderate scenarios, V1 and V2. Again, the greatest rise in temperature is expected in fall and winter (up to 1.7°C in January in V2). In the case of rainfall, regardless of the selected scenario and time horizon, the most pronounced changes can be expected in December, February, April, October, and November, when the average monthly values may increase by over 60%. On the other hand, a drop in precipitation is expected in January, March, July, and August, and will amount to more than 26% (August V3).

3. Results

3.1 Total Nitrogen and Phosphorus Loads

The total nitrogen and phosphorus loads discharged from the entire Wełna River catchment (Oborniki calculation profile) simulated in the baseline scenario (BL) reached 2 185 ty^{-1} (tonnes per year) of TN, and 51 ty^{-1} of TP (Bojanowski et al., 2022). Since the studied catchment has been divided into 7 subcatchments, their individual TN and TP loads have also been provided by the BL simulation. For TN, the loads varied greatly from over 113.0 ty^{-1} for subcatchment 7 to 719.3 ty^{-1} for catchment 5. The same subcatchments were also distinguished by the highest and lowest TP loads, i.e., 3.1 and 14.4 ty^{-1} for subcatchments 4 and 5, respectively (Table S2).

The implemented V1–V4 scenarios will result in an increase of nutrient loads for the Oborniki calculation profile. The TN loads discharged from the Wełna River catchment will be higher by over 400 ty^{-1} (19%) in the short-time perspective (V1 and V3), while in the long-time perspective this increase will be even higher, reaching almost 750 ty^{-1} for V2 and V4, respectively (about 32–34%). Similarly, for TP, a load increase of almost 12.5 ty^{-1} (24–28%) should be expected in the short-time perspective (V3 and V1, respectively), while the long-term prediction will bring TP loads elevated by more than 44 ty^{-1} (57% for V2, or even 85% for V4) (Table S2).

The climate change scenario simulations for the individual subcatchments displayed even more pronounced and variable nutrient load changes. Generally, the future TN and TP load increase is expected to reach higher values in the long-time perspective scenarios, as observed previously for the entire catchment. In case of the TN loads, the increase ranged from 14 – 222 ty^{-1} (respectively 11–31%) for all subcatchments (1–6), whereas for subcatchment 7 these changes are expected to be almost 150 ty^{-1} (increase of 89% to 127%). For the TP loads, higher changes, in each of the adopted scenarios, are to be expected in subcatchments 4, 6, and 7, where they can reach an increase of over 149% under V4. While in the remaining subcatchments the increase will average about 23% for V1 and V3, and 57% in V2 and V4.

3.2. Source Attributed Total Nitrogen and Phosphorus Loads

Following the approach adopted in the previous study (Bojanowski et al., 2022), nutrient loads attributed to the five different sources (AGRO, FOREST, URBAN, POINT, and BACKGROUND) were also tracked in the current approach. The average values for the entire catchment area for the first three are shown in Figure 3. Since agriculture (AGRO) is the dominant type of land use in the studied catchment, this source accounts for 86% and 56% of the total TN and TP loads, respectively in the BL. However, for the individual subcatchments these shares clearly differ from 64% in subcatchment 7 to 89% in subcatchment 3 for TN, and from 44% in subcatchment 7 to 74% in subcatchment 2 for TP. Implementation of the climate scenarios showed the pronounced susceptibility of this source to the future changes to the combined effects of precipitation and temperature changes. Generally, a considerable increase of AGRO loads should be expected in the closing profile of the Wełna River catchment (Oborniki), approx. by 382–734 ty^{-1} (from 21–41%), and 9–28 ty^{-1} (from 31–97%) for TN and TP loads, respectively. As observed previously, the highest values were detected for the long-term scenarios (V2 and V4). The response of the AGRO source at the level of individual subcatchments to the climate scenarios displayed an even higher increase, up to 187% in subcatchment 7 (approx. 135 ty^{-1}, V2) for TN, and to 225% (approx. 5 ty^{-1}, V4) in subcatchment 6.

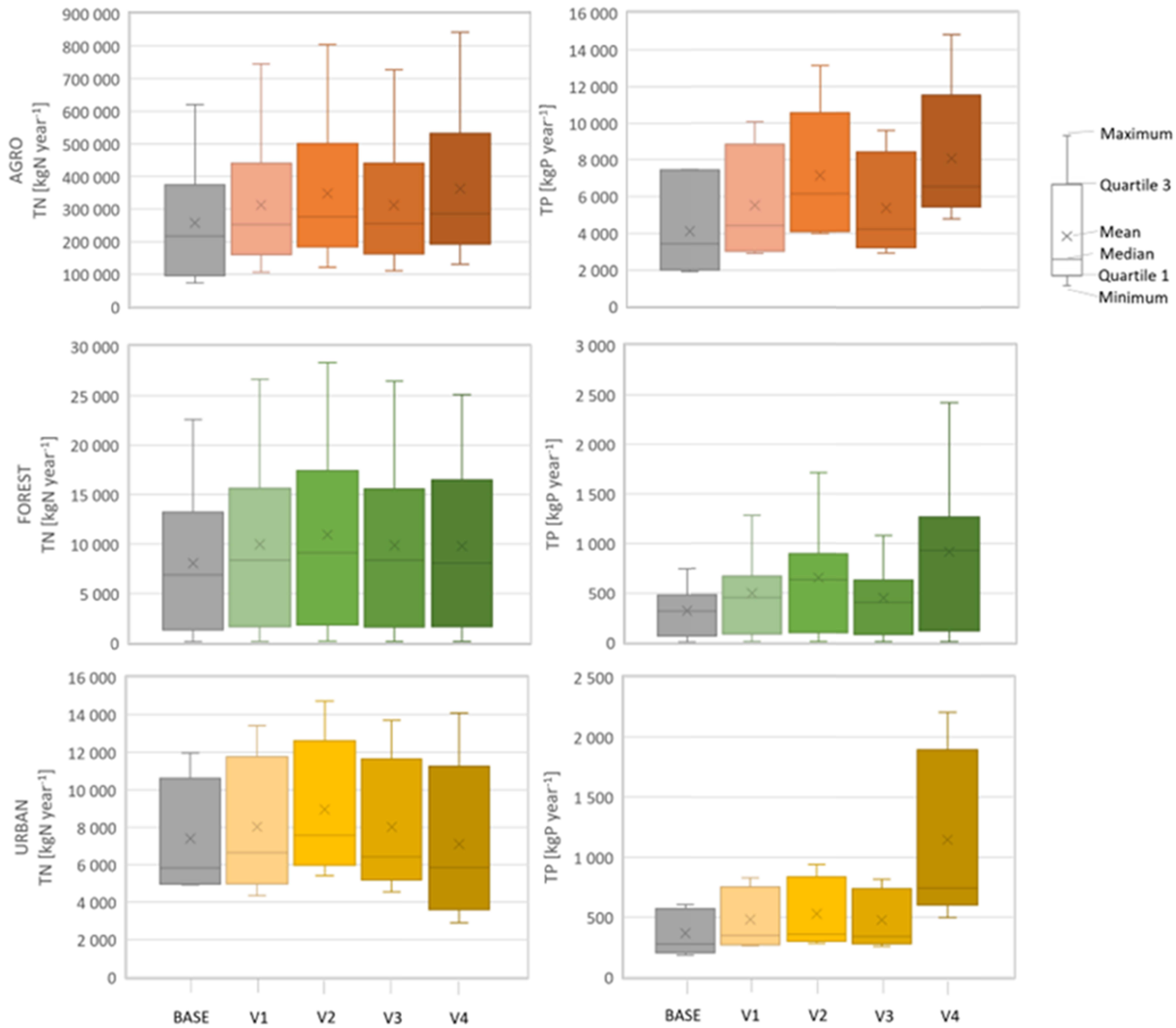

Figure 3. Average total nitrogen and phosphorus loads for the Wełna River catchment for the selected sources (AGRO, FOREST, and URBAN).

Although the forest areas constitute the second largest type of land use in the studied catchment, this source (FOREST) accounted only for 2.6% and 4.3% of the total TN and TP loads, respectively in V1. This source is characterised by large differences in the load shares at the individual subcatchment level, ranging from 0.1% for TN and TP in subcatchment 2, to even over 10% in subcatchment 6. The FOREST source is also characterised by the one with the highest reactivity to projected climate changes, especially for the long-term scenarios, approx. 20 ty^{-1} (up to 36% – V2), and approx. 4 ty^{-1} (187% – V4) for TN and TP, respectively. The expected changes in the individual subcatchments for these scenarios will be even higher, reaching approx. 126% (6ty^{-1} – V2), and 248% (0.7 ty^{-1}), for TN and TP, respectively in subcatchment 7.

Since the Wełna River catchment is not a remarkably urbanised one, and except for a few larger towns (Figure 1), its residents occupy rather scattered type dwellings, therefore, nutrient loads from the urban type of source (URBAN) accounted for less than 2% (approx. 37 ty^{-1}), and 3.5% (1.8 ty^{-1}) of the total TN and TP loads, respectively. Moreover, results for two of the subcatchments (4 and 6) were completely indiscernible, while the highest values were noted for subcatchment 1, where the town of Gniezno is located, and reached approx. 12 ty^{-1}, and 0.6 ty^{-1} for TN and TP, respectively. The changes induced by the incorporated climate scenarios again displayed a more pronounced impact of the long-term scenarios (V2 and V4), especially for the TP loads. The predicted changes display an increase of this nutrient load by 4 ty^{-1} (215%) for the total catchment TP load, and by 0.6 ty^{-1} (302%) for subcatchment 7.

The point source of nutrients (POINT) constituted the second largest source among subcatchments, accounting for the approx. 9% and 26% of the total TN and TP, respectively. Similarly, the URBAN nutrient loads showed a spatial distribution related to the localisation of these sources (Figure 1). Therefore, the largest loads should be expected in subcatchment 7, where the town of Oborniki is located, reaching approx. 27.5 ty^{-1} and 1.7 ty^{-1} for TN and TP, respectively. As expected, future changes of temperature and precipitation will generally have little impact on this type of source, with changes not exceeding -11% of the pertinent loads.

In the previously adopted approach (Bojanowski et al., 2022), the BACKGROUND source of nutrients has also been distinguished and consisted of both atmospheric deposition and the natural background. Since simulations for this source have certain limitations, related to, for example the SWAT model specificity and lack of detailed data on both the dry and wet deposition in Poland, only the total values are discussed in the rest of the study. For the closing profile of the Wełna River catchment (Oborniki) in the BL they reached nearly 99 ty^{-1} and 5.5 ty^{-1} for TN and TP, respectively, and under the implemented climate scenarios these values could increase by a further 30% (above 29 ty^{-1} – V2) for TN, and 140% (almost 8 ty^{-1} – V4) for TP loads.

To track temporal changes in the BL and climate scenarios, the monthly values of TN and TP loads were also extracted from the Wełna River model and discussed for the three main nutrient sources in this catchment (AGRO, FOREST, and URBAN). As expected, the pattern of these changes for the AGRO and FOREST sources was similar, with the largest increases occurring in the autumn and winter periods due to the forecasted precipitation and temperature changes. For AGRO, these changes reached 87% (approx. 180 tm^{-1} – tonnes per month), and 302% (approx. 9 tm^{-1}) for TN and TP, respectively in October under V2. While for the FOREST source they reached 134% (approx. 7 tm^{-1} – V2), and even over 735% (approx. 2 tm^{-1} – V4) for TN and TP, respectively (October and December). As for the URBAN source, the monthly pattern of changes notably differed. The highest response from this source could be expected in late spring, i.e., May and June. By far the weakest response to changes in precipitation and temperature is understandably exhibited by TN and TP loads from the POINT source, regardless of the month (maximum of 12% and 17% increase in January for V2 and V3, respectively) (Table 2).

Table 1. Total nitrogen and phosphorus load results for the baseline scenario in individual months for the selected sources (AGRO, FOREST, and URBAN).

Month	AGRO	FOREST	URBAN	AGRO	FOREST	URBAN
	TN – BASE [kgm^{-1}]			TP – BASE [kgm^{-1}]		
12	177 582	8 278	2 492	4 525	261	190
1	247 996	4 328	2 078	1 899	207	133
2	182 033	7 336	4 826	6 532	261	144
3	250 232	7 424	3 865	1 941	169	113
4	110 265	3 483	2 738	1 372	143	87
5	70 472	2 536	3 423	849	110	99
6	36 436	1 601	5 380	397	88	139
7	42 464	2 671	3 718	1 099	261	197
8	146 002	3 661	1 915	2 195	119	154
9	141 004	2 531	1 939	1 698	123	146
10	206 308	5 312	2 305	3 024	251	234
11	189 328	7 319	2 346	3 235	237	189
Total	1 800 123	56 478	37 026	28 766	2 231	1 823

4. Discussion

Simulations of the climate forecast impacts on pollutant loads from agricultural catchments are generally aimed at estimating changes in transport, changes, and loads of nitrogen and phosphorus from designated areas (Cho et al., 2016; Huttunen et al., 2015; Marcinkowski et al., 2017; Merriman et al., 2019; Molina-Navarro et al., 2018; Ockenden et al., 2016; Shi et al., 2021; Tattari et al., 2017). Therefore, in the current approach we decided to analyse the spatial and temporal variability of runoff as part of future climate projections, taking into account both different sources of nutrients, and the division into subcatchments. The original division of the Wełna River catchment into subcatchments, used for comparison of different methods to estimate nitrogen and phosphorus loads from different sources (Bojanowski et al., 2022), enabled a step forward in understanding responses of riverine catchments towards future precipitation and temperature changes. Having at our disposal a catchment model with a good performance (based on statistical measures), we could follow not only total load changes in particular subcatchments, as in previous studies, but also track localisation of the pollution sources and their direct impact on load estimations, and moreover, do it in future time-horizons.

Even relatively small catchments such as the Wełna River, dominated by one type of land use, are not homogeneous. The diversity of individual features of each of their subcatchments (location, area, land use, crops, soils, and slopes) significantly affect total loads of nutrients discharged from these areas. Our research showed first that the differences in these loads, in calculation profiles closing each of the analysed subcatchments (Figure 1), differ by almost 7 and 3 times for total nitrogen and phosphorus, respectively. Such large differences in nutrient loads should not be surprising since the individual subcatchments differ significantly in total surface area (from 164 km^2 – 688 km^2). Moreover, the predominant share of these subcatchments is occupied by agriculture which is the main driver of nutrient pollution in this catchment. However, it should be noticed that total loads are not simply driven by acreage of agricultural land use. When unit loads for individual subcatchments in the BL are taken into consideration (from 327 to 1538 kgkm^{-2} of TN, and from 9 to 30 kgkm^{-2} of TP), the influence of other factors is clearly visible. Among them especially is slopes (e.g., differences between the flat north-western and central part vs. southern subcatchments), and also soil type, crops, and thus fertilisation and agrotechnical treatments.

When diversity of the total subcatchments nutrient load is discussed, the impact of other land use types should be taken into consideration, e.g., forest and urban types of land use. Although their area share seems to be minimal when compared to the agricultural one, their impact on total nutrient load is meaningful. Forested areas are the only relatively natural ones characterised by high water retention (Wu et al., 2021; Zhang et al., 2017), therefore, their location is important for the pollutant transport in the land phase of the catchment. As shown in Figure 4 the spatial distribution of unit load confirms forest areas as characterised generally by low pollutant values in the surface runoff. Therefore, when they are located along the watercourse (e.g., subcatchments 4, 6, and 7) they can effectively reduce the load of nutrients from agriculture. The analysis of the spatial distribution of load units also allowed us to identify urban areas, traditionally located along the main watercourse or a confluence of its tributaries, as hot spots for both total nitrogen and phosphorus (e.g., the municipalities of Gniezno, Wągrowiec, and Oborniki). Therefore, share and location of urban impervious areas in individual subcatchments are equally important when total nutrient loads are discussed in closing calculation profiles (e.g., subcatchments 1, 2, 3, and 7).

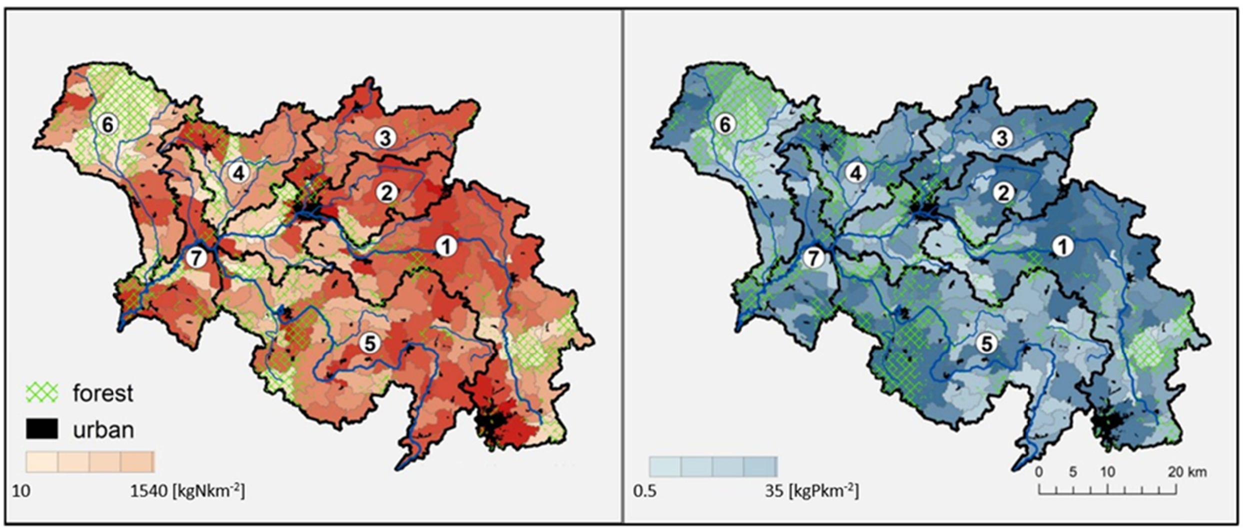

Figure 4. Distribution of total nitrogen and phosphorus loads of surface runoff in individual subcatchments of the Wełna River.

Taking advantage of possibilities embedded in the digital platform – Macromodel DNS/SWAT, we could also broaden the understanding of temporal changes in nutrient sources; discussed here in terms of short- and long-term climate forecasts, and also monthly load variability. The obtained results clearly indicated an increase of the pressure from agricultural sources, by more than 20% on average (approx. +384 ty^{-1}) in the short-term, and 38% (approx. +683 ty^{-1}) in the long-term scenarios for nitrogen. As for phosphorus this increase totalled 33% (approx. 9 ty^{-1}), and 85% (approx. 25 ty^{-1}) for the same scenarios, respectively (Figure 5). Such large high reactivity of this source to changes of precipitation and temperature patterns confirms the dominant role of agricultural systems in nutrient cycles and losses, which distinguishes them from natural systems due to intensive human intervention (Bowles et al., 2018). The similar pattern of reactivity to future climate changes is shared by the forest areas. However, their loads will remain negligible compared to agricultural ones. The response of forests to predicted changes in rainfall and temperature will not exceed on average 20 ty^{-1} and 4.1 ty^{-1} in the long-term perspective (V2 and V4) (Figure 5). Since forest areas are not commonly subjected to nitrogen and phosphorus fertilisation, in this area such an increase results mainly from the interactions between vegetation and climatic conditions that regulate the outflow of nutrients from this source. In addition, excessive inflow of nutrients from neighbouring areas (sources) may cause their accumulation in forest soils, resulting in increased nutrient leaching to surface waters (Bernal et al., 2012; Gebeyehu et al., 2019; González de Andres, 2019. In turn, the response of urbanised areas to climate change distinguishes them from the other non-point sources in this catchment (Figure 5). The climate change simulations indicated fluctuations in the expected nitrogen loads from -9% (0.2 ty^{-1}) for V4 to 22% (1.1 ty^{-1}) for V2. At the same time, an increase of over 200% (0.5 ty^{-1}) for phosphorus under V4 can be expected. Such large discrepancies between nitrogen and phosphorus loads result from different behaviours of both elements in the impervious areas. While in natural catchments phosphorus is relatively immobile, it shows high retention in soils, whereas in urban catchments this element is lost more readily through stormwater runoff. In case of nitrogen, urban catchments tend to show much greater retention due to unmeasured losses to the atmosphere and groundwater (Hobbie et al., 2017; Miller et al., 2017).

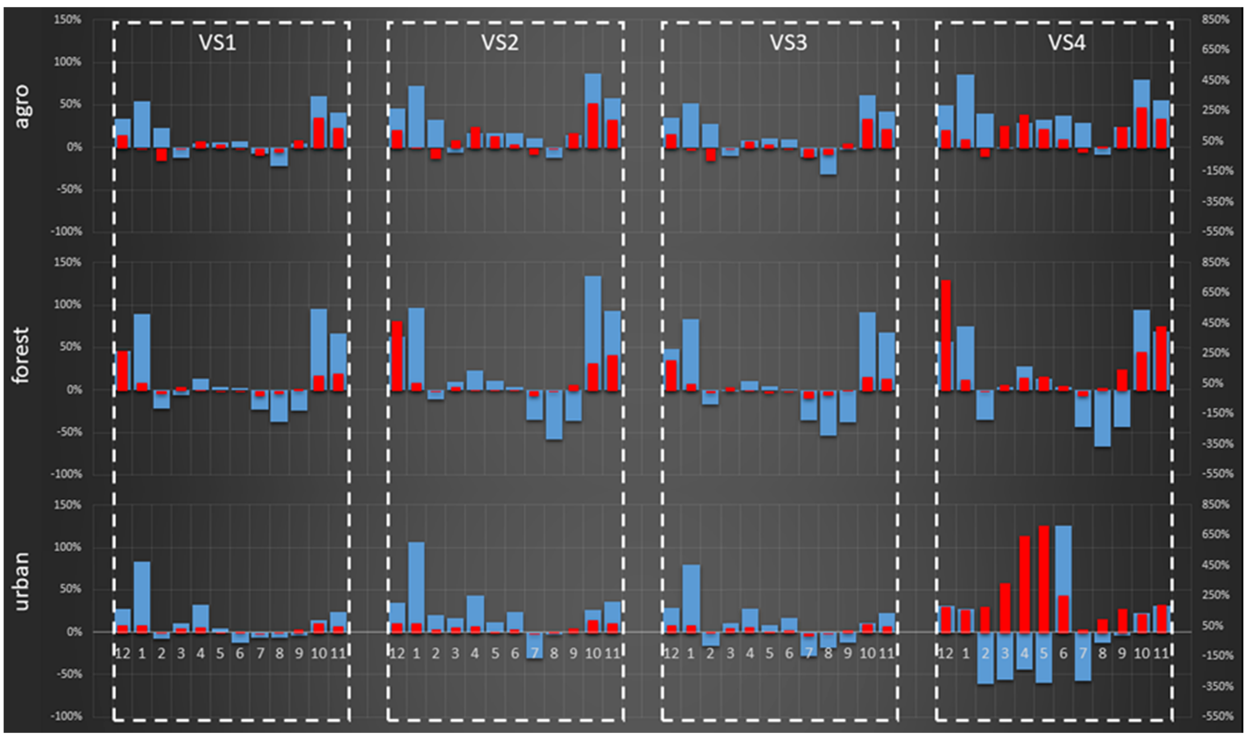

Figure 5. Total nitrogen and phosphorus load changes (percentage) for individual months in the variant scenarios V1-V4 for the selected sources (AGRO, FOREST, and URBAN).

As for the monthly load's variability from individual sources, it is largely determined by the patterns of precipitation foreseen in this area. For all non-point sources, the large pollutant outflows are observed from autumn to early spring with a noticeable decrease in the summer. Agriculture loses the most nutrients in February and March (up to 250 tm^{-1} and 6.5 tm^{-1}, TN and TP respectively) which is related to intensive fertilisation of the fields at the beginning of the vegetation season. Plants in the early stages of growth do not provide sufficient protection against rainfall, which results in loss of soil particles, and nitrogen and phosphorus compounds (Blanco-Canqui, 2018; Matej-Lukowicz et al., 2020; Sharma et al., 2018). Meanwhile, the predicted climate changes will deepen the problem of agriculture as the main pressure on surface waters for most months of the year. Particularly large changes can be expected in the autumn and winter months (even by more than 210 tm^{-1} in January for V4, and more than 9 tm^{-1} in October for V2, TN and TP respectively), where the temperature is expected to increase by even more than 2^{o}C. It will result in the shortening of the frost and snow cover period protecting the soil against the erosive action of increased precipitation, and will additionally enlarge nutrient loads (Huttunen et al., 2015). A similar monthly pattern has been observed for forest areas, however, considerable differences in nutrient loads should be noticed. From November to March, forests release the largest TN and TP loads (maximum 8.2 tm^{-1} and 0.3 tm^{-1}, respectively) when leaf litter can additionally increase nutrient loads in the outflow from this type of source (Bratt et al., 2017). Forests also show greater reactivity to changes in individual months than agriculture, which is visible for TN throughout the year, and for TP in autumn and winter (Figure 5). As for urbanised areas, they differ from other sources in terms of response to monthly changes in precipitation and temperature. Especially in the long-term RCP8.5 scenario (V4), where previously discussed changes in the behaviour of both elements in impervious areas are the most noticeable. As a consequence, we can observe a clear decrease in TN loads for most of the year, and an increase in TP loads at the same time (Figure 5).

As for the point sources our results showed that they will be the least affected by the discussed changes. Their attributed nutrient loads have been almost constant in the scale of the whole catchment with changes resulting from the introduced variant scenarios at the level of 0–2%. While at the level of individual subcatchment, differences between the BL and V1–V4 were between -11% and +11% for both TN and TP. While general invariability of loads from this source, in relation to weather conditions is evident, the minor differences at the subcatchment level results mainly from localisation of point sources and efficiency of treatment techniques. It should be also noted that available demography data does not predict major changes in the population of this area (Statistics Poland, 2022).

Moreover, the available data on spatial land use changes, based on Corine Land Cover (EEA, 2002; EEA, 2018), although does not provide a forecast, enables a valuable trend analysis. Changes in spatial development between 2002 and 2018 indicate mainly a growth of urban areas in the studied catchment by an average of 2 km^2y^{-1}. Therefore, the impact of land use changes on nutrient loads seem to be negligible in this catchment when compared to the impact of climate change. Such a trend has been confirmed for other catchments (e.g., Luo et al., 2020), however, the impact of socio-economic changes has also been recently discussed (Bartosova at al., 2019; Huttunen et al., 2021; Pihlainen et al., 2020). Since translation of shared socio-economic pathway narratives (SSP) (Riahi et al., 2017) to fertiliser and crop prices, and estimation of the impact of these changes on nutrient loading to water bodies, it is still far from being uniform; further studies on this subject are desirable. This clearly identifies gaps which can be addressed by extending variant scenario simulations under the Macromodel DNS/SWAT climate scenarios to include planned and potential nutrient stewardship techniques, and water management activities.

Such an approach is particularly desirable in catchments belonging to areas supplying water bodies particularly at risk of eutrophication. Waters of the Baltic Sea have been recognised for many years as being eutrophied due to the high inflow of nutrients from inland and atmospheric deposition (Gustafsson et al., 2012; HELCOM, 2021; Pedde et al., 2017). Moreover, the Helsinki Commission's (HELCOM) reports, and many authors indicate clearly that agriculture is the main source of nutrients discharged into the Baltic Sea (HELCOM, 2011; HELCOM, 2022; Piniewski et al., 2014). Similar studies have also identified that predicted climate change will increase nutrient outflow from these areas in the future (Arheimer et al., 2012; Andersson et al., 2015; Friedland et al., 2012; McCrackin et al., 2018). Although the Wełna River is not discharging directly into the Baltic Sea through the hydrologic network, it contributes to the total riverine input into this sea basin. Moreover, a foreseen increase of nutrient loads from this relatively small area (2 621 km^2) can reach in a long-term perspective up to 34% of TN, and 85% of TP in the scale of the whole catchment. Therefore, it serves as a good example illustrating the current situation related to the nutrient management issues in this part of the Baltic Sea catchment.

The whole area of Poland is designated as a vulnerable zone in the terms of the so-called Nitrate Directive (91/676/EEC), and measures aimed to reduce nitrate input are covered by the adequate program. However, it should be noted that the parallel program for phosphorus has never been created. Moreover, the national system of water services fees is not whatsoever related to the quantity of discharged nitrogen and phosphorus loads, nor to their concentrations in wastewater (excluding fees for exceeding substances specified in water permits). Also, nutrient emission from agricultural sources (diffuse losses) is not included in the fee system in any way. Therefore, these sources are not subjected to the polluter pays principle. Enforcement of these fees, although difficult to be introduced to national legislation and modelling tools, could contribute to changing the balance of nutrient sources into the environment. It would be also fully compatible with current insights on socio-economic-driven changes in the environment (Olesen et al., 2019; O'Neill et al., 2014). Furthermore, projects of the second update of Polish River Basin Management Plans (IIaPGW) basically do not contain technical measures aimed at reduction of agricultural origin diffuse nutrient load (SWH–PW, 2022). Most measures in this category are focused on administrative, educational, or policy activities. This as well limits their impact assessment with the tool on the SWAT software. The effects of IIaPGW on agricultural loads may be implemented only by modifying input of scenarios i.e., reducing fertiliser doses and agricultural practice calendars, reducing surface runoff, and modifying spatial development of buffer zones. However, modification of agricultural practices and crop production in SWAT input (Xie et al., 2017), fertilisation intensity (Zhang et al., 2020), and management operations offered by the SWAT tool (Himanshu, 2019) should be thoroughly tested if such measures are sufficient to prevent effects of climate changes on nutrient loads.

The performed analyses in the Wełna River catchment can also contribute to the so-called hybrid approach to the nutrient loads estimation, i.e., combining the mass-balance and modelling approaches (Bojanowski et al., 2022). The results of the climate change scenarios (modelling approach) can be recalculated to obtain new coefficients which can be then used in a mass-balance approach, with the assumption that the sources of nutrients (emission) will remain constant or increased by known forecasts. So far, in the original mass-balance approach the coefficients representing agricultural runoff from the catchment were sourced from the available literature, and in some cases raised questions on their representativeness in local conditions. Therefore, obtaining them directly from the catchment model can definitely refine mass-balance calculations which are useful in the preliminary nutrient load assessments.

Despite huge benefits of the modelling approach, it should also be remembered that the presented results must be taken as an indication of future spatio-temporal trends in this catchment, not as a source of specific values. Quite a limited number of available field monitoring values (qualitative), sufficient for the Water Framework Directive (WFD) induced measurements, is often inconsistent with data required to calibrate and validate the catchment model, which possibly leads to load over/underestimation. It should be remembered that climate change scenarios, in terms of precipitation and temperature, were obtained for the nearest meteorological station localised outside of the catchment (Poznań), and were not distributed across the land surface as the process occurs in nature. Moreover, reliable predictions of future land use changes and spatial development would definitely increase simulation accuracy. It should also be remembered that some limitations result directly from the SWAT model. Differentiation of particular nutrient sources requires many generalisations and assumptions, like in case of background source impact, which could be defined in different manners. Finally, future research should include further steps to incorporate more specific field information on specific sources, e.g., urban, to limit the use of default coefficients embedded in the model.

5. Conclusions

In this study, using possibilities of the digital platform Macromodel DNS/SWAT, we elucidated climate change effects in a middle-sized lowland catchment with emphasis on the spatio-temporal behaviour of different nutrient sources. The catchment model proved to be a fully scalable tool which enabled tracking loads in the subcatchment level in the short- and long-term perspective, therefore offering a broad range of instruments for decision makers, e.g., identification of hot-spots or contribution of sources in outflowing nutrient loads.

Our results confirmed the increase of the nutrient loads under the predicted climate changes in all the subcatchments. Chiefly from the agricultural land use type, which may constitute up to 86% and 56% of total nitrogen and phosphorus loads, respectively. This type of the land use will also remain the main pressure in the foreseen scenarios under the short- and long-term perspective. In this study we also highlighted the impact of the other land use types. Especially of forest areas, which are highly reactive to climate changes, and through their localisation within the subcatchment, can distinctly alter nutrient outflow. Moreover, our results indicated that contribution of urban areas to the total nutrient loads should be further investigated since the dynamics of nitrogen and phosphorus release, from impervious surfaces, is noticeably different from the other diffuse sources.

Furthermore, considering the current lack of concrete technical solutions aimed to reduce nutrient loads from Polish catchments, we suggest that modelling, as presented in the current example, must be recognized as an important tool for testing specific measures. Implementation of different nutrient stewardship techniques or checking the effectiveness of buffer zones along rivers will bring important information from the catchment management point of view. Finally, further studies should also take into account factors which may reflect potential changes in spatial and economic development of catchments, as specified by the Shared Socioeconomic Pathways (SSP) scenarios.

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The authors declare no competing interests.

Open Research

The output data used for analyses presented in the study are available at Mendeley Data via https://doi.org/10.17632/rkxmncmr9k.1 with CC BY NC 3.0 license

ArcSWAT 2012.10.25 of the ArcSWAT used for scenario analysis is preserved at https://swat.tamu.edu/software/, available via open source, and developed openly by Texas A&M.

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