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Prognoza wpływu zmian klimatu na ustrój hydrologiczny rzek i funkcjonowanie siedlisk rzecznych i dolinowych

Modelling the impact of climate change on the hydrological regime of rivers and the functioning of selected river and valley habitats

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Doctoral thesis

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Streszczenie

Prognoza wpływu zmian klimatu na ustrój hydrologiczny rzek i funkcjonowanie siedlisk rzecznych i dolinowych

Niniejsza rozprawa jest zbiorem trzech opublikowanych, powiązanych ze sobą tematycznie artykułów, w których wykorzystano modele hydrologiczne do analizy wpływu zmian klimatu na wybrane siedliska rzeczne i dolinowe w dorzeczach Wisły i Odry w Polsce. Wpływ zmian klimatu jest oceniany dla całego środowiska związanego z rzeką: doliny, cieku i wysp, koncentrując się odpowiednio na mokradłach zasilanych wodami powierzchniowymi, wybranych gatunkach ryb i ptaków. Dane wejściowe, które są wspólne dla trzech artykułów, składają się z wyników symulacji modelu SWAT i scenariuszy zmian klimatu, które wspólnie tworzą projekcje hydrologiczne dla okresu referencyjnego (1971-2000), bliskiej przyszłości (2021-2050) i dalekiej przyszłości (2071-2100). Dane dotyczące przepływu uzyskane z tego modelu są wykorzystywane do obliczania wskaźników opisujących funkcjonowanie wybranego siedliska lub gatunku. Wpływ zmian klimatu na mokradła zasilane wodami powierzchniowymi jest oceniany na podstawie liczby dni, w których przepływ przekracza przepływ brzegowy. Dla szczupaka, klenia i łososia atlantyckiego wybrano zestaw wskaźników zwanych Indicators of Hydrological Alteration (IHA), które reprezentują ich preferencje dotyczące przepływu podczas tarła i migracji. Występowanie katastrofalnych sezonów lęgowych mewy siwej, śmieszki i rybitwy białoczelnej oceniono na podstawie korelacji między sukcesem lęgowym a dostosowanymi wskaźnikami IHA. Wyniki pokazują, że wpływ zmian klimatu na mokradła zasilane wodami powierzchniowymi zależy od ich obecnego stanu ochrony i występowania ryzyka wysychania. Przewiduje się, że łosoś atlantycki, który migruje na dalekie odległości, aby dotrzeć do swoich tarlisk, będzie najbardziej dotknięty zmianami klimatu, ponieważ 97% odcinków rzek wykazuje zmiany w przepływie. Rybitwa białoczelna będzie musiała zmierzyć się z największym (spośród 3 analizowanych gatunków ptaków) wzrostem udziału lat z katastrofalnym sezonem lęgowym (wzrost do prawie 30%). Opracowana metoda modelowania może być stosowana z danymi wejściowymi z innych modeli klimatycznych lub hydrologicznych niż te wykorzystane w niniejszej rozprawie. Zmiana ustroju hydrologicznego wynikająca ze zmian klimatu zwiększy potrzebę uwzględniania przepływów środowiskowych w planach gospodarowania wodami, strategii łagodzenia i adaptacji do zmian klimatu.

Słowa kluczowe – modelowanie, mokradła, ptaki, ryby, wskaźniki

Summary

Modelling the impact of climate change on the hydrological regime of rivers and the functioning of selected river and valley habitats

This thesis is a collection of three published, thematically related articles that use hydrological models to analyse the impact of climate change on selected river and valley habitats in the Vistula and Odra river basins in Poland. Climate change impact is assessed for the entire environment associated with the river: the valley, watercourse and islands by focusing on riparian wetlands, selected fish and bird species, respectively. The shared input data which serves as the foundation for this dissertation consists of SWAT model simulation results and climate change scenarios that together form hydrological projections for the reference period (1971-2000), near future (2021-2050) and far future (2071-2100). Output on streamflow from those models is used for calculating indicators most suited to describe the functioning of the chosen habitat or species. Water recharge of riparian wetlands is assessed on the basis of number of days when streamflow exceeds bankfull flow. For pike, chub, and Atlantic salmon a set of Indicators of Hydrological Alteration (IHA) were chosen that represent their streamflow preference during spawning and migration. Occurrence of catastrophic breeding seasons of mew gull, black-headed gull and little tern was assessed on the basis of correlation between nesting success and adjusted IHA. The results show that climate change impact on surface water-fed wetlands depends on their current conservation status and risk of drying out. Atlantic salmon, which migrates long distances to reach their spawning grounds, are predicted to be most affected by climate change, as 97% of river sections show changes in streamflow. Little tern will face the largest (of the 3 bird species analysed) increase in the percentage of years with a catastrophic breeding season (rising to nearly 30%). The developed modelling approach can be used with inputs from other climate or hydrological models than those used in this dissertation and can be tailored to other species or habitats of interest. The changing hydrological regime resulting from climate change will increase the need for creating environmental flow management plans, mitigation and climate change adaptation strategies.

Key words: streamflow, wetlands, birds, fish, indicators

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1. Introduction

Climate change is one of the most pressing global issues of our time. It has exposed ecosystems to conditions that are unprecedented across millennia. Climate change has caused losses of local species, increases in disease and mass mortality events of animals and plants resulting in the first climate-driven extinctions, ecosystem restructuring, and declines in crucial ecosystem services. Freshwater and terrestrial ecosystems have been negatively impacted by changes in the hydrological cycle brought on by climate change (IPCC, 2022).

The three main elements that must be considered while managing a river ecosystem in a changing climate are habitat protection, heterogeneity, and biodiversity conservation. The most important challenge is to protect streamflow patterns, channel morphologies, and nutrient stability (Siddha and Sahu, 2022). The streamflow regime is a characteristic pattern of a river's streamflow quantity, timing, and variability. The natural flow paradigm identifies the natural streamflow regime together with its natural fluctuations as the optimum condition for river ecosystems (Poff et al., 1997). Any deviations from the natural flow patterns cause ecological consequences that favour invasive species rather than adapted endemic species (Schneider et al., 2013). The hydrological regime necessary to maintain freshwater and estuarine ecosystems, as well as the human livelihoods and well-being that depend on them, has come to be known as environmental flows (Arthington, 2012).

In the context of international and national policies and actions for climate change adaptation, it is necessary to assess and quantify the consequences and vulnerabilities at the global and regional scales (IPCC, 2022). Climate models are essential for understanding climate change and anticipating its risks. They serve as the foundation for projecting impacts, guiding adaptation decisions and establishing mitigation goals. For society to be able to make sound decisions in the face of rapidly intensifying climate change, more precise and in-depth knowledge is now required (The Royal Society, 2021). Models that utilize climate projections and scenarios can contribute to increasing our knowledge concerning the possible impact of climate change and the relationship between hydrology and ecology.

Ecohydrology quantifies and discusses the connections between biotic dynamics and hydrological processes at the catchment scale. It is a scientific concept used for environmental problem-solving and addressing environmental issues (Zalewski et al., 1997). Different flows in a river ecosystem serve various ecological functions and can be distinguished according to their magnitude, timing, frequency, duration and rate of change (Bunn and Arthington, 2002). Overall, diverse combinations of those streamflow features provide varied habitat characteristics and are therefore critical to maintaining a high level of regional diversity (Allan et al., 2005). The biotic composition, integrity, and evolutionary potential of riverine ecosystems, including associated floodplains and wetlands, are now understood to depend on the complete streamflow regime, which can range from hydrological droughts to floods (Mathews and Richter, 2007; Schneider et al., 2013). The distribution and abundance of some taxa can be impacted even by small changes in the spatiotemporal variability of streamflow (Bunn and Arthington, 2002).

This research utilizes the ecohydrology concept and process-based hydrological modelling to prepare interdisciplinary studies on the impact of climate change on streamflow regime important for selected habitats and species. There are three case studies, each focusing on a different ecological indicator of aquatic ecosystem health: wetland habitats, fish and bird species. Ecological indicators are biological assemblages of species or taxa that can provide information on the health of an ecosystem due to their presence or condition. Their variation can be an indicator of the pressures and impacts from anthropogenic activities and the natural world acting on ecosystems at various spatial and temporal scales (Pinna et al., 2023).

Wetlands represent the subtle link between land and water, which is why they are strongly affected by the consequences of climate change, pollution and overexploitation. Their vulnerability to change makes them a good sustainability indicator. Ramsar Convention highlights that wetlands contribute directly or indirectly to the 75 indicators of Sustainable Development Goals (SDGs). They are vital to the water cycle because they take in, store, and release water while controlling flows and sustaining life (Bullock and Acreman, 2003; Ramsar Convention on Wetlands, 2018). An appropriate hydrological regime within a wetland is essential to maintain its functions and services (Okruszko et al., 2011). Wetlands are nature-based solutions that provide a variety of ecosystem services, thus it is critical to estimate the effects that climate change may have on them (Thorslund et al., 2017). Three Natura 2000 surface water-fed habitats were chosen for analysis: hydrophilous tall herb fringe communities, alluvial forests, and riparian mixed forests. For a Natura 2000 Special Area of Conservation (SAC), there is a legal obligation (Habitats Directive) to guarantee that the habitats are restored to, or kept at, a good conservation status, therefore research on this subject is particularly crucial (European Comission, 2009). Additionally all SACs should have a Standard Data Form (SDF) which assesses the current condition of wetland habitats by giving information on the conservation status of habitats and the threats to maintaining a good habitat condition (European Commission, 2011). The availability of data on its conservation status creates a good basis for climate change impact assessment.

Fish are good indicators for the assessment of the ecological integrity of large rivers. Fish communities in large rivers are characterized by a high diversity, which reflects the structural variety and ecological richness of habitats and connected floodplains (Schiemer, 2000). Fish are suitable indicators due to their presence in almost all aquatic systems, availability of information on life history and habitat preferences, longevity in comparison to other aquatic organisms which can provide data on long term records of environmental stress. Fish species can be migratory or sedentary, and as a result, they might reflect local stresses or broader effects (Whitfield and Elliott, 2002). Three fish species were chosen in this thesis: pike, chub and Atlantic salmon. They represent different flow requirements during spawning. There is a good availability of literature concerning the streamflow preferences of these fish species. Furthermore, chub and Atlantic salmon carry out migration on different distances while pike is sedentary. The selected species can represent groups of fish with similar life cycles.

River birds can serve as valuable indicators of watershed and river quality because they are impacted by both terrestrial and aquatic processes on a variety of scales (Larsen et al., 2010). Nesting success of those birds is directly connected to the availability of river islands that are shaped by the river hydrology and hydromorphology, therefore birds can serve as indicators of river ecosystem condition. Birds that migrate and live on islands are particularly vulnerable to climate change, and factors including poor dispersal ability, low population numbers, restricted or patchy habitat, and limited climatic range exacerbate this concern. Gulls and terns are among the birds in Poland that are most sensitive to climate change (Bartosz et al., 2012). Therefore, this thesis focuses on the little tern, mew gull and black-headed gull. All three species are strictly protected in Poland which further indicates the need for the assessment of the vulnerability of these species to climate change.

2. Research objectives

The central aim of this thesis is to improve insight into the possible impacts of climate change on selected habitats and species in Poland dependent on the hydrological regime of rivers. This was achieved through modelling and linking hydrology with ecology. Hydrological projections obtained with the Soil & Water Assessment Tool (SWAT) model for greenhouse gas emission scenarios until the end of the 21st century were used to assess the impact of climate change. The indicators that were used determine the functioning of the examined ichthyofauna, avifauna, and wetland plant communities, under climate change conditions.

Research objectives:

- To establish indicators that grasp the dependency between the hydrological regime of rivers and the life cycle of organisms,
- To model potential future alterations to streamflow characteristics caused by climate change,
- To evaluate three case studies focusing on three groups of biota (selected wetland habitats, fish, and bird species) and project climate change impact on streamflow regime important for their functioning,
- To identify species and habitats that are most vulnerable to climate change.

Main research hypothesis:

It is possible to use hydrological models to analyse the impact of climate change on selected river and valley habitats.

3. Thesis outline and methods

This dissertation was prepared as a coherent collection of three published and thematically related scientific articles:

Article 1

O'Keeffe, J., Marcinkowski, P., Utratna, M., Piniewski, M., Kardel, I., Kundzewicz, Z. W., Okruszko, T., 2019. Modelling Climate Change's Impact on the Hydrology of Natura 2000 Wetland Habitats in the Vistula and Odra River Basins in Poland. *Water*, 11(10):2191. https://doi.org/10.3390/W11102191

Article 2

O'Keeffe, J., Piniewski, M., Szcześniak, M., Oglęcki, P., Parasiewicz, P., Okruszko, T., 2018. Index-based analysis of climate change impact on streamflow conditions important for Northern Pike, Chub and Atlantic salmon. *Fisheries Management and Ecology*, 26(6), 474–485. https://doi.org/10.1111/fme.12316

Article 3

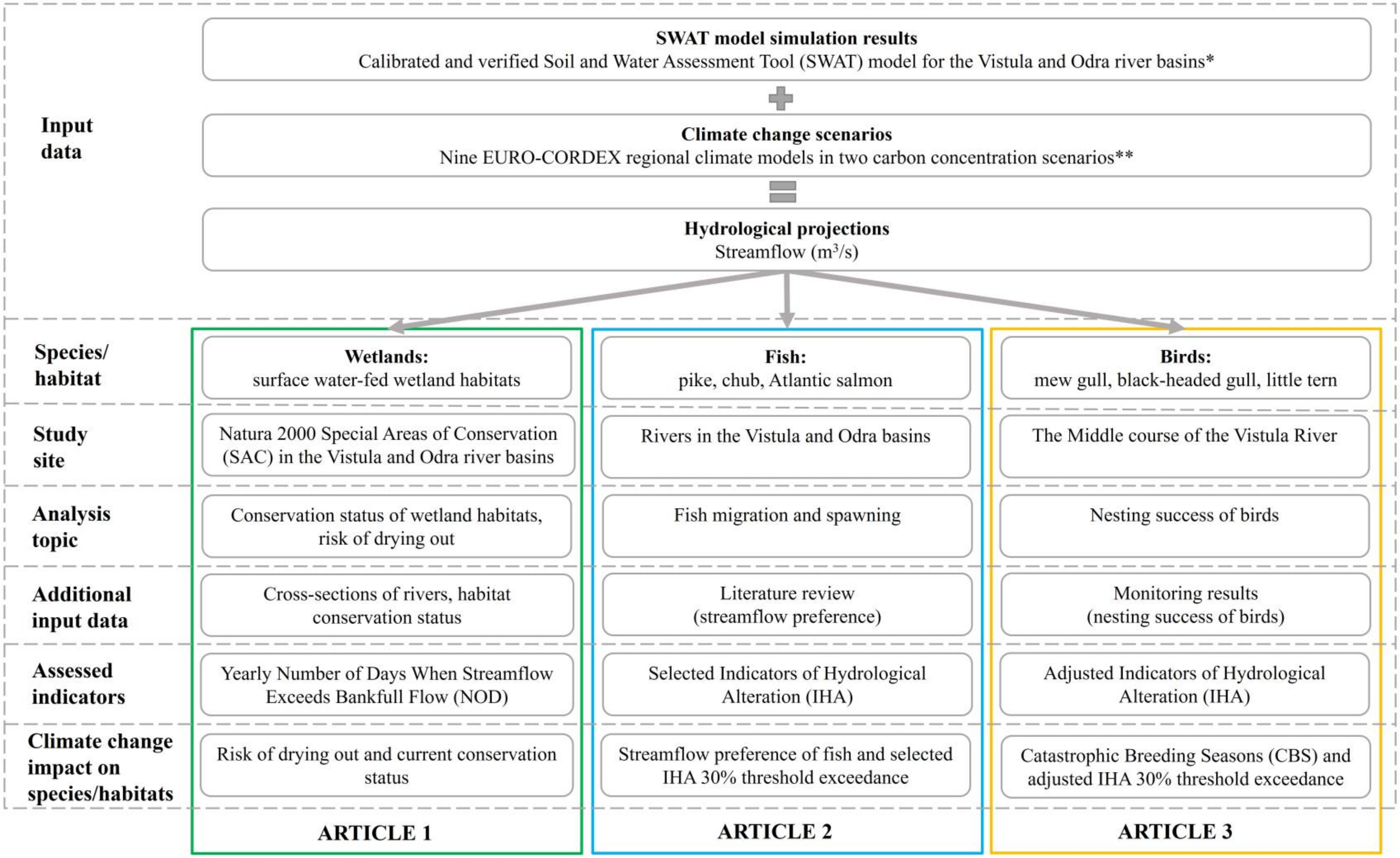
O'Keeffe, J., Bukaciński, D., Bukacińska, M., Piniewski, M., Okruszko, T., 2023. Future of birds nesting on river islands in the conditions of hydrological variability caused by climate change, *Ecohydrology & Hydrobiology*, In press, https://doi.org/10.1016/j.ecohyd.2023.03.007

Each of the articles focuses on a selected group of species and habitats: riparian wetlands (Article 1), fish (Article 2) and birds (Article 3). All three articles are appended to this dissertation (see Chapters 9-11). Articles included in this collection are multi-author publications where Joanna O'Keeffe is the first author and played a leading role during the implementation of the described research and the creation of the manuscripts. Author statements describing individual contributions to the preparation of the articles are included in Chapter 12.

The analyses presented in the articles are based on models and projections of climate change and hydrological variables prepared within the framework of the Polish-Norwegian project CHASE-PL (Climate change impact assessment for selected sectors), which is the common element and starting point for this dissertation. Hydrological input data was obtained from the SWAT model calibrated and verified for Poland (Piniewski et al., 2017) and a set of nine EURO-CORDEX regional climate models under two greenhouse gas concentrations called Representative Concentration Pathways (RCP) 4.5 and 8.5 (Mezghani et al., 2017). RCP 4.5 is described as intermediate scenario in which emissions peak around 2040 and then decline. RCP 8.5 is the highest baseline emissions scenario in which emissions continue to rise throughout the twenty-first century (IPCC, 2014). Climate parameters were simulated for the reference period (1971-2000) and for two future time horizons: near future (NF, 2021-2050) and far future (FF, 2071-2100). This thesis builds upon the modelled hydrological and climate data which is used as input to analyse the impact of climate change on the functioning of species and habitats dependent on the hydrological regime. The goal was to extend the functionality of the hydrological model. Using hydrological modelling without man made obstructions such as dams or water extraction allowed to isolate the pure effect of climate change.

The common feature of the work carried out in this dissertation is the analysis of modelled streamflow. This thesis is aimed at identifying the consequences of streamflow alterations resulting from projected climate change. Climate change-induced streamflow changes are a proxy for studying impacts on biota. Each of the articles included in this thesis is a case study which assesses the possible impact of climate change on surface water-fed wetlands, selected fish and bird species which are dependent on the hydrological regime of rivers. The choice of habitats and species allows for the tracking of changes in the entire environment associated with the river: the valley, watercourse, and islands. The analysis is carried out in a coherent way as all of the case studies utilize the same climatic forcing, SWAT model simulation results and hydrological indicators most suited to describe the functioning of the habitat or species.

Indicators are a good tool for identifying changes in ecosystem conditions and predicting the direction and potential magnitude of impacts or responses to stress (Pinna et al., 2023). A set of hydrological indicators were chosen and tailored for each study to assess the functioning of the habitats, which made it possible to prepare projections of the effects of climate change on selected ichthyofauna, avifauna, and wetland habitats. The range of variability of the indicator values between the reference and future time scenarios allowed to draw conclusions on the impact of climate change on biota. The usefulness of the developed approach and verification of the hypothesis was assessed through those three case studies (riparian wetlands, selected fish, and bird species). This method is the best available technique at the moment which was developed due to unavailability of ecohydrological models for large rivers that could directly address the research questions of this thesis. The novelty of this research is the use of quantitative modelling of hydroecological interactions, to give an insight into how different species and habitats respond to streamflow variability caused by climate change. The selected study areas are located in the Vistula and Odra river basins. A flowchart overview of thesis content is presented in Fig.1.



* Piniewski et al., 2017
** Mezghani et al., 2017

Fig. 1 Overview of the thesis content.

In **Article 1** future trends and possible effects of climate change on surface water-fed wetland habitats located in the Vistula and Odra river basins, which are SACs within the Natura 2000 network, were investigated. The study began with a selection of habitats from the Natura 2000 network that are dependent on riverine flooding: hydrophilous tall herb fringe communities of plains and of the montane to alpine levels (code 6430), alluvial forests (code 91E0) and riparian mixed forests (code 91F0). Analysis of geodetic cross sections through the river valley was used to calculate bankfull flow. This allowed for a comparison of streamflows from the hydrological projections to those determined from the cross sections to establish how often river water recharge would occur. Changes in the mean Yearly Number of Days When Streamflow Exceeds Bankfull Flow (NOD) between the reference period and future projections were examined. An analysis was performed of the current state of conservation and the occurrence of the threat of drying out that affect the habitats (Fig.2).

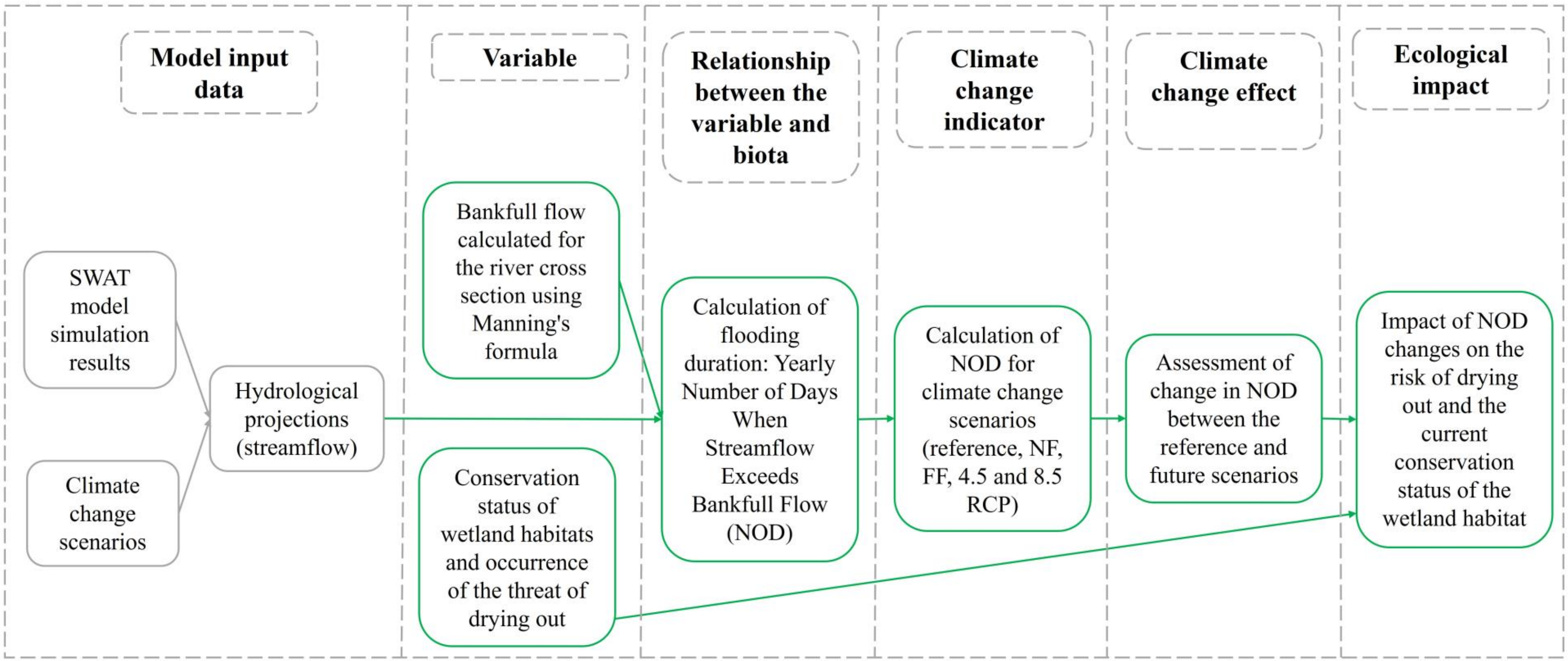


Fig. 2 Methods flowchart for riparian wetlands (Article 1)

Article 2 addresses the impact of climate change on ecologically relevant flow conditions for fish migration and spawning in the Vistula and Odra river basins. Based on the literature analysis, a subset of Indicators of Hydrological Alteration (IHA) flow characteristics was identified that are relevant to: pike (*Esox lucius*), chub (*Squalius cephalus*) and Atlantic salmon (*Salmo salar*). Selected IHA indicators were calculated and compared between reference and future scenarios, and a threshold of ±30% acceptable change was set. If the threshold was exceeded, it indicated that climate change will affect a particular fish species. Literature review on streamflow preferences of the three fish species put the results in context (Fig. 3). Climate model uncertainty was taken into account in the following way: river reaches with inconsistent findings (six or less out of nine models agreed on the presence of climate change impact on ichthyofauna) were coloured grey on the output maps to represent the uncertainty and inconsistency of results.

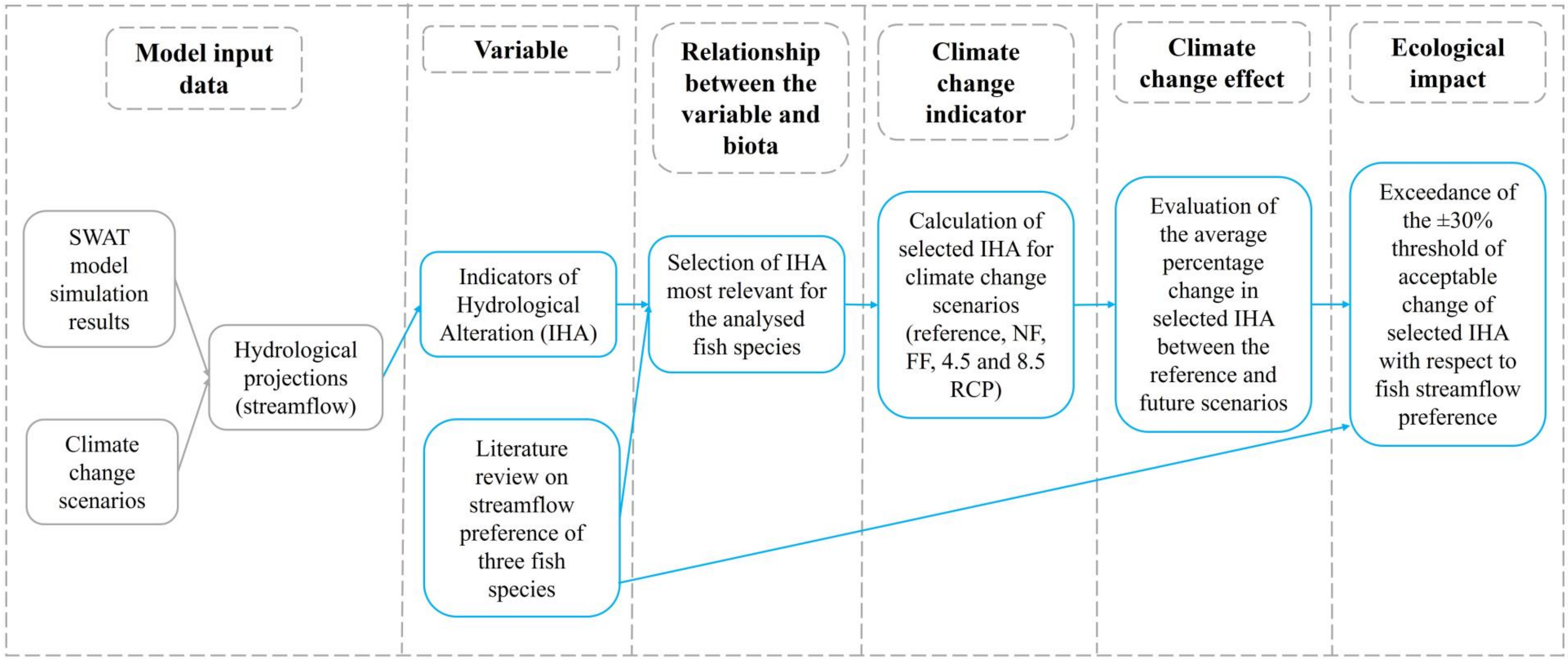


Fig. 3 Methods flowchart for selected fish species (Article 2)

Article 3 focuses on the hydrological characteristics of the Middle Vistula River that affect the stability of islands and shoals, which enables or prevents birds from establishing nests and raising young. For mew gull (*Larus canus*), little tern (*Sternula albifrons*) and black-headed gull (*Chroicocephalus ridibundus*) the period of vulnerability (the time of laying eggs, nesting and raising chicks) was determined and a set of IHA were selected, which were then adapted to the species' reproductive biology (creating adjusted IHA). Analysis of daily streamflows from the hydrological projections, allowed to obtain values of adjusted IHA hydrological characteristics and find correlations with the collected baseline data on nesting success of three bird species on islands and shoals of the Middle Vistula from 2004 to 2018. The same adjusted IHA were obtained for future scenarios and an assessment of changes was carried out in relation to the reference period. A ±30% acceptable change threshold was established after adjusted IHA were calculated and compared between the reference and future scenarios. If the cut-off point was exceeded, it meant that a certain bird species tolerance was exceeded and climate change will have an impact. In addition, an analysis of Catastrophic Breeding Seasons (CBS) was carried out to assess the percentage of years in which there will be unsuitable hydrological conditions for bird reproduction (Fig. 4).

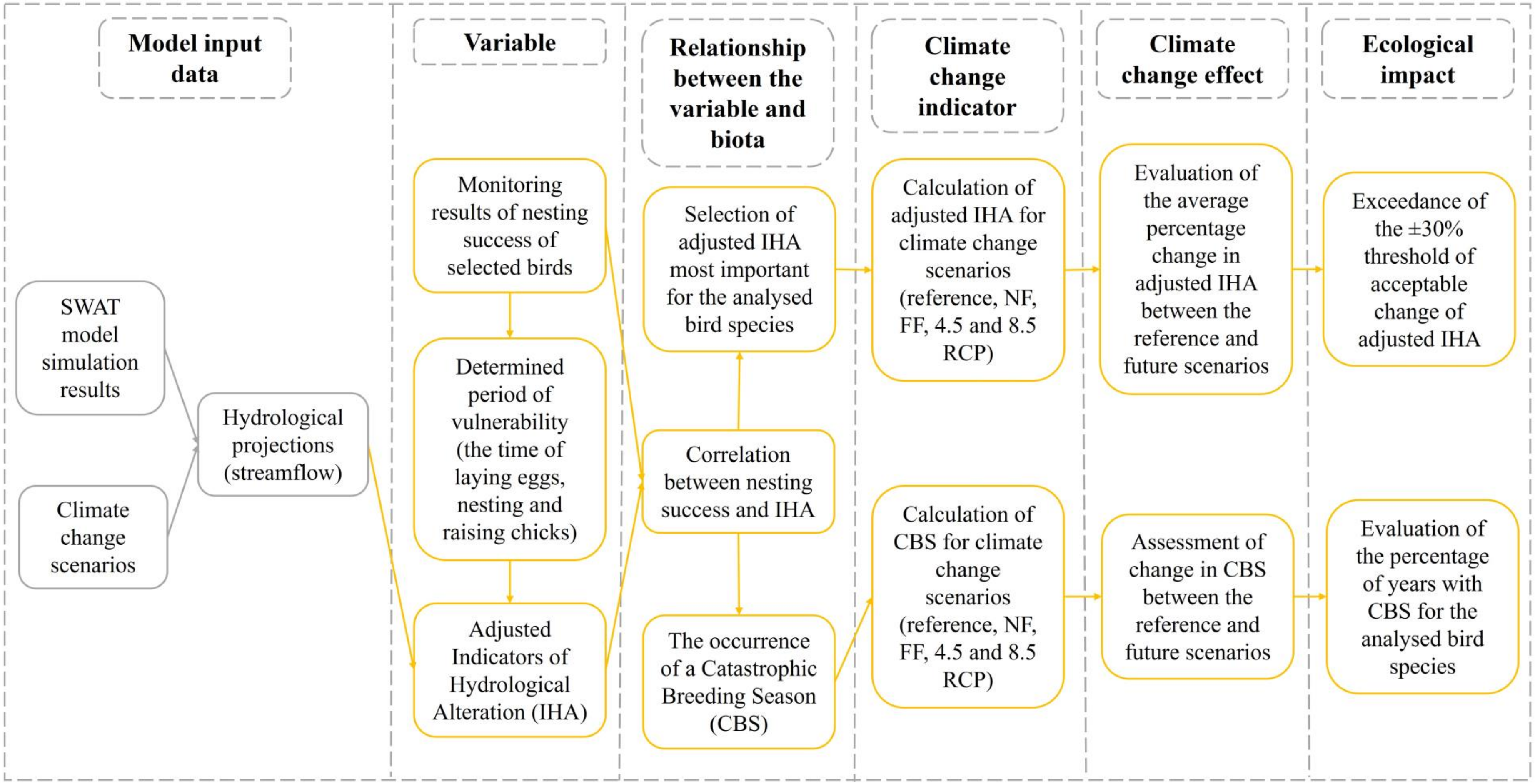


Fig. 4 Methods flowchart for selected bird species (Article 3)

The primary focus of each article was to assess if climate change is projected to have an impact on streamflow characteristics important for selected species and habitats. Particular methods included in each article allowed to carry out a prediction of the direction of change (positive, negative or inconsistent impact). The type of impact for wetland habitats was evaluated on the basis of occurrence of risk of drying out and current state of conservation. For pike, chub and Atlantic salmon the assessment focused on the literature review of streamflow preference of those species and exceedances of threshold of acceptable change of selected IHA. The direction of change for mew gull, little tern and black-headed gull was analysed on the basis of percentage of years with CBS and exceedances of threshold of tolerable change of adjusted IHA.

The progress in the development of methods is visible over the course of the articles included in this thesis. Article 1 concerning wetlands uses as an impact assessment tool a simple indicator of bankfull flow occurrence, while Article 2 concerning selected fish species utilizes more complex IHA. Article 3 goes a step further by adjusting the standard IHA to capture the vulnerability period for selected bird species nesting on river islands. The preference and tolerance of wetland habitats for flooding and waterlogging was not at the centre of interest in Article 1, while Article 2 includes a literature review of streamflow preference of selected fish species. Article 3 progresses to using monitoring data of selected bird species nesting success to establish the relationship with adjusted IHA and therefore assess the preference for streamflow characteristics.

The adopted approach of model-based assessment of climate change impact on different types of biota by a tailored set of hydrological indicators is well suited for larger scales, such as river basin-scale or country-scales and can be easily transferred to other catchments. This thesis helps to better understand the relationships between changes in streamflow brought on by climate change and the possibility of losing the favourable environmental conditions needed by selected fish and bird species as well as riparian wetlands in Poland. This method enables the monitoring of changes in the river's comprehensive ecosystem, including the valley, watercourse and islands.

4. Study sites

The study was carried out for the river network and chosen habitats of the Vistula and Odra Basins (VOB) with an area of 193,831 km^2 and 119,041 km^2, respectively and located in Central and Eastern Europe, draining to the southern Baltic Sea. The VOB is located in the temperate climatic zone, which is characterized by cold winters and warm summers. There is a moderate seasonal variability of streamflow, with the highest flows generally occurring in March and April, and the lowest flows in September and October. Water availability is among the scarcest in Europe, with mean annual run-off of 171 mm and 154 mm for the Vistula and Odra, respectively (Shiklomanov and Rodda, 2004).

The research areas were defined as follows (Fig. 5):

Article 1 focuses on 30 Natura 2000 SACs which were selected on the basis of occurrence of selected surface-water fed wetland habitats of interest.

Article 2 analyses the whole VOB river network, which in the SWAT model was represented by 2633 reaches (river segments). Since the article does not take into account anthropogenic impacts such as dams and focuses on the pure effect of climate change, the analysis assumes that the selected fish species are able to migrate within the whole VOB network. Actual range of occurrence of pike, chub and Atlantic salmon is not taken into account.

Article 3 concentrates on 22 island locations in the Middle Vistula River which are important breeding grounds for mew gull, black-headed gull and little tern. This choice was based primarily on the availability of monitoring data of nesting success of the three selected bird species in those locations.

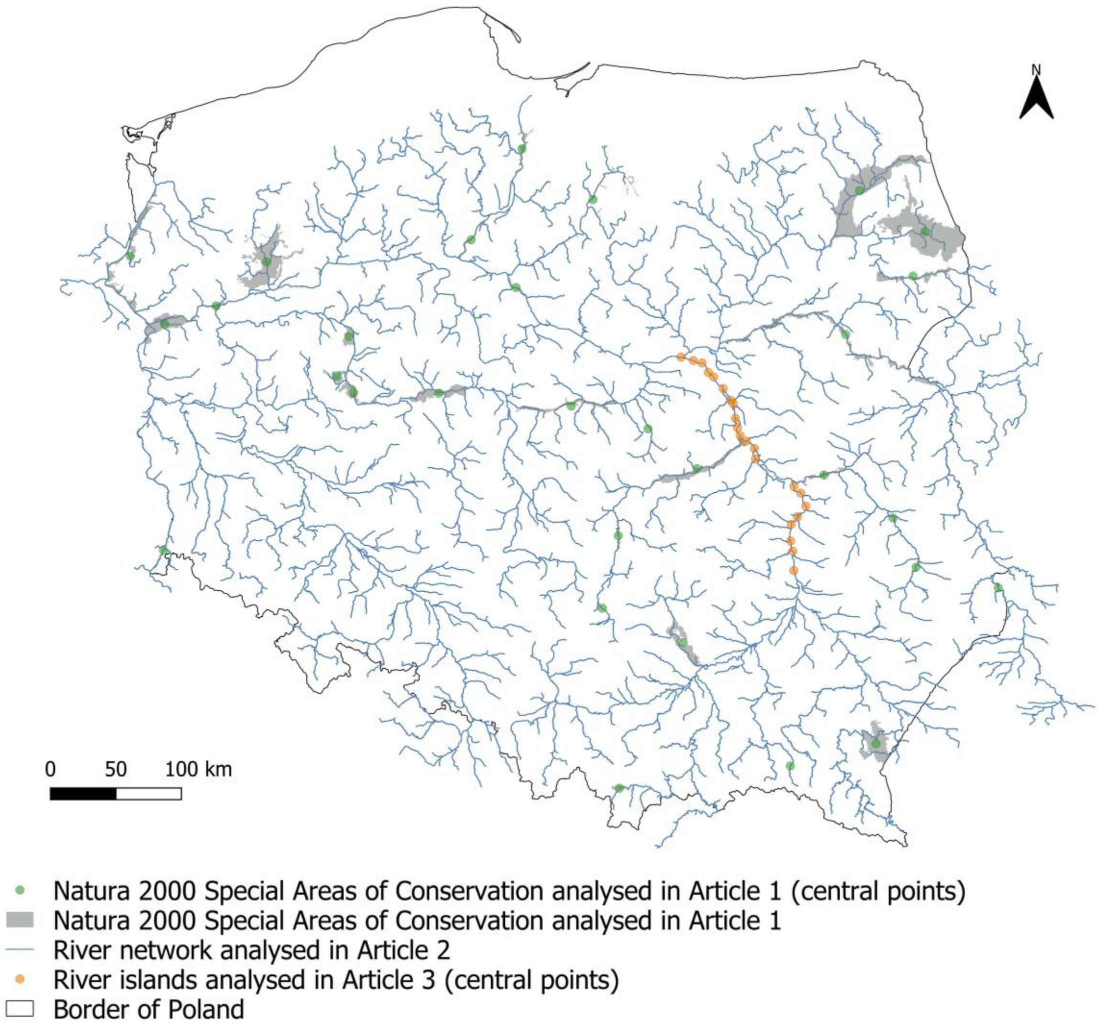


Fig. 5 Study sites included in Article 1, 2 and 3.

5. Results

5.1 Riparian wetlands

Modelling results for climate change scenarios showed a significant increase in the duration of flooding events, which will affect riparian wetland habitats included in the Natura 2000 network in Poland (**Article 1**).

The NOD is projected to increase for all three types of surface water-fed habitats; values for RCP 4.5 and 8.5 in NF are similar; in FF, the discrepancy between the two RCPs is larger. For all three types of surface water-fed habitats the NOD increases over twofold when comparing the reference period and the FF RCP 8.5 scenario.

Analysis of SACs Standard Data Forms (SDF) allowed to obtain information on the conservation status and threats to maintaining a good habitat condition. Only a small number of the assessed surface water fed habitats have conservation status category A (excellent), whereas the majority (85%) have conservation status B (good), C (average or reduced), or D (non-significant presence). Approximately half of the analysed SACs with surface water-fed habitats (51%) are threatened by drying out. The rise in the NOD might be advantageous for habitats with good, average, or reduced conservation status and threatened by drying out. However, when increases in the duration of flooding would exceed habitat tolerance, ecosystems with excellent conservation status that are currently in optimal condition can experience negative effects from climate change. Therefore, climate change impact on riparian wetlands was assessed as inconsistent.

5.2 Selected fish species

Exceedances of the thresholds for tolerable changes in selected IHA indicate that streamflow conditions important for migration and spawning of pike, chub and Atlantic salmon will change as a result of climate change (**Article nr 2**).

Atlantic salmon is projected to face the greatest risk in terms of changes in streamflow characteristics critical for its spawning, migration, and survival as an average of 97% of river reaches in the VOB will be impacted by climate change in both time horizons and RCP scenarios. According to projections, chub has the largest percentage of river reaches that are unaffected by climate change (up to 5%), and a similar share of river reaches affected by climate change as pike (between 60 and 95% in different time horizons and RCP).

The findings for pike indicate a considerable rise in the median flows in March, April, and May. Since pike lays its eggs in flooded areas, the increased spring flows may have a two-way impact on the success of pike spawning (Kottelat and Freyhof, 2007). Floodplain connection and days with inundation are projected to increase, which would be beneficial in terms of floodplain availability for spawning. However, very high streamflow or flash floods might sweep away the fish and eggs. According to Cowx et al. (2004), pike requires stable flow fluctuations between high and low levels, which might become more unbalanced under the effects of climate change. The impact of climate change on pike in the VOB is uncertain but due to acceptable 30% threshold exceedance of median flows in March and May it tilts towards a negative impact. For chub, the median streamflow for March, May, and June all surpassed the threshold of permissible variation between the IHA values in the reference period and future scenarios. Chub are only minimally impacted by floods and prefer high flows for spawning (Cowx et al., 2004; Fredrich et al., 2003; Kottelat and Freyhof, 2007). As a result, an increase in median spring streamflow may seem like a positive or neutral impact but due to threshold exceedances indicating that the range of tolerance was surpassed, the impact of climate change on this species is projected to be negative. The proportion of river reaches that are anticipated to be impacted by climate change for Atlantic salmon, a long distance migratory species, is the highest (over 90% in all RCPs, NF and FF). All parameters are surpassed, with the exception of the number of low pulses (September-October). Higher streamflow during spawning migration (September to October) could result in false spawning cues (Lindberg, 2011). Increased flows during spawning (November–December) and longer high pulse durations might lead to alevin mortality and egg mortality (Cowx et al., 2004; Cowx and Fraser, 2000). The impact of climate change on Atlantic salmon will be largely negative.

5.3 Selected bird species

According to **Article 3** climate change is projected to impact the percentage of years with CBS and adjusted IHA for mew gull, black-headed gull and little tern in the Middle Vistula River. The findings supported the notion that hydrological changes are important for successful avian reproduction.

The results for mew gull showed the lowest correlation between adjusted IHA and observed nesting success during the years 2004-2018 (baseline period) out of the three species. This suggests that mew gull nesting success in the Middle Vistula is influenced by factors other than hydrology. The little tern and black-headed gull displayed a moderate to strong correlation between nesting success and adjusted IHA, indicating that hydrology is a significant factor influencing their breeding. For mew gull, the three-day rolling mean of the streamflow maximum during the vulnerability period and nesting success had the highest correlation (-0.43). The correlation between mean streamflow during incubation and nesting success for black-headed gulls was highest, at -0.71. For the little tern, the relationship between nesting success and the average number of days during the vulnerability period when flows are above the 0.75 percentile, had the strongest correlation (-0.77). Those adjusted IHA were assessed as the most crucial for the three selected bird species. Median percentage change over time horizons and RCP scenarios of the adjusted IHA with the highest correlation to nesting success for the mew gull and black-headed gull does not exceed the ±30% threshold of tolerable deviation from the reference scenario. The 30% threshold is exceeded in both FF scenarios (32.9% in 4.5 and 37.5% in 8.5) for the highest correlated adjusted IHA for little tern.

The percentage of years with CBS for the adjusted IHA that has the strongest correlation to nesting success (estimated for nesting success = 0.1) rises along with RCP and time horizons for the little tern reaching 29.6% in FF 4.5 and FF 8.5. In the reference period, NF 4.5, FF 4.5, and NF 8.5, the black-headed gull's percentage of years with CBS remained constant (median 3.7%), and it increased to 11.1% in FF 8.5. According to the projections for the mew gull, the percentage of years with CBS in the NF will drop to 3.7% and rise in the FF scenarios to 7.4% in FF 4.5 and 14.8% in FF 8.5. Climate change will have the most significant negative impact on the little tern due to a substantial increase of the percentage of years with CBS and exceedance of the threshold of acceptable change for the adjusted IHA with the highest correlation to NS. The impact on the mew gull is inconsistent while the impact on the black-headed gull is projected to be minor but negative.

5.4 Climate change impact uncertainty

The summary of climate change impact on species and habitats included in the three articles and a severity and uncertainty assessment is presented in Tab.1. The context and results of assessing the direction of climate change impact and severity is presented in Chapters 5.1-.5.3. The inconsistent impact of climate change on riparian wetlands and mew gull made it impossible to determine the severity of change. The uncertainty originates from the fact that impact and severity assessment is an expert evaluation. Climate model uncertainty, which is addressed in the discussion (Chapter 6.2), is a separate matter.

For riparian wetlands the medium uncertainty originates from linking quantitative values for the increases in the NOD with descriptive data on conservation status and presence of the threat of drying out. The threshold of acceptable change of the selected IHA (±30%) that was set on the basis of literature and the use of descriptive streamflow preferences of fish, are a source of high uncertainty for pike, chub and Atlantic salmon. In the case of mew gull, black-headed gull and little tern, the assessment relates to the percentage of years with CBS which were a quantitative assessment and the threshold of acceptable change originating from literature. Therefore uncertainty was judged as medium for the selected bird species.

Tab. 1 Summary of climate change impact on analysed habitats and species

Habitat/Species	Climate change impact	Severity	Uncertainty
Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels (code 6430)	Inconsistent	-	Medium
Alluvial forests (code 91E0)	Inconsistent	-	Medium
Riparian mixed forests (code 91F0)	Inconsistent	-	Medium
Pike (*Esox Lucius*)	Negative	Small	High
Chub (*Squalius cephalus*)	Negative	Small	High
Atlantic salmon (*Salmo salar*)	Negative	Large	High
Mew gull (*Larus canus*)	Inconsistent	-	Medium
Black-headed gull (*Chroicocephalus ridibundus*)	Negative	Small	Medium
Little tern (*Sternula albifrons*)	Negative	Large	Medium

6. Discussion

This thesis fulfilled its goal of providing more insight into the possible future effects of climate change on certain habitats and species in Poland that depend on the hydrological regime of rivers. The modelling results confirmed that projected climate change will affect the hydrological regime of rivers and in consequence will affect selected fish, birds and wetland habitats. It was not possible to unequivocally demonstrate the direction of impact (positive or negative) of climate change on all species or habitats analysed in this thesis as impact on all riparian wetland habitats and mew gull was inconsistent. As the British statistician George E.P Box said ‘all models are wrong but some are useful’ the results are not certain to occur but they indicate further need for research and application of mitigation and adaptation measures.

6.1 Impact of climate projections on the results

There is a common belief that warmer climate would cause more severe hydrological droughts in the future, but in a systematic-style review prepared by Piniewski et al. (2022) most model studies project increases in low flows in Central Europe. The model simulations prepared by Mezghani et al. (2017) for Poland used as input data for this research showed warmer and wetter conditions on an annual scale, demonstrating an amplification of the change's magnitude near the end of the 21st century. The different models' anticipated changes in seasonal mean precipitation vary widely and are occasionally inconsistent, showing regional variances that depend on the season, location, future horizon, and RCP. According to climate change forecasts for the VOB, precipitation is expected to transition from falling as snow and remaining as snow cover to falling as rain and entering or draining into rivers. While rising temperature has a slight impact on streamflow by increasing evapotranspiration, increased precipitation is the primary cause supporting elevated run-off and hence driving streamflow (Piniewski et al., 2017). The projected increase in future mean streamflow directly impacts the modelling results obtained for the habitats and species chosen for the analysis in this thesis.

6.2 Modelling uncertainty

Future streamflow estimations employed in this thesis have large uncertainty because they are dependent on climate projections from models. Two RCPs and nine climate models were used, resulting in 18 scenarios for each time horizon. The results were prepared as box plots to demonstrate the range of outcomes and uncertainty caused by the use of the nine climate models. Other studies generally use fewer climate models and illustrate the results using only the mean, therefore uncertainty is better quantified here than in similar studies. The spread of outliers indicates that the uncertainty of the results is high. In Article 2 the model uncertainty was addressed also through an aggregation procedure that evaluated discrepancies in the model's answer.

The modelling method developed in this study for assessing climate change impact on streamflow regime important for selected habitats and species remains innovative, but the modelling input data could get updated. Next generations of climate models provide new projections, which are generally considered better than previous ones, so it is advisable to repeat this study in the future using newer projections, e.g. CMIP6 from IPCC AR6. New CMIP6 projections differ from CMIP5 and EURO-CORDEX over Europe (including Central Europe) as they project smaller increases in precipitation and decreases instead of increases in streamflow (Di Sante et al., 2021).

6.3 Data gaps and possible further research

Modelling is a simplified representation of ecological interactions and does not take into account all factors responsible for the presence of a species or habitat. This thesis focuses on the exclusive effects of climate change on hydrology, without other human-induced disturbances and changes, such as dams, water abstraction and land use changes. The already occurring impact of climate change on hydrology and species adaptation to those changes was not isolated and assessed in this research. It must be highlighted that the presented work is a conceptual model based on projected streamflow, and that additional verification studies are needed.

The change in river morphology during the time periods of the future scenarios (NF, 2021–2050, and FF, 2071–2100) in comparison to the reference or baseline scenario was not taken into account in this thesis. Changes in river morphology can impact water supply to wetlands, habitat suitability for fish and the availability of islands for nesting birds. This thesis scope centred on hydrological indicators rather than modelling morphological changes throughout time.

Natural stressors such as erosion, land subsidence, droughts were not taken into account while modelling climate change impact on riparian wetlands. Neither was the potential application of flood control measures in the research areas which might have a significant impact on the water supply for surface water-fed wetlands. Including information on the variability of wet and dry years, and the amplitude of these changes would provide additional insight that was lost while carrying out an analysis of average values. A larger focus could be placed on assessing the occurrence of extreme floods, which are necessary to stop the succession of riparian forests. Carrying out a monitoring of the effects of increased duration of flooding on long-term habitat condition and determining the range of tolerance would create a more solid basis for the assessment of climate change impact on wetland habitats. Another interesting direction would be assessing the duration of individual flood events in relation to the duration of the growing season to check if modelling would yield much different results than when assessing the whole calendar year. Preparation of recommendations for Natura 2000 management plans, which take into account the possible positive impact of climate change on habitats threatened by drying out could be a further step.

Fish preferences for water quality and temperature, river substrate, flow velocity, aquatic vegetation, river depth constituting habitat suitability were not analysed in this study. Fish species have varying range of tolerance of maximum water temperature. Projected changes for Poland showed that annual air temperature mean is expected to increase by approximately 1 °C until 2021–2050 and by about 2 °C until 2071–2100, under the RCP 4.5 scenario (Mezghani et al., 2016). Air temperature influences water temperature and potential changes could have a profound impact on fish wellbeing and range of occurrence, which is another direction worth investigating (Baptist et al., 2014). Especially salmon species could be under more pressure as cold water species. Including in the analysis an invasive species better adapted to warmer water would offer an interesting insight into fish community dynamics in the conditions of climate change.

Fish species differ in their ability to adapt to shifting hydrologic regimes and warming waters (van Vliet et al., 2013). At the time of preparation of this thesis there was no data available on the three fish species selected for this study's response to climate change or adaptation capability which is a significant data gap. Conducting observations of hydrological regime preferences and range of tolerance of fish during their migration and spawning period in Poland would provide a more detailed basis for this assessment. Currently the study does not take into account the presence of dams which significantly reduces fish ability to migrate and spawn. Including in the analysis the actual range of occurrence of fish species in the Vistula and Odra catchment areas would provide a more realistic overview of the spatial patterns of habitat suitability in climate change conditions. Besides hydrology there are other factors impacting birds breeding success such as: predation, weather conditions, outbreaks of disease, uncontrolled livestock grazing, operation of hydro-technical measures, presence of tourists and motorists. Those were not the subject of this study but including them would offer a full insight into the threats that those birds face (Bukaciński et al., 2018). The three bird species assessed in this thesis differ in their tendency towards natal site fidelity and preferences including vegetation type, island substrate, island height, and proximity to the water. Because each bird species prefers to live in a distinct area of river islands, this affects how vulnerable they are to flooding. Those factors were not taken into account in this thesis.

Birds were most likely already impacted by climate change during the baseline period, when the data on nesting success was recorded, and therefore could have been in the process of adapting. For example, there is evidence from 20 years ago that birds are already adjusting the timing of their breeding seasons and that their egg size, hatching success, and nesting success is altered by warmer springs (Sparks et al., 2002). This study did not attempt to differentiate between natural behaviour and adaptation or species range shifts occurring due to climate change.

The relationship between birds nesting success and adjusted IHA was established using linear regression, which is a simplistic method, and more sophisticated models would yield more thorough results. Including a 2D hydrodynamic model to assess changes in water levels and river morphology in temporal and spatial scales would give more insight for the assessment of the availability of islands for nesting birds. High flows have an immediate effect on the nesting success of birds, while the results of droughts can become apparent later on. Over time droughts promote vegetation succession and allow for an easier access of islands by people and mammalian predators resulting in depletion of areas suitable for breeding. Including or developing indicators that would take into account the delayed impact of drought could provide further insight.

6.4 Management and conservation implications

According to current trends in riverine species loss, human population growth, climate change, and land use change, freshwater ecosystems will remain under risk further into the future (Richter et al., 2012). Climate change-related alterations to streamflow regimes are likely to present new difficulties and increase the need for conservation and adaptation measures to ensure proper management of species and habitats dependent on them. Climate change may cause species to become extinct, alter their abundance and range, or evolve (Holt, 1990). Fish and birds have the ability to move and search for the right environment while wetland habitats are static and therefore more at risk. The framework presented in this thesis allowed to determine the most vulnerable species and habitats: Atlantic salmon and little tern, among the selected ones which need most urgent conservation measures. All of those vulnerable species are impacted not only by climate change but also by manmade obstructions to streamflow.

River channelization and regulation, construction and upkeep of dikes and dams, and alterations to land use are other man made factors that put a lot of strain on today's rivers in addition to climate change (Middleton, 2012). Flow regulation in Poland is less intensive than in Western Europe and large parts of the river network upheld semi-natural or moderately disturbed conditions. Due to the less extensive alterations made to the river beds and the availability of refugia, fish habitats can be considered as being more intact than in the rivers of Western Europe. On the other hand, large rivers like the Vistula and Odra, and their tributaries had dams constructed on them, which restricted or even prevented migratory fish species from traveling upstream, frequently as a result of poor fish ladder design (Kruk et al., 2017). For many large rivers sandbar habitat availability has decreased due to flow regulation and channelization, making its restoration a top priority (Tracy-Smith et al., 2012). Less sandbars and islands translates to less available nesting habitats for bird species and the presence of dams and scheduled flow releases can destroy the yearly broods downstream. Alteration in water supply to wetlands and reduced flooding due to damming can cause wetland fragmentation, reduction or loss (Zheng et al., 2019).

7. Conclusions

The modelling approach utilized in this thesis allowed to project climate change impact on the entire environment associated with the river: the valley, watercourse and islands by focusing on riparian wetlands, selected fish and bird species, respectively. It was possible due to applying process-based modelling coherent for all the habitats and species. The developed modelling approach is universal and can be used with input data from other climate or hydrological models than those used in this dissertation.

The modelling outcomes demonstrated that anticipated climate change will have an impact on the hydrological regime of rivers, which will affect selected fish and bird species as well as wetland habitats. Impact on riparian wetlands depends on their current conservation status and presence of risk of drying out. Projected twofold increases in flooding duration might be advantageous for habitats with good, average, or reduced conservation status and threatened by drying out. The same increase can have a negative consequence for habitats with excellent conservation status which are already in their optimal condition. Atlantic salmon which migrates long distances to reach its spawning grounds is projected to be most impacted as on average 97% of river reaches show changes in streamflow due to climate change. Projections for all analyzed fish species show exceedances of the 30% acceptable threshold of change between reference and future scenarios for median flows during migration and spawning (spring or autumn). Most likely variables other than hydrology affect the nesting success of mew gull, while the correlation between nesting success and hydrological characteristics was more profound for black-headed gull and little tern reaching values of -0.71 and -0.77, respectively. The 30% threshold of acceptable change of highest correlated adjusted IHA was exceeded only for little tern. This species is projected to face the highest increase of the percentage of years with catastrophic breeding seasons (up to almost 30% in FF).The framework provided in this study thesis enabled for the identification of the species and habitats most in need of immediate conservation efforts: Atlantic salmon and little tern.

The findings of this thesis highlight that environmental flow management plans and climate change mitigation strategies for Poland are extremely necessary and water resources managers and decision-makers can play an important role in reducing the negative effects.

8. References

Allan, J.D., Palmer, M.A., Poff, N.L., 2005. Climate change and freshwater ecosystems, in: Climate Change and Biodiversity. Yale University Press, New Haven CT, pp. 272–290.

Arthington, A.H. (Ed.), 2012. Environmental Flows: Saving Rivers in the Third Millennium. University of California Press. https://doi.org/10.1525/california/9780520273696.002.0004

Baptist, F., Poulet, N., Séon-Massin, N., 2014. Freshwater fish and climate change. Current situation and adaptation strategies. Onema.

Bartosz, R., Bukowska, M., Chylarecki, P., Ignatowicz, A., Puzio, A., Wilińska, A., 2012. Ocena wpływu zmian klimatu na różnorodność biologiczną oraz wynikające z niej wytyczne dla działań administracji ochrony przyrody do roku 2030. Generalna Dyrekcja Ochrony Środowiska.

Bukaciński, D., Bukacińska, M., Buczyński, A., 2018. Threats and the active protection of birds in a riverbed: postulates for the strategy of the preservation of the middle Vistula River avifauna. Stud. Ecol. Bioethicae 16, 5–23. https://doi.org/10.21697/seb.2018.16.4.01

Bullock, A., Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrol. Earth Syst. Sci. 7, 358–389. https://doi.org/10.5194/hess-7-358-2003

Bunn, S.E., Arthington, A.H., 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. Environ. Manage. 30, 492–507. https://doi.org/10.1007/s00267-002-2737-0

Cowx, I.G., Fraser, D., 2000. Monitoring the Atlantic Salmon Salmo salar (No. 7), Conserving Natura 2000 Rivers Monitoring Series. Peterborough.

Cowx, I.G., Welcome, R.L., Noble, R.A.A., Nunn, A.D., Halls, A., Harvey, J.P., 2004. Flow and level criteria for coarse fish and conservation species. R&D technical report to the environment agency (W6-096). UK: Environment Agency, Bristol.

Di Sante, F., Coppola, E., Giorgi, F., 2021. Projections of river floods in Europe using EURO-CORDEX, CMIP5 and CMIP6 simulations. Int. J. Climatol. 41, 3203–3221. https://doi.org/10.1002/joc.7014

European Comission, 2009. Wildlife and Sustainable Farming and the Birds and Habitats Directives: How Species Conservation Can Be Supported through Rural Development Programmes—Good Practice Examples. European Comission, Brussels, Belgium.

European Commission, 2011. Commission Implementing Decision of 11 July 2011 concerning a site information format for Natura 2000 sites (notified under document C(2011) 4892).

Fredrich, F., Ohmann, S., Curio, B., Kirschbaum, F., 2003. Spawning migrations of the chub in the River Spree, Germany. J. Fish Biol. 63, 710–723. https://doi.org/10.1046/j.1095-8649.2003.00184.x

Holt, R.D., 1990. The microevolutionary consequences of climate change. Trends Ecol. Evol. 5, 311–315. https://doi.org/10.1016/0169-5347(90)90088-U

IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Kottelat, M., Freyhof, J., 2007. Handbook of European Freshwater Fishes. Cornol & Freyhof, Berlin.

Kruk, A., Ciepłucha, M., Zięba, G., Błońska, D., Tybulczuk, S., Tszydel, M., Marszał, L., Janic, B., Pietraszewski, D., Przybylski, M., Penczak, T., 2017. Spatially diverse recovery (1986-2012) of fish fauna in the Warta River, Poland: the role of recolonizers' availability after large-area degradation. Ecol. Eng. 102, 612–624.

Larsen, S., Sorace, A., Mancini, L., 2010. Riparian Bird Communities as Indicators of Human Impacts Along Mediterranean Streams. Environ. Manage. 45, 261–273. https://doi.org/10.1007/s00267-009-9419-0

Lindberg, D.-E., 2011. Atlantic salmon (Salmo salar) migration behavior and preferences in smolts, spawners and kelts. Introductory Research Essay, Department of Wildlife, Fish, and Environmental Studies Swedish University of Agricultural Sciences 49.

Mathews, R., Richter, B.D., 2007. Application of the Indicators of Hydrologic Alteration Software in Environmental Flow Setting. J. Am. Water Resour. Assoc. 43, 1400–1413. https://doi.org/10.1111/j.1752-1688.2007.00099.x

Mezghani, A., Dobler, A., Haugen, J.E., 2016. CHASE-PL Climate Projections: 5-km Gridded Daily Precipitation and Temperature Dataset (CPLCP-GDPT5). https://doi.org/10.4121/UUID:E940EC1A-71A0-449E-BBE3-29217F2BA31D

Mezghani, A., Dobler, A., Haugen, J.E., Benestad, R.E., Parding, K.M., Piniewski, M., Kardel, I., Kundzewicz, Z.W., 2017. CHASE-PL Climate Projection dataset over Poland – bias adjustment of EURO-CORDEX simulations. Earth Syst. Sci. Data 9, 905–925. https://doi.org/10.5194/essd-9-905-2017

Middleton, N., 2012. Tamed rivers, in: Middleton, N. (Ed.), Rivers: A Very Short Introduction. Oxford University Press, p. 144. https://doi.org/10.1093/actrade/9780199588671.003.0005

Okruszko, T., Duel, H., Acreman, M., Grygoruk, M., Flörke, M., Schneider, C., 2011. Broad-scale ecosystem services of European wetlands—overview of the current situation and future perspectives under different climate and water management scenarios. Hydrol. Sci. J. 56, 1501–1517. https://doi.org/10.1080/02626667.2011.631188

Piniewski, M., Eini, M.R., Chattopadhyay, S., Okruszko, T., Kundzewicz, Z.W., 2022. Is there a coherence in observed and projected changes in riverine low flow indices across Central Europe? Earth-Sci. Rev. 233, 104187. https://doi.org/10.1016/j.earscirev.2022.104187

Piniewski, M., Szcześniak, M., Kardel, I., Berezowski, T., Okruszko, T., Srinivasan, R., Vikhamar Schuler, D., Kundzewicz, Z.W., 2017. Hydrological modelling of the Vistula and Odra river basins using SWAT. Hydrol. Sci. J. 62, 1266–1289. https://doi.org/10.1080/02626667.2017.1321842

Pinna, M., Zangaro, F., Saccomanno, B., Scalone, C., Bozzeda, F., Fanini, L., Specchia, V., 2023. An Overview of Ecological Indicators of Fish to Evaluate the Anthropogenic Pressures in Aquatic Ecosystems: From Traditional to Innovative DNA-Based Approaches. Water 15, 949. https://doi.org/10.3390/w15050949

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The Natural Flow Regime. BioScience 47, 769–784. https://doi.org/10.2307/1313099

Ramsar Convention on Wetlands, 2018. Global Wetland Outlook: State of the World's Wetlands and their Services to People. Ramsar Convention Secretariat, Gland, Switzerland.

Richter, B.D., Davis, M.M., Apse, C., Konrad, C., 2012. A Presumptive Standard for Environmental Flow Protection. River Res. Appl. 28, 1312–1321. https://doi.org/10.1002/rra.1511

Schiemer, F., 2000. Fish as indicators for the assessment of the ecological integrity of large rivers. Hydrobiologia 422, 271–278. https://doi.org/10.1023/A:1017086703551

Schneider, C., Laizé, C.L.R., Acreman, M.C., Flörke, M., 2013. How will climate change modify river flow regimes in Europe? Hydrol. Earth Syst. Sci. 17, 325–339. https://doi.org/10.5194/hess-17-325-2013

Shiklomanov, I.A., Rodda, J.C. (Eds.), 2004. World water resources at the beginning of the twenty-first century. Choice Rev. Online 41, 41-4063-41–4063. https://doi.org/10.5860/CHOICE.41-4063

Siddha, S., Sahu, P., 2022. Chapter 5 - Impact of climate change on the river ecosystem, in: Madhav, S., Kanhaiya, S., Srivastav, A., Singh, V., Singh, P. (Eds.), Ecological Significance of River Ecosystems. Elsevier, pp. 79–104. https://doi.org/10.1016/B978-0-323-85045-2.00014-5

Sparks, T., Crick, H., Elkins, N., Moss, R., Moss, S., Mylne, K., 2002. Birds, weather and climate. Weather 57, 399–410. https://doi.org/10.1256/wea.142.02

The Royal Society, 2021. Next generation climate models: a step change for net zero and climate adaptation. The Royal Society, United Kingdom.

Thorslund, J., Jarsjo, J., Jaramillo, F., Jawitz, J.W., Manzoni, S., Basu, N.B., Chalov, S.R., Cohen, M.J., Creed, I.F., Goldenberg, R., Hylin, A., Kalantari, Z., Koussis, A.D., Lyon, S.W., Mazi, K., Mard, J., Persson, K., Pietro, J., Prieto, C., Quin, A., Van Meter, K., Destouni, G., 2017. Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management. Ecol. Eng., Ecological Engineering of Sustainable Landscapes 108, 489–497. https://doi.org/10.1016/j.ecoleng.2017.07.012

Tracy-Smith, E., Galat, D.L., Jacobson, R.B., 2012. Effects of Flow Dynamics on the Aquatic-Terrestrial Transition Zone (ATTZ) of Lower Missouri River Sandbars with Implications for Selected Biota. River Res. Appl. 28, 793–813. https://doi.org/10.1002/rra.1492

van Vliet, M.T.H., Ludwig, F., Kabat, P., 2013. Global streamflow and thermal habitats of freshwater fishes under climate change. Clim. Change 121, 739–754. https://doi.org/10.1007/s10584-013-0976-0

Whitfield, A.K., Elliott, M., 2002. Fishes as indicators of environmental and ecological changes within estuaries: a review of progress and some suggestions for the future. J. Fish Biol. 61, 229–250. https://doi.org/10.1111/j.1095-8649.2002.tb01773.x

Zalewski, M., Janauer, G.A., Jolánkai, J., 1997. Ecohydrology: a new paradigm for the sustainable use of aquatic resources. Conceptual background, working hypothesis, rationale and scientific guidelines for the implementation of the IHP-V Projects 2.3/2.4. (No. IHP-V Technical Documents in Hydrology No. 7). UNESCO.

Zheng, Y., Zhang, G., Wu, Y., Xu, Y.J., Dai, C., 2019. Dam Effects on Downstream Riparian Wetlands: The Nenjiang River, Northeast China. Water 11, 2038. https://doi.org/10.3390/w11102038

9. Article 1

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Article

Modelling Climate Change's Impact on the Hydrology of Natura 2000 Wetland Habitats in the Vistula and Odra River Basins in Poland

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Abstract: Climate change is expected to affect the water cycle through changes in precipitation, river streamflow, and soil moisture dynamics, and therefore, present a threat to groundwater and surface water-fed wetland habitats and their biodiversity. This article examines the past trends and future impacts of climate change on riparian, water-dependent habitats within the special areas of conservation (SAC) of the Natura 2000 network located within Odra and Vistula River basins in Poland. Hydrological modelling using the Soil and Water Assessment Tool (SWAT) was driven by a set of nine EURO-CORDEX regional climate models under two greenhouse gas concentration trajectories. Changes in the duration of flooding and inundation events were used to assess climate change's impact on surface water-fed wetland habitats. The groundwater-fed wetlands were evaluated on the basis of changes in soil water content. Information about the current conservation status, threats, and pressures that affect the habitats suggest that the wetlands might dry out. Increased precipitation projected for the future causing increased water supply to both surface water and groundwater-fed wetlands would lead to beneficial outcomes for habitats with good, average, or reduced conservation status. However, habitats with an excellent conservation status that are already in optimum condition could be negatively affected by climate change as increased soil water or duration of overbank flow would exceed their tolerance.

Keywords: conservation status; hydrology; benefits; modelling; SWAT

1. Introduction

Wetland bio-production has been used by man for many centuries, including fish for protein, peat for fuel, and timber and reeds for building materials [1]. More recently, it has been shown that wetlands play a vital role in the hydrological cycle, controlling flood generation, groundwater recharge, dry season flows [2], and water quality [3]. In order to maintain ecosystem services, it is essential to keep an appropriate hydrological regime within a wetland. This regime is related to the source of water which is different for specific kinds of wetlands [4] and may be altered by rising temperatures and changing patterns of precipitation [5]. Natural ecosystems are exposed to periodical changes of the habitat state, and due to evolution, they are well adapted to a wide range of amplitudes of abiotic conditions. However, the rapidity of the ongoing and projected climatic change manifested by rising temperatures and different rainfall patterns, combined with high anthropopressure may impact particular ecosystems beyond the resilience point, so that they could not bounce back [6].

Climate change and its implied threats are among the utmost challenges of modern times. According to Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report [7], climate change will cause substantial alterations in the quality and availability of water resources. Precipitation is projected to increase in northern Europe and decrease in southern Europe [8], both yearly and during the summer, but changes in central and eastern Europe are more complex. There is a moderate agreement amongst large-scale hydrological projections driven by EURO-CORDEX, that hydrological extremes (floods and droughts) might be on the rise in this region [9,10]. Assessing and quantifying the impacts and vulnerabilities at the global and regional scale is crucial in the context of international and national policies and actions for climate change adaptation [7]. It is widely recognized that in the future, climate change, increasing water use, and land-use change are likely to affect the flow regimes of European rivers. The projected changes in climate are likely to affect wetlands significantly, by impacting their spatial extent, distribution, and function [11].

Studies projecting climate change's impact and linking soil water or bankfull flow modelling with the well-being of wetlands are rare. An evaluation carried out by Schneider et al. [12,13] focused on the effect of climate change on floodplain inundation for the chosen important floodplain wetlands in Europe and in the world. That study was performed with the use of the WaterGAP 3 model driven by bias-corrected, daily climate data from five different general circulation models (GCMs). House et al. [14], with the use of the MIKE-SHE model, investigated the hydrological impacts of climate change on a 10 ha, lowland riparian wetland in the UK depending on the degree of groundwater or surface water interactions. A study by Holsten et al. [15] used the Soil and Water Integrated Model (SWIM) to investigate climate change's impact on soil moisture in Brandenburg (Germany) and special areas of conservation (SACs) located within. No similar studies have been carried out with the use of the Soil and Water Assessment Tool (SWAT) model.

This study assesses climate change-induced hydrological impacts on the wetland habitats of Natura 2000 SACs located within the Vistula (Wisła) and Odra river basins in Poland. The assessment of climate change's effects on wetland habitats requires projections of appropriate hydrological variables for the watershed. These were developed with the help of the (SWAT) hydrological model set up at high resolution (the median modelling unit area was equal to 10.7 km^2). The model was driven by an ensemble of nine bias-corrected EURO-CORDEX simulations under two representative concentration pathways (RCPs): 4.5 and 8.5 for two projection horizons (2024–2050; i.e., near future denoted as NF, and 2074–2100, i.e., far future, denoted by FF) and compared to the baseline period (1971–2000). The novel component of this research allows us to link climate change's impact on hydrology with Natura 2000's wetland habitats' well-being. This was achieved by considering soil water content and the duration of flooding and inundation events obtained from the model as proxies of wetland habitat's condition. In order to evaluate the impact of climate change on those hydrological variables we compared their values obtained for the two future periods to the equivalent ones from the baseline period. The results were set in an ecological context by analyzing the current conservation status, threats, and pressures affecting habitats.

2. Materials and Methods

2.1. Study Area

The natural and drained wetlands in Poland cover an area of 4.4 million ha which is approximately 14.2% of the country's area. Some 30% of wetlands are mires and 70% are other types of wetlands. Mires cover 1.3 million ha which constitutes 4% of the area of the country and it is estimated that "live" preserved, peat-accumulating ecosystems occupy an area of 202,000 ha (0.6% of Poland). Fens constitute 92% of mires, and the largest fens are located in the river valleys of Biebrza and Narew. Bogs cover an area of 62,000 ha (4.7% of all the mires) and mostly occur in lakelands, uplands, and in the mountains. Transitional bogs cover 3% of the total area of mires in Poland. Over 80% of the area of mires were dried to varying degrees and mostly began to be used as meadows and pastures [16].

Other wetlands which do not accumulate peat, cover an area of 3.1 million ha (70% of all wetlands and 10% of the country area). Even though they occupy an area larger than mires, they are far less researched. There is a lack of detailed data on their area and state of preservation, as most commonly, they occur in a patchy mosaic and the range of particular habitats is difficult to assess. Marshes dominate among the non-peat accumulating wetlands and swamps are rarer. Marshes can be found in most of the river valleys in Poland [16].

Natura 2000 SACs cover 11.2% (about 3.49 million ha) of the total land area of Poland. Wetlands of international importance (RAMSAR areas) designated on the basis of "The Convention on Wetlands of International Importance especially as Waterfowl Habitat" consist of 153,400 ha (data from 2018) within Poland (which is approximately 0.5% of the country's area, including inland water bodies) [17].

This study focuses on wetland habitats of Natura 2000 SACs located within the two largest river basins in Poland, the Vistula and Odra basins (VOB) which cover 88% of the Polish territory (i.e., approximately 275,000 km^2 of 312,873 km^2). Both rivers drain into the southern Baltic Sea. The VOB region has a temperate climate. This study did not assess the areas in Northern Poland which drain directly to the Baltic Sea. All SACs in Poland and those with wetland habitats chosen for analyzes in the VOB are presented in Figure 1.

2.2. Classes of Wetlands according to Hydrological Characteristics

In order to investigate the riparian vegetation response to stressors and avoid the confusing number of terms and names, for the purpose of this work, wetlands were divided into two general classes based on major hydrological characteristics; i.e., the source of water. Riparian wetlands where surface water plays a dominant role (associated with a river, lake, or pond) can be either covered by forest and bushes (mainly alder, poplar, and willow) or by non-forest vegetation; i.e., grasses, sedges and reeds. Groundwater and precipitation-fed wetlands where peat has or is being accumulated are called mires, which develop on a river valley edge or in higher elevated landscapes. Their basic characteristics are given in the subsequent sections.

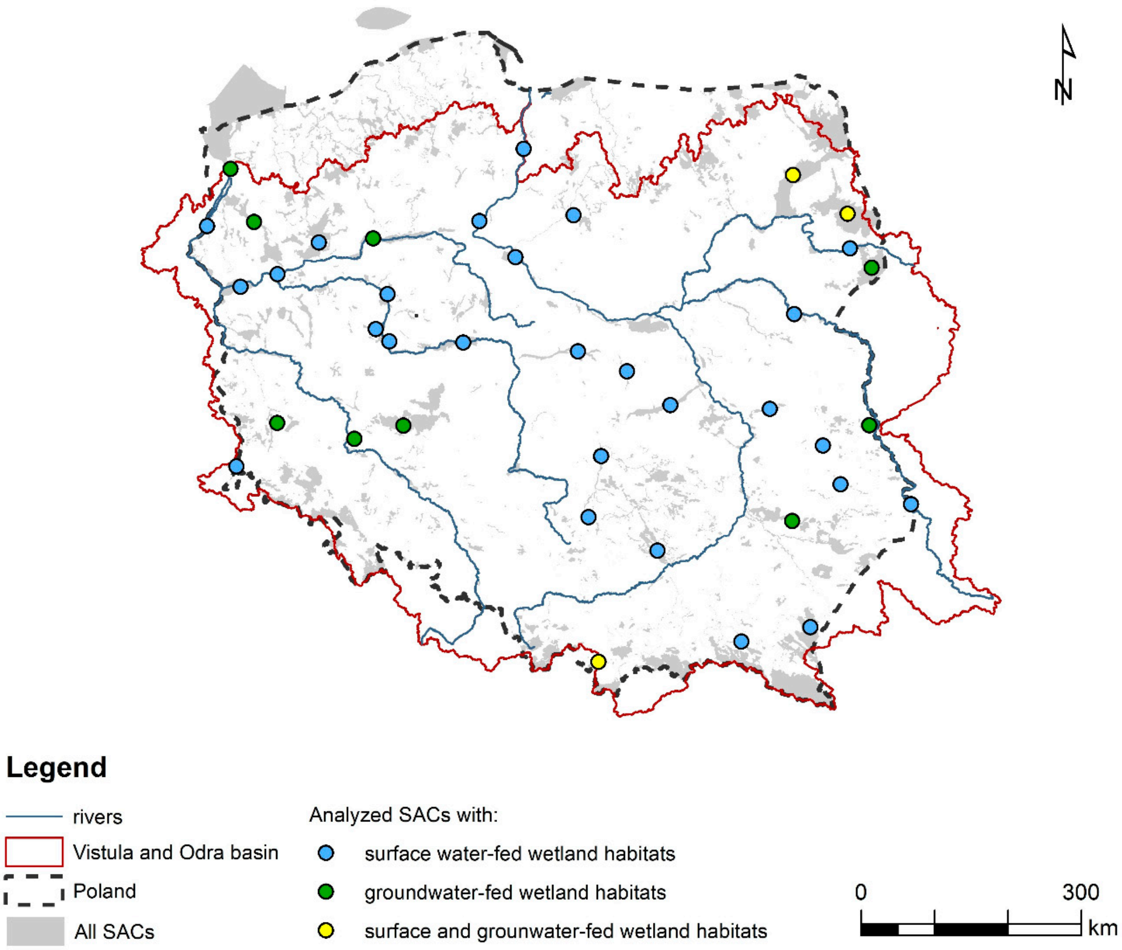


Figure 1. Location of special areas of conservation (SACs) within the Vistula and Odra basins (VOB) in Poland. Color coding represents the type of wetland habitats present in the SACs selected for analysis: groundwater-fed (green) and surface water-fed (blue) wetland habitats, and both types of habitats (yellow).

2.2.1. Wetlands with a Dominant Role of Surface Water

One can distinguish two types of surface water-fed wetlands which differ in their lengths of inundation. In this paper, it is assumed that a swamp is inundated by shallow water [18] for a relatively long period with a substantial number of hummocks or dry land protrusions present on the floodplain. Swamps are not always peat-accumulating wetlands, and in a number of cases, the major soil type developing in those areas is alluvium. This is contradictory to fens and bogs which accumulate peat. Due to environmental conditions, swamp vegetation is adapted to growth in stagnating or slowly flowing water. As the water in swamps is rich in tannins from decaying vegetation, it has a characteristic brownish color. Swamps are usually associated with adjacent rivers or lakes.

A marsh has less open water than a swamp but is frequently inundated. The flooding phenomenon is much more dynamic, leading to the development of alluvial soils. Moreover, in contrast to a swamp, a marsh has no woody vegetation and is dominated by grasses, rushes, reeds, and sedges. A marsh obtains most of its water supply from surface water, and sometimes it is also fed by groundwater. Nutrients are abundant and the pH is usually neutral which causes an abundance of plant and animal life. Plants are rooted in mineral soil substrate and they are well adapted to saturated soil conditions over long time periods. Marshes are often grazed by wild animals and domestic cattle which suppress woody vegetation and maintain grassland communities [16,19].

2.2.2. Wetlands with a Dominant Role of Groundwater

On the basis of the main source of water, mires can be divided into bogs (fed by rain) and fens (fed by groundwater). The term peatland is used for areas of peat accumulation which are being drained for agricultural farming, peat extraction, or any other purposes.

Fens usually form in land depressions or river valley bottoms and are fed mainly by groundwater, but often have additional inputs of surface water and rain. Nutrient and mineral supply to vegetation is provided by water's movement through the shallow peat layers. Due to alkalinity, fen vegetation is dominated by grasses (mostly sedges), reeds, and trees communities, such as birches (*Betula L.*), willows (*Salix sp.*), and alders (*Alnus sp.*).

Bogs can form either in locations where rainfall has no drainage network and causes local inundations over a long period, or where the peat layer builds-up and then isolates the fen from its groundwater supply. When that happens, a fen is fed only by direct rainfall, receives less nutrients, and could grow above the fen level and transform into an acidic bog. Rain, besides washing the hydroxide ions out of the peat, adds carbonic acid from carbon dioxide dissolved in rain water, making the soil pH more acidic. Nutrients are provided to bogs solely by precipitation. The presence of vegetation adapted to acidic conditions, e.g., *Sphagnum* moss and small sedges, pines, and dwarf birches, is characteristic of bogs [16,19].

2.3. Data on Wetland Habitats in Poland

As we were not able to acquire data for all Polish wetlands, we conducted an analysis using the GIS data on SACs and wetland habitats in Poland protected under the Habitat Directive [20] and managed by the General Directorate for Environmental Protection (GDEP) [21]. We assumed that projections done for those areas would give us good, representative information on the fate of important wetlands under changing climatic conditions. Habitats located within the Natura 2000 SACs and recognized as representative for the surface and groundwater-fed wetlands are presented in Table 1. Out of 13 habitat types that depend on either surface water or groundwater, nine were present in the VOB and suitable for further analysis (in bold in Table 1).

Table 1. The Natura 2000 habitats occurring in Poland and fed by groundwater or surface waters (in bold habitats assessed in this study).

Natura 2000 Habitats (With Codes)	Surface Water-Fed	Groundwater-Fed
Wetlands		
7110—Active raised bogs		•
7120—Degraded raised bogs still capable of natural regeneration		•
7140—Transition mires and quaking bogs		•
7150—Depressions on peat substrates of the Rhynchosporion		•
7210—Calcareous fens with *Cladium mariscus* and species of the *Caricion davallianae*		•
7220—Petrifying springs with tufa formation (Cratoneurion)		•
7230—Alkaline fens		•
Heaths, meadows		
4010—Northern Atlantic wet heaths with *Erica tetralix*		•
6410—Molinia meadows on calcareous, peaty or clayey-silt-laden soils (*Molinion caeruleae*)		•
6430—Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels	•	
Forests and woodlands		
91D0—Bog woodland		•
91E0—Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion, Alnion incanae, Salicion albae*)	•	
91F0—Riparian mixed forests of *Quercus robur*, *Ulmus laevis* and *Ulmus minor*, *Fraxinus excelsior* or *Fraxinus angustifolia*, along the large rivers (*Ulmenion minoris*)	•	

A grouping of Natura 2000 wetland habitats into surface water or groundwater-fed was carried out in order to gather the habitat types in communities with similar preferences for hydrologic features. The three surface water-fed habitat types were analyzed separately: 6430—hydrophilous, tall-herb fringe communities of plains and of the montane to alpine levels; 91E0—alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion*, Alnion incanae, *Salicion albae*); and 91F0—riparian mixed forests of *Quercus robur*, *Ulmus laevis*, and *Ulmus minor*, *Fraxinus excelsior*, or *Fraxinus angustifolia*, along the great rivers (*Ulmenion minoris*). The six habitat types relying on groundwater were split into three groups and analyzed independently. The first group contained the class 91D0—bog woodland. The second group consisted of two types of fens: 7210—calcareous fens with *Cladium mariscus* and species of *Caricion davallianae* and 7230—alkaline fens. The third group included bogs: 7110—active raised bogs; 7120—degraded raised bogs still capable of natural regeneration and 7140—transition mires and quaking bogs. Only a portion (see Table 2) of Natura 2000 wetland habitat areas in Poland was suitable for this study due to procedures described in Sections 2.4.3 and 2.4.4. The share of Natura 2000 wetland habitat area in Poland analysed in this project amounted to a maximum of 31.37% (habitat 7120), minimum of 6.01% (habitat 7210), and averaged to 15.19% (Table 2). This was judged to be a representative sample.

Table 2. Comparison of average and total Natura 2000 wetland habitat area (km^2) in Poland to area of habitats analyzed in this project. Percentage of total wetland habitat area in Poland analyzed in this project.

Type of Water Supply	Natura 2000 Habitats	Average Area (km^2)		Total Area (km^2)		Share of Wetland Habitat Area in Poland Analysed in This Project (%)
	Code	Poland	Project	Poland	Project	
Surface water-fed	6430	0.02	0.03	15.76	1.80	11.40
	91E0	0.02	0.04	1437.49	231.45	16.10
	91F0	0.03	0.08	347.65	46.34	13.33
Groundwater-fed	91D0	0.03	0.04	649.16	74.47	11.47
	7110	0.03	0.08	51.35	6.27	12.22
	7120	0.03	0.14	23.84	7.48	31.37
	7140	0.02	0.04	153.34	14.78	9.64
	7210	0.08	0.15	15.26	0.92	6.01
	7230	0.03	0.04	23.18	5.84	25.19

2.4. Hydrological Modelling Approach

2.4.1. Modelling with the Use of SWAT

SWAT is a process-based, continuous-time model which simulates hydrology on a catchment scale with a daily time step [22]. It is a complex tool designed to enable simulations of long-term impacts of land use and climate changes on water, sediment, and nutrient conditions. In this study, we built upon the existing, extensively calibrated and validated SWAT model of the VOB [23]. Two output variables simulated by SWAT were of main interest: streamflow (m^3 s^{-1}) and soil water content (amount of water in the soil profile, mm).

In SWAT, river basins are divided into sub-basins, which are then split into hydrological response units (HRUs). An HRU is a combination of land cover, soil, and slope overlaid within each sub-basin. Water balance components (such as water yield, which includes evapotranspiration; soil water content; and percolation) are calculated separately for individual HRUs and then aggregated at the sub-basin level. Three components contribute to water yield (and streamflow) in SWAT: surface runoff, lateral flow, and groundwater flow (baseflow). Water yield reaching the stream network is routed to the outlet of the basin. The median sub-basin and HRU areas for this model setup were 115 km^2 and 10.7 km^2, respectively [23].

2.4.2. Climate Change Scenarios

For the purpose of this paper, SWAT was driven by climate forcing data from the CHASE-PL Climate Projections: 5 km Gridded Daily Precipitation and Temperature Dataset (CPLCP-GDPT5) [24]. This dataset includes projections from an ensemble of nine bias-corrected climate model simulations from the EURO-CORDEX data set [8] up to the year 2100 and under two RCPs, called 4.5 and 8.5. The RCPs are plausible scenarios (based on various assumptions on future atmospheric concentrations of greenhouse gases and socio-economic development) towards reaching specific trajectories of target radiative forcing [25]. Two RCPs used in this paper correspond to the 4.5 W m^{-2} and 8.5 W m^{-2} levels of radiative forcing in the year 2100. The SWAT model runs represent pure climate change effects, assuming constant land use, which is typical for most hydrological impact studies.

The projected mean annual temperature in Poland is expected to rise by approximately 1.1 °C in the NF (near future, 2021–2050) and 2 °C in the FF (far future, 2071–2100) under the RCP 4.5, with a strong seasonal variation: the highest change occurs in winter (2.5 °C in FF) and the lowest in summer (1.7 °C in FF). For the RCP 8.5 scenario, the temperature increase rate seem to quicken in the second half of the century, reaching a mean of 3.6 °C in FF, whereas in NF, it is alike to RCP 4.5 (1.3 °C versus 1.1 °C). Poland is expected to get more precipitation in the future and for all seasons (with the highest increase in winter and spring). In the intermediate emission scenario (RCP 4.5), the projected annual mean precipitation increase is approximately 6% in NF and 10% in FF, while for RCP 8.5, the projections show a 16% increase in FF [26].

2.4.3. Assessment of Flooding Events

The magnitude, timing, and duration of inundation influences the abiotic conditions in floodplain ecotones [27]. Flood duration impacts abiotic soil conditions, the amount of fine sediment settlement, and groundwater contact [28]. The quality and functioning of floodplain wetland ecosystems that have evolved under, and are dependent on regular inundation, are vulnerable to hydrological alterations. Inundation (flooding) assures floodplain aquatic connectivity and allows the transport of matter and organisms [13,29]. Plant roots cannot function properly if they are experiencing excess inundation which cuts off or limits the availability of oxygen. Washing out nutrients and irreversible root decay caused by too much water results in the plant wilting [30]. Too much water can also cause washing out nutrients and irreversible root decay. If there is not enough water supplied by inundation and flooding and falls below some (species-specific) levels, plants suffer from water stress and decrease their physiological activities. This affects the transpiration rate, biomass production, and carbon assimilation and eventually causes wilting [31,32].

Assessment of impact of climate change on surface water-fed wetlands was carried out with the use of streamflow simulations obtained from the SWAT model for the particular river sections with the support of GIS tools. Out of all the SACs acquired from the GDEP [21], surface water-fed habitats located within the Vistula and Odra catchments were chosen. The next steps included linking sub-basin outlets to SACs by checking if the river network and land use data from SWAT sub-basins represented a wetland and if a geodetic wet cross-section of the river was available. Wet cross-sections were obtained during a nationwide project [33]. Measurements were carried out upstream and downstream from any hydro-technical structure, and in natural river-sections, every 1 km, using the real-time kinematic Global Positioning System (RTK GPS) technique combined with bathymetry of the channel bed. The land part of these sections covered the embankments and went out 5–20 m beyond the riverbed. The rest of the cross-section included the entire floodplain terrace and was developed from LIDAR images with a density of 4 beams per 1 m^2. The combined data formed one cross section perpendicular to the valley [33]. The river-cross sections allowed for a manual, visual assessment, based on the topography of the river valley of the water table level at which bankfull flow occurs. Bankfull flow takes place when the channel is full to its capacity (to the top of the banks) and the flow begins to enter the active floodplain [34]. It is a suitable parameter for large-scale modelling, especially for the analysis of environmental flows and flood-related hydrological processes [28]. The calculation of bankfull flow was carried out with the use of the Manning equation. This procedure determined 30 SACs suitable for analysis (Figure 1). Each SAC was associated with a single SWAT river sub-basin and contained one or more of the considered habitats.

Obtaining the projected daily streamflow for the future scenarios allowed us to assess how the yearly number of days when streamflow exceeded bankfull flow (NOD) changes in comparison to the baseline scenario. Due to seasonal variation in the occurrence of flooding and inundation [35], a yearly time step was chosen for the assessment of the number of days when streamflow exceeds bankfull flow, instead of looking at, e.g., only the growing season. The NOD for each cross-section was calculated. It was decided that this indicator represents the hydrological requirements of the chosen habitats sufficiently well. If the daily streamflow modelled by SWAT exceeded the threshold of the calculated bankfull flow at a given cross-section, then an assumption was made that a flooding event occurred; if it was not exceeded then no flooding event occurred. Those calculations were carried out for each cross-section in 9 climate models for the baseline (1971–2000) and two future horizons (NF and FF) under two RCPs 4.5 and 8.5. The NODs from all cross-sections representing a habitat were calculated as a mean for each climate model. In the final step, the climate change impact on surface water-fed wetlands was presented as the change in the NOD for three different types of Natura 2000 habitats. For two future horizons, the calculations were carried out and presented separately for both RCPs studied. The uncertainty resulting from the use of nine climate models was addressed by preparing the results as box plots (Figure 4). The analysis scheme is presented in Figure 2.

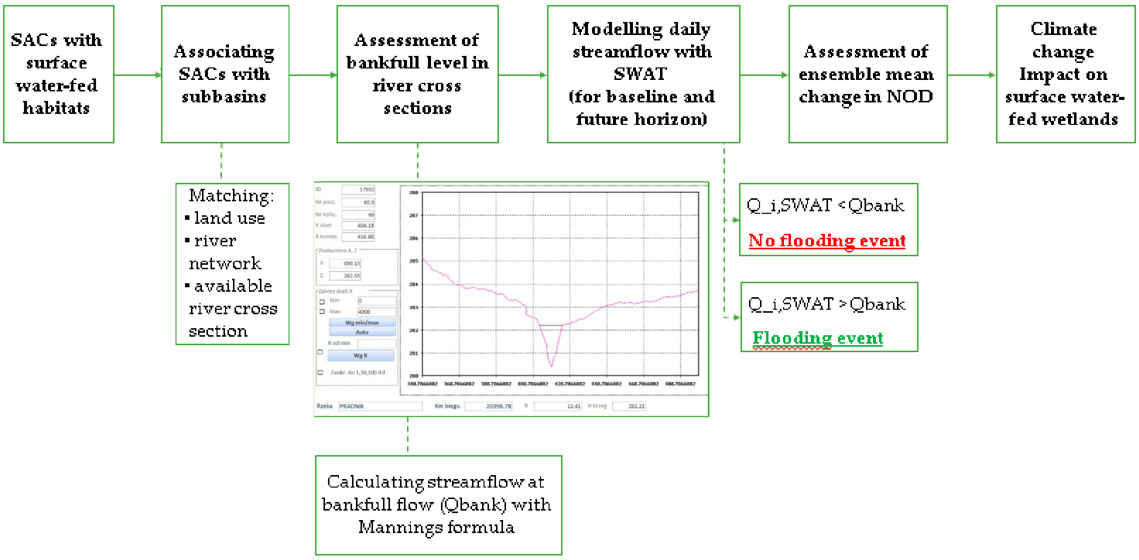


Figure 2. Scheme of the analysis procedure for surface water-fed wetlands, where Q_i,SWAT is the streamflow obtained from SWAT model and Qbank is the bankfull flow at a given cross-section; the NOD is a yearly number of days when streamflow exceeds bankfull flow.

2.4.4. Soil Water Assessment

Soil water is of highest importance for vegetation growth and they mutually influence each other through the process of transpiration [36,37]. If soil water content decreases below a certain (species-specific) level, plants experience water stress, during which they decrease their physiological activities. This affects the transpiration rate, biomass production, and carbon assimilation and eventually causes wilting [30,32]. Excess waterlogging limits or cuts of the supply of oxygen which is essential for roots to function properly. Too much water can also cause washing out nutrients and irreversible root decay [30].

Assessing the groundwater-fed wetlands required a similar approach as for the riparian wetlands: acquiring the data on Habitat Directive [20] protected areas, which consists of habitats depending on precipitation and groundwater supply (Table 1). As a state indicator, we chose soil water content which results from water balance in the wetland area.

The investigation process was mainly based on a spatial analyzes and the use of the SWAT model's output for particular locations. The entire procedure was supported with GIS tools. The first step included selection of SACs, acquired from GDEP, with groundwater-fed habitats located within Vistula and Odra catchments. Afterwards, the output map was overlaid with the HRUs to check if they contained organic soils (as soil class) and wetland vegetation (as land-use). For each habitat type in a given SAC, spatially associated HRUs that fulfilled the aforementioned conditions were attributed. Each habitat within a given SAC could be represented by more than one HRU. Each SAC could contain one or more of the considered groups of habitats. If the habitat constituted less than 1% of the HRU area, it was then considered non-representative, and in consequence, was removed from the analysis. Twelve SACs were considered in further analysis (Figure 1).

Available water capacity (AWC) of the soil layer (mm H_2O/mm soil), which is an input for the SWAT model, is estimated by determining the amount of water released between in situ field capacity (the soil water content at soil matric potential of −0.033 MPa) and the permanent wilting point (the soil water content at soil matric potential of −1.5 MPa) [23,38]. The SWAT model produces as an output simulated soil water (SW) as mm of water in a soil column with varying depth, depending on the type of soil and location. Soil classes vary in terms of soil retention parameters and are affected by climatology, specific for a given area. Due to this fact, the results were normalized by dividing the average yearly SW in selected HRUs by AWC of each soil column and expressed in dimensionless units. Normalized data enables a better spatial comparison across a large-scale study [39]. This method allowed for a comparison of results between different soil types. Surface water-fed wetland characteristics are maintained by periodic waterlogging which typically occurs with a seasonal variation [35], so it was decided to asses SW in a yearly time step rather than looking at, e.g., only the growing season.

The significance of changes in the ratio between SW and AWC for groundwater-fed habitats was assessed by interpreting the magnitude of impact on habitats, based on SWAT model simulations run under 4.5 and 8.5 RCP scenarios, nine climate change projections, and two time horizons: NF and FF for each combination of SAC-habitat type-climate projection–RCP scenario. For two future horizons, the calculations were carried out and presented separately for both studied RCPs. The uncertainty resulting from the use of nine climate models was addressed by preparing the results as box plots (Figure 5). The analysis scheme is presented in Figure 3.

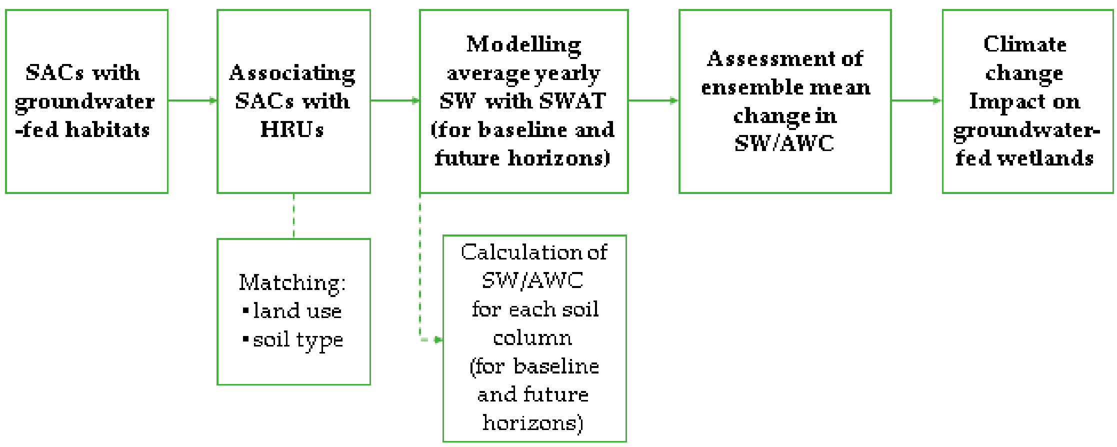


Figure 3. Scheme of the analysis procedure for groundwater-fed wetlands, where SW is soil water and AWC is available water capacity.

2.4.5. Analysis of the Current Conservation Status, Threats, and Pressures Affecting Habitats

To assess the current condition of wetland habitats within the VOB, we reviewed the available resources. Information on (1) the conservation status of habitats and (2) the threats to maintaining a good habitat condition was extracted from the Standard Data Forms (SDF) for analyzed Natura 2000 SACs [40]. The SDFs contain a description of the site and its ecology. The analyzed SDFs were updated in 2017 and are available on the website of GDEP (http://natura2000.gdos.gov.pl/).

Conservation status included in the SDFs is the degree of conservation of the structure and functions of the considered natural habitat type and its restoration possibilities. This assessment criterion comprises three sub-criteria: (i) the degree of conservation of the structure, (ii) degree of conservation of the functions, and (iii) restoration possibility. For each SAC, the information on the conservation status of habitats of interest was gathered. The grading of this status was: (A) excellent conservation, (B) good conservation, and (C) average or reduced conservation. A habitat type that was present on the analyzed site in a non-significant manner was included in category (D)—non-significant presence. One of the aims of the Natura 2000 Network is to ensure that habitats are restored to, or maintained at, a favorable conservation status [41,42]. The information gathered was used to assess whether the current state of analyzed habitat in a given SAC was in its optimum condition (A) or had been already impacted by stressors and had a status B, C, or D.

Threats and pressures to maintaining a good habitat condition in SACs were narrowed down to those related to hydrology and grouped into two categories: (1) drying out (including K01.03—drying out; M01.02—droughts and less precipitations; J02.04.02—lack of flooding; J02.03—canalization and water deviation; J02.03.01—large scale water deviation; J02.03.02—canalization; J02.05—modification of hydrographic functioning, general) and (2) inundation: (L08—inundation (natural processes)). This information gave a wider view on what the stressors currently affecting habitats of interest were.

Gathering the information about current conservation status of habitats, threats, and pressures affecting SACs determined whether the projected changes in the average flooding duration and soil water could become an additional stressor or have a beneficial impact on further possibilities of maintaining or achieving an excellent conservation status "A" and eliminating or intensifying the threats. The analysis of the possible climate change impact on the habitat's conservation status will be carried out in the discussion.

Due to a time discrepancy between information included in the Natura 2000 SDF and the shapefile layer of habitats obtained from GDEP, a given habitat may not appear in the SDF, but it may exist in the shapefile layer. If such a situation occurred, we assumed that such a habitat existed within the SAC, but was probably too small to be included in the SDF; therefore, it was included in the analysis with a conservation status D (assigned by authors).

3. Results

3.1. Climate Change's Effect on Surface Water-Fed Wetlands

According to Figure 4, the impact of climate change on surface water-fed habitats is rising along with the increase in the RCP scenario and time horizon. The NOD is projected to increase for all three types of habitats; values for RCP 4.5 and 8.5 in NF are similar; in FF, the discrepancy between the two RCPs is larger. The minimum and maximum values of the NOD spread out further and are more divergent in the FF. The highest changes in the NOD are projected for riparian mixed forests (91FO) and the lowest for Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels (6430). The number of analyzed sub-basins and SACs for given habitats are presented in Table 3.

3.2. Climate Change Effect on Groundwater-Fed Wetlands

The impact of climate change on groundwater-fed habitats, according to Figure 5, is projected to slightly increase the SW/AWC. Impact rises along with the increase in the RCP scenario and time horizon. The SW/AWC is projected to increase for bog and fen habitats, while for bog woodlands, the results show ambiguity. Median SW/AWC values are similar in NF, when comparing results for RCP 4.5 and 8.5. For FF, the median value is higher for RCP 8.5. The projected changes are expected to have the largest impact on bogs which show the highest increase in soil water and the lowest on bog woodlands. As indicated by the span of the outliers, the uncertainty of the results is high, mostly in the NF scenarios but also for the historical period. The presence of outliers might suggest that the soil water content parameter is more sensitive to climate change and also more uncertain than NOD. Groundwater-fed habitats are strongly dependent on vegetation which directly uptakes the water from the soil profile. This means that their intensive growth is regulated not only by water supply but also air temperature, which for some climate models, might be higher and may cause higher evapotranspiration and water uptake from the soil profile. The number of analyzed HRUs and SACs for given habitats are presented in Table 3.

3.3. Current Habitat Conservation Status, Threats, and Pressures

Approximately half (51%) of the analyzed SACs with surface water-fed habitats have identified threats connected to drying out (Table 3). On average, 85% of the analyzed habitats have a conservation status B (good), C (average or reduced), or D (non-significant presence), and just a few have status A (excellent). The number of threats for habitats 6430 and 91F0 is 1.7 threats per SAC and for habitat 91E0 is 1.4 threats per SAC. Only two SACs with surface water-fed habitats are threatened with inundation: one with A conservation status and second with D status.

The number of considered SACs with groundwater-fed habitats is smaller than for surface water-fed habitats. Over half (54%) of the analyzed SACs are threatened with drying out, but none of them are threatened with inundation. For bogs and fens, all the analyzed habitats within the SACs have a conservation status B, C, or D. None of the groundwater-fed habitats have a conservation status A. There is approximately one threat per SAC.

Summaries of the results are presented in Table 3, and Figures A1 and A2 in the Appendix A.

SACs with surface water-fed habitats which are under the highest number of threats are: Solecka Dolina Wisły (four); Dolina Środkowej Pilicy (three); and for groundwater-fed habitats: Lasy Sobiborskie and Puszcza Białowieska (two). The most commonly occurring threats within the study were: J02.03—canalization and water deviation (10 SACs), J02.05—modification of hydrographic functioning, general (seven SACs), K01.03—drying out (six SACs) (Figures A1 and A2). Only two SACs are threatened with inundation and concern habitat 91E0. A list of analyzed SACs with conservation status and threats that apply to them are presented in Figures A1 and A2 in the Appendix A.

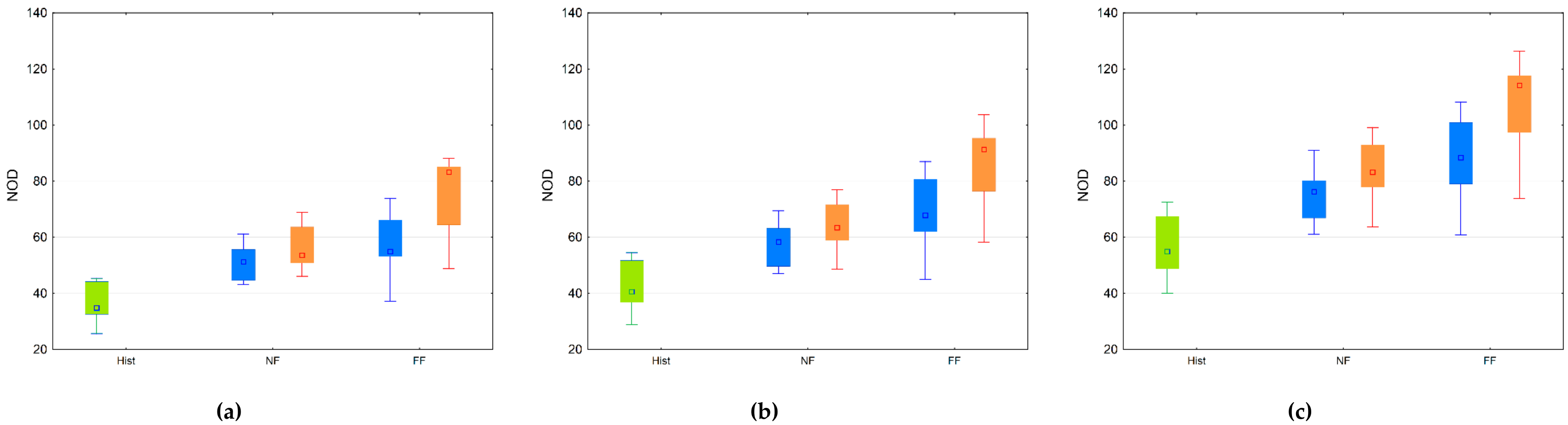
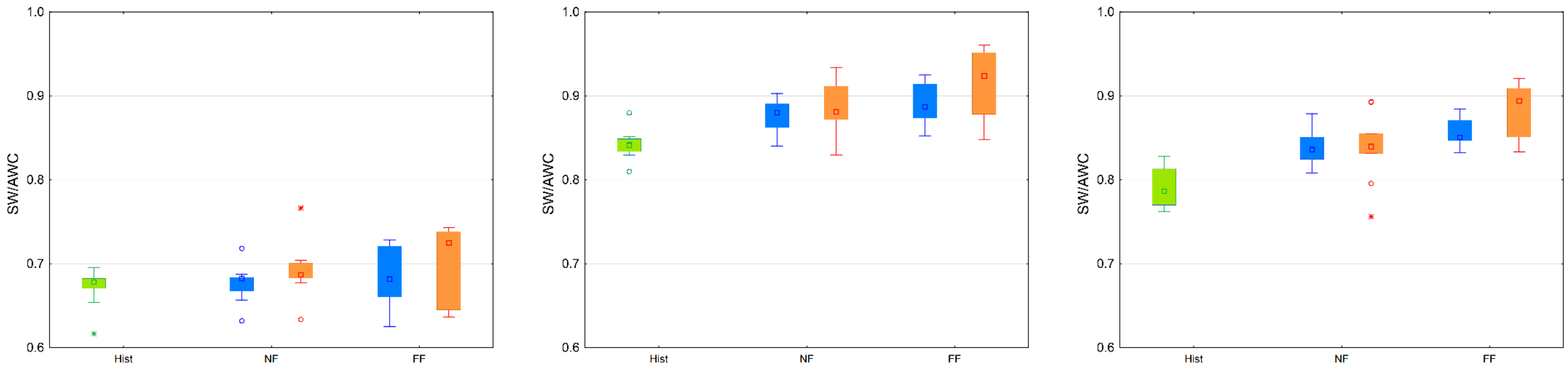


Figure 4. Projected changes in yearly number of days when streamflow exceeds bankfull flow (NOD) for habitat: (**a**) 6430—hydrophilous, tall-herb fringe communities of plains and of the montane to alpine levels, (**b**) 91E0—alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, *Alnion incanae*, *Salicion albae*); (**c**) 91F0—riparian mixed forests of *Quercus robur*, *Ulmus laevis*, and *Ulmus minor*, *Fraxinus excelsior*, or *Fraxinus angustifolia*, along the large rivers (*Ulmenion minoris*) in RCP 4.5 (blue) and 8.5 (orange), and the baseline scenario (green).



(**a**) (**b**) (**c**)

Figure 5. Projected changes of soil water (SW) in relation to available water capacity (AWC) for habitat: (**a**) bog woodland (91D0—bog woodland); (**b**) bog habitats (7110—active raised bog; 7140—transition mires and quaking bogs; 7120—degraded raised bogs still capable of natural regeneration), (**c**) fen habitats (7210—calcareous fens with *Cladium mariscus* and a species of the *Caricion davallianae*, 7230—alkaline fens) in RCP 4.5 (blue), 8.5 (orange), and the baseline scenario (green).

Table 3. Number of SWAT sub-basins and hydrologic response units (HRUs) included in the analysis for given types of habitats within the Vistula and Odra basins with an assessment of threats connected to drying out and inundation according to the conservation status of SACs (A or B, C, D). Number of threats identified within all the considered SACs (threats and pressures of drying out: K01.03—drying out; M01.02—droughts and less precipitations; J02.04.02—lack of flooding; J02.03—canalization and water deviation; J02.03.01—large scale water deviation; J02.03.02—canalization; J02.05—modification of hydrographic functioning, general and threats and pressures of inundation: L08—inundation (natural processes)).

Type of Water Supply	Habitat Type	No. of Analyzed Sub-Basins	No. of Analyzed HRU	No. of Analyzed SACs	No. of SACs with Identified Threats and Pressures	Threat of Drying Out				Threat of Inundation			
						No. of Analyzed Sub-Basins or HRU (B, C, D)	No. of Threats (B, C, D)	No. of Analyzed Sub-Basins or HRU (A)	No. of Threats (A)	No. of Analyzed Sub-Basins or HRU (B, C, D)	No. of Threats (B, C, D)	No. of Analyzed Sub-Basins or HRU (A)	No. of Threats (A)
Surface water-fed	6430	13		13	7	5	10	2	2	0	0	0	0
	91E0	30		30	17	14	22	1	1	1	1	1	1
	91F0	15		15	7	7	12	0	0	0	0	0	0
Groundwater-fed	Bog woodlands 91D0		34	8	5	3	5	2	2	0	0	0	0
	Bogs (7110, 7120 and 7140)		8	5	2	2	2	0	0	0	0	0	0
	Fens (7210 and 7230)		10	5	3	3	3	0	0	0	0	0	0

4. Discussion

Climate change projections prepared for the VOB suggest predominantly an increase in seasonal and annual runoff [23,43]. This partly explains the increases in other hydrological variables reported in this study. The data acquired from the SWAT model forced by rainfall and temperature projections show, for the majority of rivers in the Vistula and Odra basins, an increase in high and low flows and soil water [44]. Increasing trends are visible for NOD and SW/AWC, but changes are more significant for NOD, which suggests that surface water-fed wetlands will be more impacted by climate change. The rate of these increases is higher for the long-term future than for the near future; the same pattern is apparent for RCPs where changes in 8.5 are larger than in RCP 4.5. This suggests that wetland habitats which are well adapted to moist conditions should be the least affected by climate change.

The established modelling framework is a simplified representation of the ecological interactions and does not contain all the factors responsible for presence of a particular ecosystem. This approach is suitable for larger scales (river basin or country-scale) and transferring the framework to other catchments. This study focuses on the sole effect of climate change on hydrology, without other disturbances and man-made alterations, such as dams, water abstractions, and land-use changes. While focusing on mean values from long periods of time, information on the variability of wet and dry years and the amplitude was lost. As indicated by the outliers in Figures 4 and 5, the results are highly uncertain. The current regional soil water pattern depends on the spatio-temporal interaction and distribution of temperature, soil texture, radiation, and atmospheric CO_2 [32]. The last two components were not included in the SWAT model set up for VOB.

Most of the climate change projections for Eastern Europe show a decrease in the flooding duration; therefore, this study deals with an opposite situation. A study conducted by Schneider et al. [45] projected a decrease in flood volume for inundation and duration of overbank flows in Central and Eastern European rivers. Projections carried out by Dankers and Feyen [46] found a significant decrease in the occurrence of flood hazards in the northeast of Europe. Simulations prepared for global Ramsar sites by Schneider et al. [12] showed a significant decrease in flood pulses in 8% of them. Eastern Europe could become a hotspot of further flow modifications due to climate change [12]. Overall, it should be noted that there are numerous reasons why hydrological projections differ, so a direct comparison to other studies is usually hampered with methodological differences [47].

Numerous studies for temperate climates project a decrease in soil water of riparian areas, wetlands, and groundwater-dependent ecosystems due to climate change [32,48]. Similar trends are projected for other parts of Europe [49,50]. This study, along with several others, indicates a reverse trend. A clear increase in relative soil water content for terrestrial ecosystems in the regions north of ~50° N, which include Poland, was projected by Gerten et al. [32] for all prepared climate scenarios. A modelling study carried out by Holsten et al. [15] for the German state of Brandenburg projected, for all climate realizations, a decrease of average soil water content of 4% to 15% by 2050. The same study also found that available soil water content in SACs was higher while soil water dynamics were lower, mostly due to their favorable edaphic conditions. SACs within Brandenburg showed stronger absolute and relative changes in the projected trends for the past and future in comparison to the whole state, which indicates a high level of risk for wetland areas. Under the conditions of climate change, soil water content in SACs is projected to remain higher than average, and therefore, SACs have an important function as buffers [15]. Similar results were obtained for wetland habitats within SACs in VOB in this study.

4.1. Change in the Habitat Conservation Status

The important implication of our study is the possible impact of increases of SW/AWC and NOD on the analyzed habitats. Information about the current conservation status of habitats, threats, and pressures affecting SACs determines whether the projected changes in the average flooding duration and soil water could become an additional stressor or have a beneficial impact on further possibilities of maintaining or achieving an excellent conservation status "A" for habitats. In Webb et al. [51], the eco evidence method for systematic review was used to analyze literature for evidence of relationships between components of wetland water regimes (waterlogging, inundation, depth, duration, frequency, and timing) and their effects on riparian plant establishment, growth, reproduction, assemblage composition, and diversity. Waterlogging in the Webb et al. [51] study applies to the substrate when it is inundated, but not above soil level or when it is at field capacity (compared to dry or well-drained substrates). Inundation (submersion) refers to the situation when the water is present above soil level. Depth, duration, frequency, and timing relate to inundation events. Plant assemblage composition and diversity is relevant for this study. Due to the tools that were available for this study, it was possible to analyze waterlogging, inundation, and the duration of flooding. Waterlogging applies to groundwater-fed wetlands and inundation to surface water-fed wetlands (Table 4).

Table 4. Causal criteria analysis results for hypotheses linking changes in wetland plant assemblage-composition and plant diversity, to increases in components of the water regime according to a systematic review carried out in [52].

Components of Water Regime	Plant Assemblage Composition	Plant Diversity
Waterlogging	Insufficient evidence	Insufficient evidence
Inundation	Inundation affects plant assemblage composition	Inundation decreases plant diversity
Duration of inundation	Inundation duration affects plant assemblage composition	Increasing flood duration does not increase plant diversity

Climate change is likely to affect the water regime, and in the light of the systematic review presented in [51], this will impact and alter the abiotic conditions important for wetlands. The literature supports the hypotheses that inundation and flood duration alter the composition of wetland plant assemblages. There was insufficient evidence to examine the effects of waterlogging on plant assemblages and diversity occurring in wetlands. Support was found for the hypothesis that inundation reduces plant diversity. It was concluded that increasing flood duration does not increase plant diversity [51].

Assuming that the habitats with excellent conservation status (A) are at their optimum, they could be the most affected by climate change, as increased soil water or overbank flow can exceed their tolerance. Surface water-fed habitats with status A, which are already in their optimum condition, might be subject to an increase in the duration of inundation expressed as NOD. Habitats with non-significant presence indicated as conservation status D and threatened by drying out could encounter opportunities to extend their range. Habitats with conservation status B (good), C (average or reduced), threatened with drying out, in the projected wetter conditions, could benefit from the changing climate. The scale of this potential improvement cannot be assessed in this study due to internal mechanisms of habitats that were not included here.

4.2. Impact on Analyzed Habitats

One of the primary determinants of species distribution is water availability, which also impacts community composition, ecosystem processes, and services like carbon sequestration [52]. Climate conditions and land use affect water availability. The likely result of anthropogenic climate and land-use change is the alteration of the hydrology of a substantial portion of the global terrestrial ecosystems [53–56]. Thus, there is a clear need to develop models suitable for simulating soil moisture and other hydrological conditions [52].

According to a study by Schneider et al. [13], focusing on habitats 91E0 and 91F0, extreme floods should occur at least every 10–20 years in order to halt the succession to a terrestrial forest. Richter and Richter [57] found that 125% of bankfull can be essential to create new pioneer sites along meandering rivers to colonize by succession precursors of alluvial and riparian forests. In order to maintain optimal conditions, flooding should occur for less than 40 days/year. The duration of the flood event should be no longer than 60% of the growing season and not two seasons in a row, which would give no time for the recovery of the habitat. Recruitment does not occur when the habitat is flooded more than 30–40% of the growing season [58]. Chronic increase in summer inundation can impact species composition in existing sites [13]. Flooding tolerance classes according to Glenz et al. [58] describe *Alnus glutinosa* as having a very high tolerance and *Fraxinus excelsior* an intermediate flooding tolerance. Both of those tree species are included in habitat 91E0—alluvial forests. For riparian mixed forests 91E0, according to Glenz et al. [58], *Quercus robur*, *Ulmus minor*, and *Fraxinus excelsior* have an intermediate flooding tolerance, while *Ulmus laevis* and *Fraxinus angustifolia* were not included in the analysis.

For 91E0, the NOD for the baseline period has a mean value of 42 days/year (Figure 4b) which is very close to condition set by Schneider et al. [13] of 40 days/year in order to maintain optimal inundation. For 91F0, it is 56 days (Figure 4c) which already exceeds the optimum value. In the future, for both habitats, the NOD is projected to increase even further up to 87 days in FF 8.5 for 91E0 and 108 days for 91F0. This might indicate that in the future, the NOD will exceed the flooding tolerance of both habitats.

A key factor is the individual habitat or species water condition preferences, but the range of tolerance is not available for all the remaining habitats analyzed. Ecohydrological guidelines for wetland plant communities available for the UK [59,60] try to tackle this issue, but they do not contain information about the optimal number of days with inundation or soil water content for Natura 2000 habitats. The increase in soil water or in frequency of flooding may trigger biological and ecological processes of changes in wetlands, which so far cannot be predicted. Research on this topic is especially significant in Natura 2000 SACs, in which there is a legal obligation (Habitats Directive) to ensure that the habitats are restored to, or maintained at, a favorable conservation status [42]. According to our findings, surface water-fed wetland habitats especially, will face a new standard in their habitats and whether they will be able to adapt is uncertain.

5. Conclusions

The SWAT modelling results showed a significant increase in the length of inundation and a slight increase in soil water content. According to the climate change projections prepared for the Vistula and Odra basins, the increase of yearly number of days when streamflow exceeds bankfull flow (NOD) and soil water in relation to available water capacity (SW/AWC) would be caused by an increase in precipitation and runoff. This study also examined the conservation status of habitats and the threats and pressures they are subject to. This allowed the conclusion that habitats that are under the threat of drying out might benefit from alterations induced by climate change. As those habitats will experience wetter conditions, possibly, with time, the threat of drying out will be reduced or eliminated without any man-made measures. Habitats with a conservation status A which are already in optimum condition could be negatively affected by climate change, as increased soil water or overbank flow can exceed their tolerance. This issue should be addressed by conducting monitoring and research on the impact of increased moisture on the long-term condition and of those habitats.

As most literature focuses on droughts, there is a knowledge gap about climate change and the potential increase of water availability. Attention should be placed on the research of waterlogging's impact on the plant community's composition and diversity, as according to Webb et al. [51] there is an insufficient evidence base. An increase in flooding duration and frequency could cause the application of flood protection measures. Such a possibility was not included in this research, but should be monitored. All flood protection measures should be conducted in such a way as to minimize disturbance of natural processes in river valleys. More detailed studies on the possibilities of incorporating the hydrotechnical infrastructure in climate change mitigation and adaptation plans are needed.

The presented issues and projections pose a challenge for the preparation of Natura 2000 management plans by raising questions on how to include the possible positive impact of climate change on reducing the habitat threats of drying out. The possibilities of fulfilling objectives of the Natura 2000 network should also be assessed with the inclusion of climate change projections. This study shows that the protection of status quo of wetland habitats within Natura 2000 might encounter new challenges caused by climate change.

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Appendix A

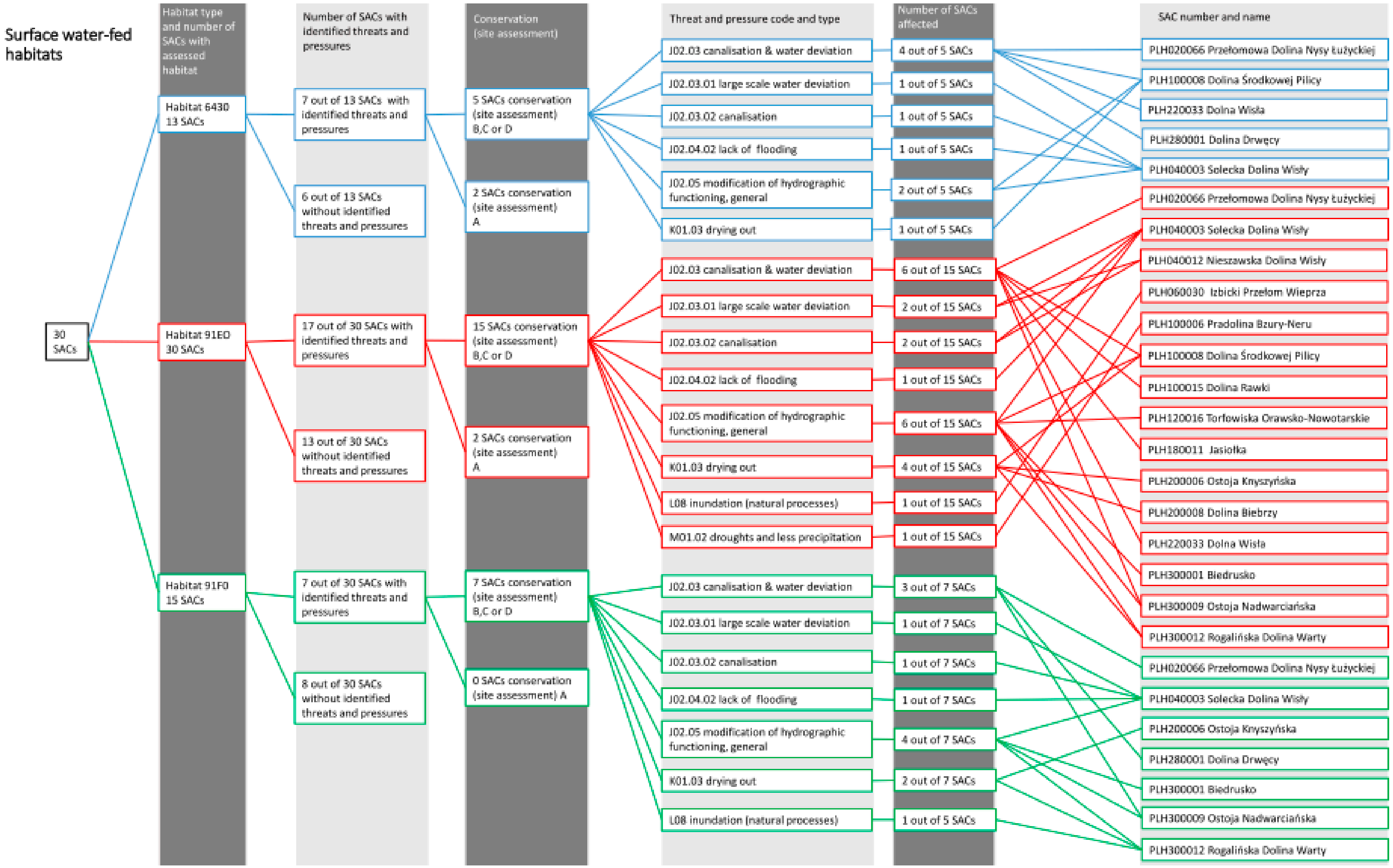

Figure A1. Analysis scheme for identified threats, pressures, and conservation status of surface water-fed habitats within SACs.

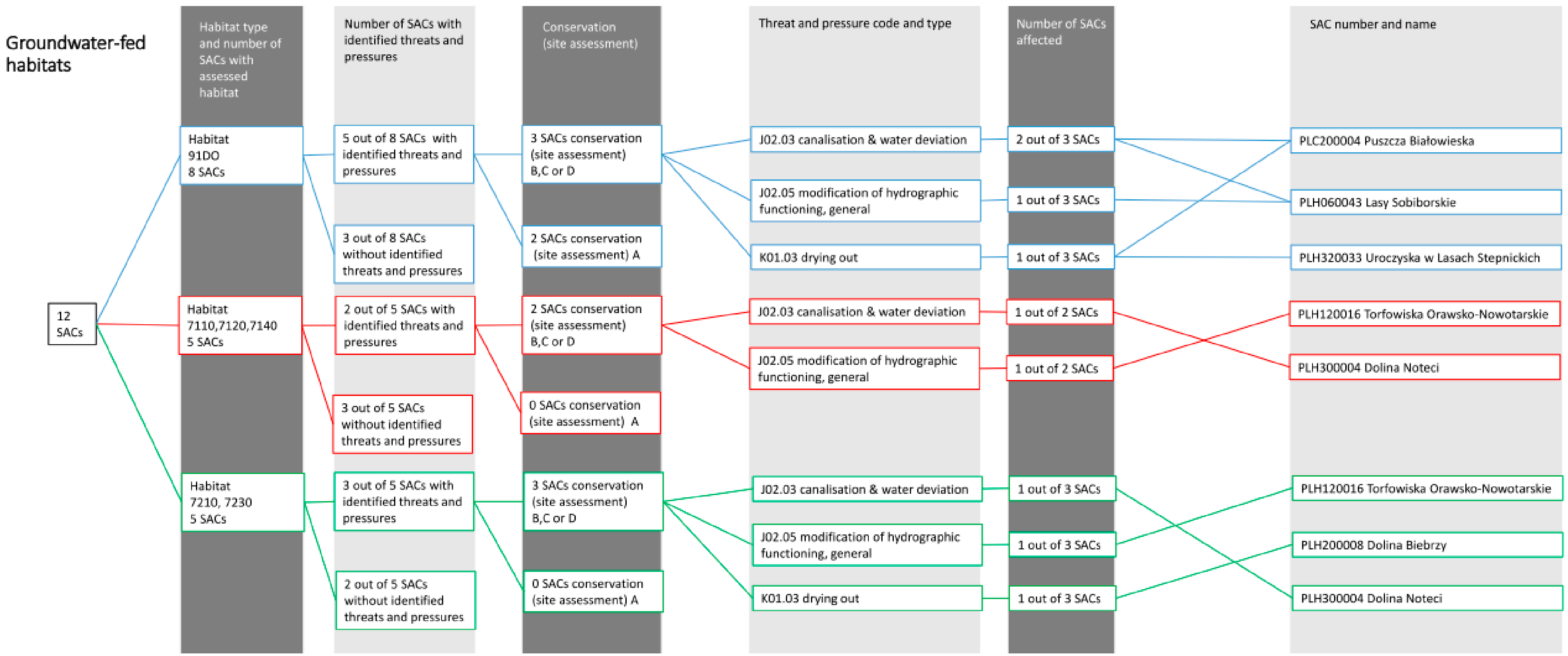

Figure A2. Analysis scheme for identified threats, pressures, and conservation status of groundwater-fed habitats within SACs.

References

1. Maltby, E. *Waterlogged Wealth: Why Waste the World's Wet Places?* International Institute for Environment and Development: London, UK, 1986; ISBN 0905347633.
2. Bullock, A.; Acreman, M. The role of wetlands in the hydrological cycle. *Hydrol. Earth Syst. Sci.* **2003**, *7*, 358–389. [CrossRef]
3. Verhoeven, J.T.A.; Arheimer, B.; Yin, C.; Hefting, M.M. Regional and global concerns over wetlands and water quality. *Trends Ecol. Evol.* **2006**, *21*, 96–103. [CrossRef]
4. Acreman, M.C.; Miller, F. Practical approaches to hydrological assessment of wetlands lessons from the UK. In *Wetlands: Monitoring, Modelling and Management*; Okruszko, T., Maltby, E., Szatyłowicz, J., Świątek, D., Kotowski, W., Eds.; Taylor & Francis: London, UK, 2007.
5. Okruszko, T.; Duel, H.; Acreman, M.; Grygoruk, M.; Flörke, M.; Schneider, C. Broad-scale ecosystem services of European wetlands—Overview of the current situation and future perspectives under different climate and water management scenarios. *Hydrol. Sci. J.* **2011**, *56*, 1501–1517. [CrossRef]
6. Côté, I.M.; Darling, E.S. Rethinking ecosystem resilience in the face of climate change. *PLoS Biol.* **2010**, *8*, e1000438. [CrossRef]
7. IPCC. Summary for Policymakers. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O.R., Pichs-Madruga, Y., Sokona, E., Farahani, S., Kadner, K., Seyboth, A., Adler, I., Baum, S., Brunner, P., Eickemeier, B., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
8. Jacob, D.; Petersen, J.; Eggert, B.; Alias, A.; Christensen, O.B.; Bouwer, L.M.; Braun, A.; Colette, A.; Déqué, M.; Georgievski, G.; et al. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Reg. Environ. Chang.* **2014**, *14*, 563–578. [CrossRef]
9. Roudier, P.; Andersson, J.C.M.; Donnelly, C.; Feyen, L.; Greuell, W.; Ludwig, F. Projections of future floods and hydrological droughts in Europe under a +2 °C global warming. *Clim. Chang.* **2016**, *135*, 341–355. [CrossRef]
10. Alfieri, L.; Burek, P.; Feyen, L.; Forzieri, G. Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 2247–2260. [CrossRef]
11. Candela, L.; Von Igel, W.; Elorza, F.J.; Aronica, G. Impact assessment of combined climate and management scenarios on groundwater resources and associated wetland (Majorca, Spain). *J. Hydrol.* **1997**, *376*, 510–527. [CrossRef]
12. Schneider, C.; Flörke, M.; De Stefano, L.; Petersen-Perlman, J.D. Hydrological threats to riparian wetlands of international importance—A global quantitative and qualitative analysis. *Earth Syst. Sci* **2017**, *215194*, 2799–2815. [CrossRef]
13. Schneider, C.; Flörke, M.; Geerling, G.; Duel, H.; Grygoruk, M.; Okruszko, T. The future of European floodplain wetlands under a changing climate. *J. Water Clim. Chang.* **2011**, *2*, 106–122. [CrossRef]
14. House, A.R.; Thompson, J.R.; Acreman, M.C. Projecting impacts of climate change on hydrological conditions and biotic responses in a chalk valley riparian wetland. *J. Hydrol.* **2016**, *534*, 178–192. [CrossRef]
15. Holsten, A.; Vetter, T.; Vohland, K.; Krysanova, V. Impact of climate change on soil moisture dynamics in Brandenburg with a focus on nature conservation areas. *Ecol. Model.* **2009**, *220*, 2076–2087.
16. Dembek, W.; Grotek, A.; Jakubowski, W.; Piórkowska, H.; Oświecimska-Piasko, Z.; Siedlecki, T.; Szewczyk, M. *System Informacji Przestrzennej o Mokradłach Polski "GIS-Mokradła"*; IMUZ: Falenty, Poland, 2006.
17. Statistics Poland. *Statistical Analyses Environment 2018*; GUS: Warsaw, Poland, 2018; ISBN 0867-3217.
18. Okruszko, T.; Kiczko, A. Assessment of Water Requirements of "Swamp Communities: The River Narew Case Study. *Publ. Inst. Geophys. Pol. Acad. Sci.* **2008**, *E-9*, 27–39.
19. Dembek, W.; Pawlaczyk, P.; Sienkiewicz, J.D.P. *Obszary Wodno-Błotne w Polsce*; IMUZ: Falenty, Poland, 2004.

20. EU. *Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora*; EU: Brussels, Belgium, 1992.
21. GDEP. *Spatial Information Database of Natura 2000 sites and habitats prepared by General Directorate for Environmental Protection (GDEP)*; GDEP: Warsaw, Poland, 2016. Available online: https://natura2000.gdos.gov.pl/ (accessed on 9 September 2018).
22. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modeling and assessment part I: Model development. *J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [CrossRef]
23. Piniewski, M.; Szcześniak, M.; Kardel, I.; Berezowski, T.; Okruszko, T.; Srinivasan, R.; Vikhamar Schuler, D.; Kundzewicz, Z.W. Hydrological modelling of the Vistula and Odra river basins using SWAT. *Hydrol. Sci. J.* **2017**, *62*, 1266–1289. [CrossRef]
24. Mezghani, A.; Dobler, A.; Haugen, J.E.; Benestad, R.E.; Parding, K.M.; Piniewski, M.; Kardel, I.; Kundzewicz, Z.W. CHASE-PL Climate Projection dataset over Poland – bias adjustment of EURO-CORDEX simulations. *Earth Syst. Sci. Data* **2017**, *95194*, 905–925. [CrossRef]
25. Moss, R.H.; Edmonds, J.A.; Hibbard, K.A.; Manning, M.R.; Rose, S.K.; van Vuuren, D.P.; Carter, T.R.; Emori, S.; Kainuma, M.; Kram, T.; et al. The next generation of scenarios for climate change research and assessment. *Nature* **2010**, *463*, 747–756. [CrossRef]
26. Piniewski, M.; Mezghani, A.; Szcześniak, M.; Kundzewicz, Z. Regional projections of temperature and precipitation changes: Robustness and uncertainty aspects. *Meteorol. Zeitschrift* **2017**, *26*, 223–234. [CrossRef]
27. Hughes, F.M.R. Floodplain biogeomorphology. *Prog. Phys. Geogr. Earth Environ.* **1997**, *21*, 501–529. [CrossRef]
28. Schneider, C.; Flörke, M.; Eisner, S.; Voss, F. Large scale modelling of bankfull flow: An example for Europe. *J. Hydrol.* **2011**, *408*, 235–245. [CrossRef]
29. Tockner, K.; Malard, F.; Ward, J.V. An extention of the flood pulse concept. *Hydrol. Proc.* **2000**, *14*, 2861–2883. [CrossRef]
30. Cooper, D.J.; Merritt, D.M. *Assessing the Water Needs of Riparian and Wetland Vegetation in the Western United States*; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2012.
31. Smith, J.A.C.; Griffiths, H. *Water Deficits: Plant Responses from Cell to Community*; Bios Scientific Publishers: Oxford, UK, 1993; ISBN 1-872748-06-5.
32. Gerten, D.; Schaphoff, S.; Lucht, W. Potential future changes in water limitations of the terrestrial biosphere. *Clim. Chang.* **2007**, *80*, 277–299. [CrossRef]
33. KZGW. *Baza Danych Przekroi Mokrych Rzek Polski Wykonana w Ramach Projektu "Informatyczny System Osłony Kraju Przed Nadzwyczajnymi Zagrożeniami" (ISOK)*; KZGW: Warsaw, Poland, 2014.
34. Leopold, L.B.; Wolman, M.G.; Miller, J.P. *Fluvial Processes in Geomorphology*; Dover Publications, Inc.: New York, NY, USA, 1964.
35. Maltby, E. *Functional Assessment of Wetlands: Towards Evaluation of Ecosystem Services*; Woodhead Publishing Limited: Cambridge, UK, 2009; ISBN 9781855738348.
36. Stephenson, N. Climatic control of vegetation distribution: The role of the water balance. *Am. Nat.* **1990**, *135*, 649–670. [CrossRef]
37. Yang, Y.; Watanabe, M.; Wang, Z.; Sakura, Y.; Tang, C. Prediction Of Changes In Soil Moisture Associated With Climatic Changes And Their Implications For Vegetation Changes: Waves Model Simulation On Taihang Mountain, China. *Clim. Chang.* **2003**, *57*, 163–183. [CrossRef]
38. Arnold, J.G.; Kiniry, J.R.; Srinivasan, R.; Williams, J.R.; Haney, E.B.; Neitsch, S.L. *Soil and Water Assessment Tool Input/Output Documentation*; Texas Water Resources Institute: College Station, TX, USA, 2012.
39. Andreadis, K.M.; Clark, E.A.; Wood, A.W.; Hamlet, A.F.; Lettenmaier, D.P. Twentieth-Century Drought in the Conterminous United States. *J. Hydrometeorol.* **2006**, *6*, 985–1001. [CrossRef]

40. EC. *Natura 2000 Standard Data Form: Explanatory Notes*; European Comission: Brussels, Belgium, 2011.
41. Cowx, I.G.; Fraser, D. *Monitoring the Atlantic Salmon Salmo Salar*; English Nature: Peterborough, UK, 2000.
42. EC. *Wildlife and Sustainable Farming and the Birds and Habitats Directives: How Species Conservation Can Be Supported through Rural Development Programmes—Good Practice Examples*; European Comission: Brussels, Belgium, 2009.
43. Marcinkowski, P.; Piniewski, M.; Kardel, I.; Szcześniak, M.; Benestad, R.; Srinivasan, R.; Ignar, S.; Okruszko, T. Effect of Climate Change on Hydrology, Sediment and Nutrient Losses in Two Lowland Catchments in Poland. *Water* **2017**, *9*, 156. [CrossRef]
44. Piniewski, M.; Szcześniak, M.; Kundzewicz, Z.W.; Mezghani, A.; Hov, Ø. Changes in low and high flows in the Vistula and the Odra basins: Model projections in the European-scale context. *Hydrol. Process.* **2017**, *31*, 2210–2225. [CrossRef]
45. Schneider, C.; Laizé, C.L.R.; Acreman, M.C.; Flörke, M. How will climate change modify river flow regimes in Europe? *Hydrol. Earth Syst. Sci.* **2013**, *17*, 325–339. [CrossRef]
46. Dankers, R.; Feyen, L. Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations. *J. Geophys. Res.* **2008**, *113*, D19105. [CrossRef]
47. Kundzewicz, Z.W.; Krysanova, V.; Dankers, R.; Hirabayashi, Y.; Kanae, S. Differences in flood hazard projections in Europe-their causes and consequences for decision making. *Hydrol. Sci. J.* **2017**, *62*, 1–14. [CrossRef]
48. Dwire, K.A.; Mellmann-Brown, S.; Gurrieri, J.T. Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. *Clim. Serv.* **2017**, *10*, 44–52. [CrossRef]
49. Jones, A.; Stolbovoy, V.; Rusco, E.; Gentile, A.-R.; Gardi, C.; Marechal, B.; Montanarella, L. Climate change in Europe. 2. Impact on soil. A review. *Agron. Sustain. Dev.* **2009**, *29*, 423–432. [CrossRef]
50. Mihailović, D.T.; Drešković, N.; Arsenić, I.; Ćirić, V.; Djurdjević, V.; Mimić, G.; Pap, I.; Balaž, I. Impact of climate change on soil thermal and moisture regimes in Serbia: An analysis with data from regional climate simulations under SRES-A1B. *Sci. Total Environ.* **2016**, *571*, 398–409. [CrossRef]
51. Webb, J.A.; Wallis, E.M.; Stewardson, M.J. A systematic review of published evidence linking wetland plants to water regime components. *Aquat. Bot.* **2012**, *103*, 1–14. [CrossRef]
52. Maclean, I.M.D.; Bennie, J.J.; Scott, A.J.; Wilson, R.J. A high-resolution model of soil and surface water conditions. *Ecol. Model.* **2012**, *237–238*, 109–119. [CrossRef]
53. Alcamo, J.; Döll, P.; Henrichs, T.; Kaspar, F.; Lehner, B.; Rösch, T.; Siebert, S. Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. *Hydrol. Sci. J.* **2003**, *48*, 339–348. [CrossRef]
54. Foley, J.A.; Defries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Chapin, F.S.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; et al. Global Consequences of Land Use. *Science* **2005**, *309*, 570–574. [CrossRef]
55. Neilson, R.P. Model for predicting continental-scale vegetation distribution and water balance—ScienceBase-Catalog. *Ecol. Appl.* **1995**, *5*, 362–385. [CrossRef]
56. Oki, T.; Kanae, S. Global hydrological cycles and world water resources. *Science* **2006**, *313*, 1068–1072. [CrossRef]
57. Richter, B.D.; Richter, H.E. Prescribing Flood Regimes to Sustain Riparian Ecosystems along Meandering Rivers. *Conserv. Biol.* **2000**, *14*, 1467–1478. [CrossRef]
58. Glenz, C.; Schlaepfer, R.; Iorgulescu, I.; Kienast, F. Flooding tolerance of Central European tree and shrub species. *For. Ecol. Manag.* **2006**, *235*, 1–13. [CrossRef]

59. Wheeler, B.D.; Gowing, D.J.G.; Shaw, S.C.; Mountford, J.O.; Money, R.P. *Ecohydrological Guidelines for Lowland Wetland Plant Communities*; Brooks, A.W., Jose, P.V., Whiteman, M.I., Eds.; Environment Agency Kingfisher House: Peterborough, UK, 2004.
60. Barsoum, N.; Anderson, R.; Broadmeadow, S.; Bishop, T.N.H. *Eco-Hydrological Guidelines for Wet Woodland—Phase 1*; English Nature: Peterborough, UK, 2001; pp. 1990–2001.

10. Article 2

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Index-based analysis of climate change impact on streamflow conditions important for Northern Pike, Chub and Atlantic salmon

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Abstract

Climate change is expected to affect the flow regime, cause loss of habitat, change community composition and behavioural habits of fish. This study assessed the impact of climate change on ecologically relevant streamflow conditions for fish migration and spawning in the Vistula and the Odra river basins. Streamflow simulations obtained with the Soil and Water Assessment Tool (SWAT) for the historical period and two future horizons were driven by nine bias-corrected EURO-CORDEX Regional Climate Models under two greenhouse gas concentration trajectories. This study identified a subset of Indicators of Hydrological Alteration (IHA) that are relevant for pike, *Esox lucius* L., chub, *Squalius cephalus* (L.), and Atlantic salmon, *Salmo salar* L. IHA indicators were calculated and compared for different scenarios. An index-based framework identified that all considered species will be impacted by climate change, with Atlantic salmon facing the largest impact. The model's uncertainty was addressed through an aggregation method that assessed inconsistencies in the model's response.

KEYWORDS

flow regime, Indicators of Hydrologic Alteration, migration, *Salmo salar*, spawning, SWAT

1 | INTRODUCTION

Streamflow can be considered a "master variable" that limits the abundance and distribution of riverine species (Poff et al., 1997; Power, Sun, Parker, Dietrich & Wootton, 1995; Resh et al., 1988). Weather (precipitation and temperature) interacts with geology, topography, soil and vegetation to influence infiltration, evaporation and run-off generation, which together determine streamflow (Dhungel, Tarboton, Jin & Hawkins, 2016). Streamflow quantity and timing are critical components of environmental flows and ecological integrity of river systems. This "master variable" also influences fish feeding, migration, nesting and spawning conditions, and determines river habitats. As reported in various studies from different regions of the globe, streamflow is likely to be sensitive and vulnerable to climate change (Dhungel et al., 2016; Döll & Zhang, 2010; Gibson, Meyer, Poff, Hay & Georgakakos, 2005; Kundzewicz et al., 2009; Piniewski, Okruszko & Acreman, 2014; Schneider, Laizé, Acreman & Flörke, 2013; Thompson, Laizé, Green, Acreman & Kingston, 2014; van Vliet, Ludwig & Kabat, 2013). It is expected that climate change will have a strong impact on fishes as it affects the flow regime and thus may cause loss of habitat, changes in area and connectivity of habitats, community composition and behavioural habits, species losses (local extinctions) and reduced biodiversity (EPA (U.S. Environmental Protection Agency), 2008).

Fish biological research could provide answers about possible reactions and adaptation strategies of fish. Organisms can evolve in response to pressures associated with climate change through changing timing of life history events and ability to tolerate biotic and abiotic stresses arising from climate change. There is, however, concern that the rate of environmental change associated with climate change is occurring too fast to allow some organisms to maintain adaptability (Merilä & Hoffmann, 2016). Fish occur at a variety of spatial scales and occupy a wide range of ecological niches, and therefore, they are a good indicator of ecological status of rivers (Karr, 1981; Noble, Cowx & Starkie, 2007; Roset, Grenouillet, Goffaux, Pont & Kestemont, 2007). Projecting impact of climate change on fish is a pressing matter as climate change may have significant consequences for fish biological diversity (Guse et al., 2015; Yan, Huang, Wang, Gao & Qi, 2016). A typical approach for assessing the impacts of climate change on streamflow conditions important for fish is through applying future climate change scenarios in hydrological models. The next step is post-processing hydrological model outputs according to various methodologies dealing with ecologically relevant flow metrics (Arthington, 2012). The latter are treated as a proxy for representing suitable hydrologic conditions for fish. Studies that used hydrological modelling and flow metrics for identifying ecologically relevant changes in flow conditions for fish were carried out by van Vliet et al. (2013) with the use of the Variable Infiltration Capacity (VIC) model and Xenopoulos et al. (2005) and Döll and Zhang (2010) who employed the Water-Global Assessment and Prognosis (Water- GAP) model. In climate change impact research, the Soil and Water Assessment Tool (SWAT) has been coupled with fish habitat modelling by Guse et al. (2015). SWAT is a hydrological model that simulates run-off and streamflow (among other variables) with a daily time step on a catchment scale, which is suitable for large-scale studies (Arnold, Srinivasan, Muttiah & Williams, 1998). The SWAT model has been used in combination with the Indicators of Hydrologic Alteration (IHA) methodology (Richter, Baumgartner, Braun & Powell, 1998; Richter, Baumgartner, Powell & Braun, 1996) to assess climate change impact on a single fish species habitat suitability by Morid, Delavar, Eagderi and Kumar (2016) and Papadaki et al. (2015). The IHA consists of 33 parameters that describe the hydrological regime as: magnitude, timing, frequency, duration and rate of change (The Nature Conservancy 2009). Indicators of Hydrological Alteration is a good tool for recognising features that create the unique character of river streamflow (Laizé et al., 2010).

The objective of this paper was to project the impact of streamflow alteration due to climate change on spawning life stage of three fish species: pike. *Esox lucius* L., chub, *Squalius cephalus* (L.), and Atlantic salmon, *Salmo salar* L., occurring in the Vistula and Odra basins (VOB) in Poland. To this end, an index-based framework was developed, combining the hydrological SWAT model driven by a large ensemble of the state-of-the-art, bias-corrected EURO-CORDEX climate projections. This produced streamflow values for the baseline and two future time horizons. A set of suitable IHA indicators were selected for each fish species. Their values were modelled on the basis of streamflow data and then compared between the baseline and future scenarios. The projected changes and their impact on these three fish species were analysed. A spatially explicit output was produced in the form of traffic light maps, which assigned colours to river reaches and incorporated the climate model and emission scenario uncertainty.

2 | STUDY AREA AND DATA

2.1 | Vistula and Odra basins

The study was carried out for the river network of the VOB located in Central and Eastern Europe, draining to the southern Baltic Sea. The areas of the Vistula and Odra basins are 193,831 km^2 and 119,041 km^2, respectively. Eighty-eight percent of the VOB is located in Poland (87% of the Vistula basin and 88% of Odra basin). The remaining areas of the VOB are located in the neighbouring countries: Czech Republic, Germany, Slovakia, Belarus and Ukraine. The sources of the Vistula and Odra rivers lie in the Carpathian Mountains and the Sudetes, respectively, in the southern portions of the basins. The VOB is in the temperate climatic zone, which is characterised by cold winters and warm summers. An east to west temperature gradient in the VOB is created by continental influence in the east and a maritime influence in the west. Rivers in this region of Europe are characterised by moderate seasonal variability of streamflow, with the highest flows typically occurring in March and April, and the lowest flows in September and October. Water availability is among the lowest in Europe, with mean annual runoff of 171 mm and 154 mm for the Vistula and Odra, respectively (Shiklomanov & Rodda, 2003). Spatial variability of the blue water flow is very high, with the lowest values in the north-western part of the Polish Plain (Kujawy and Wielkopolska regions), intermediate values along the northern edge, and the highest values along the southern mountainous edge of the basins.

Flow regulation in this region is lower than in Western Europe, which means that large parts of the river network are still in semi-natural, or moderately disturbed conditions. Fish habitats in the VOB can be described as more intact than in the rivers of Western Europe due to the lesser extent of modifications done in the river beds and the presence of refugia. On the other hand, dams were built on large rivers such as the Vistula, the Odra and their tributaries, limiting or even blocking migrating fish species from moving upstream, often due to faulty design of fish ladders (Kruk et al., 2017).

2.2 | Simulated natural streamflow data

The SWAT model is a process-based, semi-distributed, continuous-time, hydrological model that simulates the movement of water, nutrients and sediment with a daily time step on a catchment scale (Arnold et al., 1998). The details of the SWAT (SWAT2012 rev. 635) model set-up for the VOB and the groundwork for this paper is presented in Piniewski, Szcześniak, Kardel, et al. (2017). Daily climate data from 1951 to 2013 were obtained at a resolution of 5 km from the gridded daily precipitation and temperature data set (CHASE-PL Forcing Data CPLFD-GDPT5) (Berezowski et al., 2016). The model was calibrated with the SUFI-2 algorithm (Abbaspour, Johnson &

van Genuchten, 2004), available in the SWAT-CUP software package and the Kling-Gupta Efficiency (KGE) objective function (Gupta, Kling, Yilmaz & Martinez, 2009). Calibration and evaluation of model runs on the daily time step were carried out for a set of 110 flow gauging stations representing catchments with diverse flow regimes, climate conditions, landscape and topography settings. The median KGE value for the data set of 30 gauges used for spatial evaluation was 0.76, which was assessed as a good fit. The list of gauge stations is presented in Supporting information Table S1. Furthermore, the model was extensively evaluated in terms of low and high flow simulations Piniewski, Szcześniak, Kundzewicz et al., 2017), which are quite important for the IHA indicators, many of which correspond to extreme flows. The analysis showed that the model performance for high flows was noticeably higher than for low flows (as illustrated by R^2 equal to 0.9 vs 0.61 for the calibration period), which is consistent with the recent assessment of nine hydrological models' performance in 12 large river basins (Huang et al., 2017). Huang et al reported that the bias of models in the low segment of the Flow Duration Curve (FDC) was significantly higher than the bias in the high segment of the FDC. This demonstrates that the model can be applied for spatial analysis of climate change impacts on hydrological indicators in the VOB. It is noteworthy that modelling was carried out for natural streamflow, without consideration of water management and man-made disturbances, which interact with and are impacted by climate change. This method enables assessment of the pure effect of climate change on streamflow and not driven by any other factors.

2.3 | Climate change forcing

The climate projections consist of a set of nine bias-corrected EURO-CORDEX (Jacob et al., 2014) combinations of Global and Regional Climate Models under two Representative Concentration Pathways (RCPs) of greenhouse gas concentration trajectories: 4.5 and 8.5 (Supporting information Table S2). The original EURO-CORDEX simulations were bias-corrected using the quantile mapping method, the CPLFD-GDPT5 (Berezowski et al., 2016) as reference data, and transformed onto a 5 by 5-km grid. Climate parameters were simulated for the historical period (1971-2000) and for two future horizons: near future (NF, 2021-2050) and far future (FF, 2071-2100). The final product, the CHASE-PL Climate Projections: 5-km Gridded Daily Precipitation and Temperature Dataset (CPLCP-GDPT5) is available for free use for research purposes (Mezghani et al., 2017).

Projected changes in temperature and precipitation over the VOB were analysed in Piniewski, Szcześniak, Kardel, et al., (2017). Depending on the time period and RCP projections of the annual daily means of minimum (Tmin) and maximum (Tmax), air temperature showed an increase ranging from 1.2 to 3.7°C for Tmin and from 1.0 to 3.3°C for Tmax. The highest predicted increase, occurring in all combinations of parameters, time horizons and RCPs, was projected to occur in winter but the magnitude of increase varied for the remaining seasons.

The projections of annual precipitation showed a mean increase of 5.5%-16.2% across the area of the VOB under different time horizons and RCPs. Predominantly, the precipitation increase was more significant during winter and spring (7.3%-27.9%) than in the summer and autumn (1.4%-9.1%). Both for precipitation and temperature, changes are greater in the far future time horizon and RCP 8.5.

2.4 | Future streamflow data

Future average daily streamflow data (m^3/s) was derived by forcing the SWAT model with the CPLCP-GDPT5 data set. The first 3 years of each 30-year simulation period were removed from the analysis as they constituted the warm-up period of the SWAT model. Analysis nodes were the outlets of 2,633 SWAT reaches distinguished in the model set-up. All reaches with upstream sub-catchment areas higher than 100 km^2 were thus represented. For each node, 45 time series with daily flow values were available (nine climate models, one reference period and two future periods under two RCPs).

3 | METHODS

3.1 | Assessment of streamflow change with Indicators of Hydrological Alteration (IHA)

The IHA method was implemented to assess hydrological alteration of streamflow regime parameters between two defined periods: historical and far or near future at a given river reach (Richter et al., 1996, 1998). The IHA method contains a subset of 33 parameters grouped into five sets of hydrologic features: magnitude, timing, frequency, duration and rate of change (The Nature Conservancy 2009). Indicators of Hydrological Alteration parameters recognise that all aspects of streamflow regime are ecologically important and capture almost the entire spectrum of all available hydrological indicators (Laizé et al., 2010). By choosing the most important flow-related drivers, a different subset of IHA indicators was selected for the three studied fish species. The method for choosing IHA indicators is described in Section 3.2. The IHA parameters were calculated in GNU R (R Development Core Team 2008) with the use of the EflowStats package (Thompson & Archfield, 2015).

3.2 | Streamflow regime relevance for fish

Fish species differ in their optimal water temperature, river substrate, flow velocity, vegetation, river depth and migration distance. This study focuses on streamflow patterns during spawning period to relate species requirements to streamflow characteristics (Noble et al., 2007). The influence of streamflow regime on freshwater fish community structures is related to the volume of flow, its rate, extremes and variability (Cowx et al., 2004). These flow components are captured by IHA indicators.

Managing streamflow for multiple species is difficult to balance as fish with a similar streamflow preference may differ in spawning

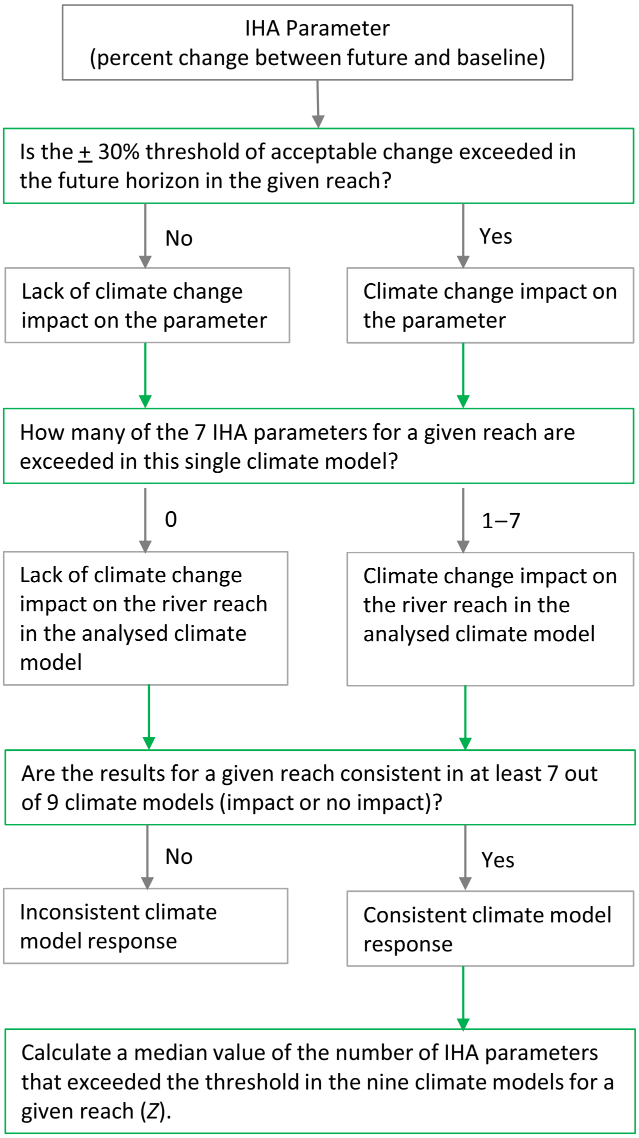

FIGURE 1 Workflow for the analysis of models response on climate change impact on a given fish species, in a defined time horizon and representative concentration pathways (RCP) scenario for a particular, single river reach on the basis of indicators of hydrological alteration (IHA) parameter percentage change between future and baseline

timing, water temperature requirements, life cycle type (catadromous, anadromous, potamodromous) or other life history traits. To demonstrate the concept of proposed climate change impact assessment scheme, this study focused on three fish species present in Poland in the VOB: pike, chub and Atlantic salmon, which represent different streamflow requirements during spawning (Błachuta et al., 2010). Each of the species shows different migration patterns, which is one of the factors related to streamflow regime. Pike is potamodromous, migrating mostly laterally to the nearest suitable habitats and does not carry out long spawning migrations. Chub is a potamodromous, lithophilic species migrating up to approximately 50 km. Atlantic salmon is an anadromous, migratory species mostly travelling long distances to reach its spawning grounds (and possibly returning from them). These species were chosen because of the availability of literature on their streamflow regime requirements. Findings of the literature review are available in the Supporting information S1. This allowed fish species to be linked with suitable streamflow regime characteristics and assess the expected impact of streamflow regime alteration in the conditions of projected climate change on fish. It was assumed that at least one or more of the three species is present in each reach of VOB analysed.

A summary and comparison of characteristics related to streamflow for the three fish species is presented in Supporting information Table S3. Seven IHA parameters were analysed for each fish. A total of 14 different IHA parameters were analysed; four of them were calculated twice for a different set of months and three parameters (March, April, May median flows) are included in the analysis for both pike and chub (Supporting information Table S4).

3.3 | Impact analysis

To evaluate the impact of climate change on parameters of hydrological regime important for the three selected fish species, the parameters calculated for two future horizons were compared to the equivalent ones from the reference period. The percentage change between the future and historical periods was assessed.

A threshold of acceptable change was set to aggregate the results in a convenient manner. Any alteration greater than that threshold would indicate a significant difference from the historical period. Other studies considered the change between the two time periods not significantly different from the baseline if the indicator change was within ±30% (Laizé et al., 2010; Schneider et al., 2013; Thompson et al., 2014; Wang et al., 2016). For the purpose of this study, it was also decided to use a fixed threshold of ±30%, which demonstrates the vulnerability of different fish to changes in most crucial streamflow parameters.

This study assessed the projected change in IHA parameter values at a river reach level. An indicator value of 1 (impact) was assigned if the threshold of ±30% change criterion was exceeded or 0 (no impact) if this threshold was not surpassed. Since each fish was influenced by seven indicators, every river reach could obtain a score from 0 to 7 presenting the number of altered indicators and offering information about the magnitude of impact. If the score amounted to 0, then it was assumed that climate change will not have an impact on streamflow parameters important for fish. If the score was from the range of 1-7, then that impact appeared.

Since there are three fish species assessed with nine climate models, within two RCPs and two future time spans, a total of 108 output maps were obtained. While it is useful to keep separate maps for different fish, RCPs and time horizons, it is more intelligible to aggregate values from nine different climate models into a single value, provided that the method of aggregation takes into account climate model uncertainty. In this study, the aggregation method applied was as follows. If simulation results based on at least seven ensemble members agreed on the lack (score 0) or the presence (score 1-7) of climate change impact, it was assumed that this (dominant) class can represent the ensemble. Reaches that are projected to be under no impact were coloured blue and reaches with impact were presented with a gradient colour. Reaches that did not obtain consistent results (i.e., there were six or less models agreeing on the class) were not assigned any impact class and coloured grey on the maps to show the uncertainty and inconsistency of results.

The output maps are presented as reach-specific median values of the number of IHA parameters that exceeded the predefined threshold of 30% calculated across the nine climate models. The median value was always calculated from the seven most accordant models (even when nine of them agreed that there is going to be an impact). The analysis process is presented in Figure 1.

4 | RESULTS

4.1 | Modelled impact of climate change on flow metrics relevant for fish

Changes in streamflow were modelled using the SWAT model and forced with climate change scenario input data, and then interpreted through associated changes in the IHA indicators. There is a change in the streamflow characteristics relevant for fish, increasing with changing RCP values and with more distant future periods. The projected multi-model ensemble maps for all fish species display a domination of climate change impact on streamflow conditions important for their spawning. The number of river reaches with IHA parameters that exceeded the 30% threshold of acceptable change, indicating an impact on streamflow increased with the RCP scenarios and time horizons. The median number

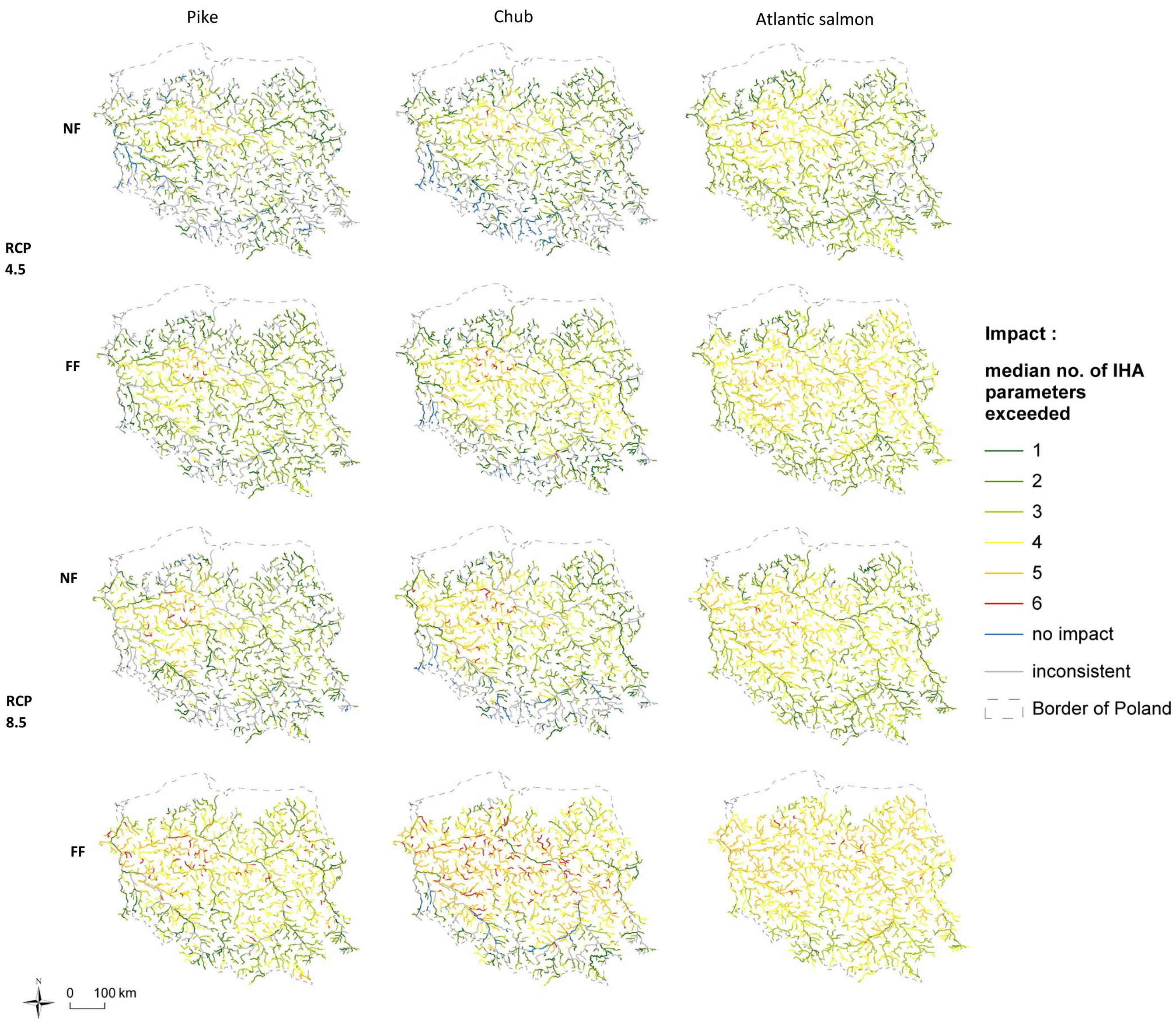

FIGURE 2 Projected impact of climate change on ecologically relevant river flow characteristics. Future occurrence of impact classes for pike, chub and Atlantic salmon, aggregated from the multi-model ensemble

TABLE 1 Median number and percentage of river reaches in the Vistula and Odra Basins under impact or no impact of climate change on streamflow conditions relevant to pike, chub and Atlantic salmon, as well as reaches with inconsistent model response. Results are presented for a total of 2,633 reaches in the study area in near future (NF), far future (FF) and representative concentration pathways (RCP) 4.5 and 8.5

			Impact		No impact		Inconsistent	
			No. of reaches	% of all reaches	No. of reaches	% of all reaches	No. of reaches	% of all reaches
Pike	RCP 4.5	NF	1,582	60.1	83	3.2	968	36.8
		FF	2,123	80.6	13	0.5	497	18.9
	RCP 8.5	NF	1,915	72.7	16	0.6	702	26.7
		FF	2,489	94.5	1	0.0	143	5.4
Chub	RCP 4.5	NF	1,707	64.8	138	5.2	788	29.9
		FF	2,133	81.0	38	1.4	462	17.5
	RCP 8.5	NF	1,986	75.4	66	2.5	581	22.1
		FF	2,322	88.2	59	2.2	252	9.6
Atlantic salmon	RCP 4.5	NF	2,438	92.6	1	0.0	194	7.4
		FF	2,588	98.3	1	0.0	44	1.7
	RCP 8.5	NF	2,559	97.2	1	0.0	73	2.8
		FF	2,620	99.5	0	0.0	13	0.5

of IHA parameters exceeded for river reaches displayed a similar tendency. The number of reaches with inconsistent responses was higher in NF than in FF (Figure 2, Table 1).

Analysis of streamflow parameters important for pike found the largest number of river reaches with inconsistent climate model results (36.8% in RCP 4.5 in NF and 26.7% in RCP 8.5; decreasing to 18.9% in RCP 4.5 in FF and 5.4% in RCP 8.5). Most reaches are impacted by climate change (60.1% for RCP 4.5 and 72.7% for RCP 8.5) for pike in the near future as well as in the far future (RCP 4.5: 80.6% and RCP 8.5: 94.5%). Results for chub are similar to pike in terms of the percentage of river reaches under impact of climate change, but differ in terms of the proportion of reaches under no impact (ranging from 2.2% to 5.2%, with higher amounts in NF), which is the highest among the three fish species. Atlantic salmon is under the highest threat of impact of climate change on streamflow characteristics important for its breeding, migration and survival, as on average 97% of river reaches in the VOB will be impacted in both time horizons and RCP scenarios. Almost all of the remaining reaches showed inconsistent results for Atlantic salmon. This species experiences the most extensive impact as the share and rate of increase in reaches under climate change impact are extensive. For all species, on average, 14.9% of reaches showed inconsistent impact in the nine models (Table 1).

The north-western corner of the inner part of the VOB has repetitively the highest median number of IHA parameters exceeded, while the areas along the southern mountainous edge are characterised by inconsistent model response (in particular for pike and chub) (Figure 2). This is likely related to the precipitation projections in this part of the VOB being less significant and less consistent on the sign of change than in other parts of both river basins (Piniewski, Szcześniak, Kardel, et al., 2017). Reaches with inconsistencies among models were also located throughout Poland and tend to occur on first-order tributaries.

Aggregation of modelling results of the nine climate model projections into a single map for each fish species downplays the uncertainty. Therefore, it is important to consider the agreement between the results driven by different models. The occurrence of inconsistent impact depicted by grey colour in Figure 2 results from discrepancies between the nine models (Supporting information Figure S1).

In the case of pike and chub, the Vistula river appears mostly as reaches with inconsistent results except for the FF in RCP 8.5, where it appears to be under no impact (chub results in the upper course) or with just one or two median number of IHA parameters exceeded. The Odra River shows highly variable results for its upper, mid and lower course and in different RCP scenarios and future horizons for pike and chub.

The Vistula, Odra and Bug rivers appear to be the predominant rivers that exceeded median numbers of parameters for Atlantic salmon, ranging from 1 to 3 in all RCP scenarios and time horizons. The rivers that showed the largest proportion of reaches with no impact are the Bóbr and Nysa Łużycka (for pike and chub), which are Odra tributaries.

4.2 | Projections of changes in IHA parameters

Calculation of projected changes of IHA parameters across 9 climate models enabled the investigation of parameters which drive the impact of climate change on fish (Figure 3). Box plots of IHA parameter changes across the multi-model ensemble illustrate the spread of the parameter values in different projections (RCP 4.5 and 8.5, NF, FF). Plots illustrate median changes and the spread of the box and whisker plots concerns only climate models and not individual reaches (which are averaged over the entire study area). In general, Figure 3 explains the variability in impact shown in Figure 2.

Parameters showing increasing changes were either the box plots exceeding the upper threshold of 30% acceptable change or

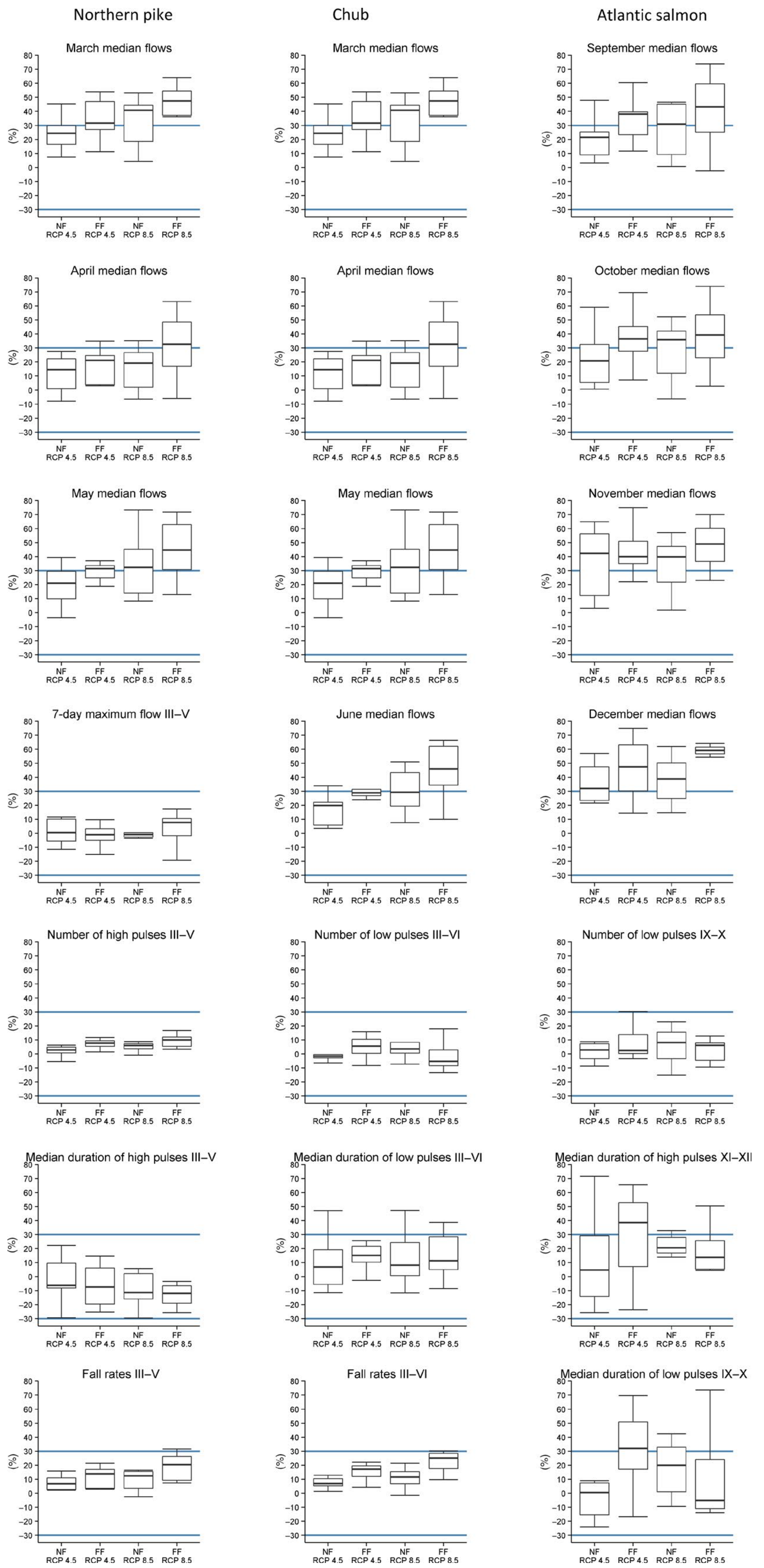

FIGURE 3 Box plots of projected percent changes in indicators of hydrological alteration (IHA) parameters selected for pike, chub and Atlantic salmon. Blue lines indicate the ±30% threshold of acceptable change. Plots illustrate median changes for all reaches calculated across different climate models for the near (NF) and far (FF) future under representative concentration pathways (RCP) 4.5 and 8.5

remaining within the set threshold, except for the median duration of high pulses in March-May whose changes were decreasing but remained within the threshold range. The highest increases in parameter values were observed for: median duration of high pulses (November-December); median duration of low pulses (September-October); May, September, October, November and December median flows. Twelve parameters have box plots (upper and lower extremes) that exceed the set threshold: six with a gradual increase over the time horizons and RCP scenarios and the remaining six without any clear patterns. Four parameters that remained within the set threshold and do not show large fluctuations were 7-day maximum flow, number of high pulses (March-May), fall rates (March-June) and number of low pulses (March-June and September-October).

Parameters that are most likely driving the results for pike are March, April and May median flows as out of seven parameters only those three significantly exceeded the set threshold (Figure 3). Projected impact of climate on chub was caused by an increasing median duration of low pulses (III-VI) as well as March, April, May and June median flows. For Atlantic salmon, significant thresholds surpassed were observed for all parameters, except for number of low pulses (IX-X).

5 | DISCUSSION

Most broad-scale studies investigating the effect of climate change on freshwater species focused on temperature, with less emphasis on flow regime and biotic interactions (Papadaki et al., 2015; Wenger et al., 2011). The current approach included a subset of IHA parameters calculated from daily stream flows for specific fish species. From this, quantitative information was obtained about projected changes due to climate change on rivers in Eastern Europe. Other studies have carried out descriptive examinations of change in IHA parameters by climate change and their implications on aquatic organisms (Gibson et al., 2005). The majority of studies projected an increase in frequency and magnitude of the low flow events or drought (Guse et al., 2015; Papadaki et al., 2015; Paparrizos & Matzarakis, 2016), but this study found a contrary situation. This is not surprising as climate projections and their impacts are region-specific and each generation of climate models or emission scenarios can potentially suggest a different future. While most of the previous studies used between one and four climate scenarios and often presented an averaged output value, this study used two RCPs and nine climate models, which produced 18 scenarios for each time horizon. Hence, the uncertainty originating from the top of uncertainty pyramid (i.e., emission scenarios and climate models; Wilby & Dessai, 2010) is better quantified here than in similar studies published to date. This study also proposed a simple aggregation method of assessing the dominant direction of change within the ensemble, which explicitly included the lack of consistency between model simulations in the assessment. It must be emphasised that the present work is a conceptual model based on the literature data and modelling, and further verification research is needed.

5.1 | Interrelation of the results with meteorological variables

Climate change projections for the VOB suggest a shift from precipitation falling as snow and being retained as snow cover, to precipitation falling as rain and infiltrating or running off to rivers (Piniewski, Szcześniak, Kardel, et al., 2017). Increased precipitation is the main factor supporting elevated run-off and thus driving streamflow, whereas increased temperature has a small effect leading to an increase in evapotranspiration and attenuating streamflow increase. Future climate and hydrological conditions are projected to be wetter for the VOB, which was also reported in several recent pan-European modelling studies (cf. Alfieri, Burek, Feyen & Forzieri, 2015; Papadimitriou, Koutroulis, Grillakis & Tsanis, 2016; Roudier et al., 2016).

It is consistent in all scenarios that the north-western corner of the inner part of the VOB appears as a highly impacted area (displays the utmost median number of IHA parameters exceeded). This is related to this region being the driest in Poland, which has been demonstrated also by the SWAT model simulations for the historical period (Piniewski, Szcześniak, Kardel, et al., 2017). If the baseline run-off is low, a given precipitation increase is likely to give a higher relative increase in run-off than when the baseline run-off is high Piniewski, Szcześniak, Kundzewicz, et al., 2017) .

5.2 | Projected impact of climate change on selected fish species

The future climate and hydrological conditions are projected to be more "wet" for the VOB, which could have a negative or positive effect on fish species. Derived projections suggest a change in suitability of streamflow conditions for all considered fish in the VOB. The methodology developed focuses on indicating changes by setting a threshold of acceptable deviation from the baseline scenario and focusing on streamflow conditions important for migration and spawning of pike, chub and Atlantic salmon.

The results for pike show a significant increase in March, April and May median flows (Figure 3). The increased spring flows might impact the spawning success of pike, since it deposits eggs in flooded areas (Kottelat & Freyhof, 2007). This can impact this species in two ways. It can increase days with floodplain inundation and floodplain connectivity which would be beneficial to the species, but abnormal high streamflow or flash floods could wash away the fish and eggs. Pike prefer low variability in flow and steady fluctuation between high and low flow (Cowx et al., 2004), which in the conditions of climate change could become more imbalanced.

For chub, the threshold of acceptable change between the IHA parameter values in the baseline and future scenarios was exceeded for the median duration of low pulses (III-VI) as well as March, April, May and June median flows (Figure 3). The increased flows in spring might impact its spawning success. Chub prefer high flows for spawning and are marginally affected by flooding (Cowx et al., 2004;

Fredrich, Ohmann, Curio & Kirschbaum, 2003; Kottelat & Freyhof, 2007). Thus, increase in the median duration of low pulses could be significantly negative for this fish.

Atlantic salmon—this long-distant migrator has the largest percentage (above 90% in both RCPs, NF and FF) of river reaches that are projected to be impacted by climate change (Table 1). All parameters except for number of low pulses (IX-X) are exceeded. The increased streamflow during spawning migration (September-October), accompanied by increased duration and number of low pulses, may send misleading spawning cues (Lindberg, 2011). Increased number and duration of low pulses could also impact the breeding success by delaying or reducing the number of spawning fish (Jonsson & Jonsson, 2009; Solomon & Sambrook, 2004). The increased flows during spawning (November-December) and increased duration of high pulses could contribute to washing out eggs and alevin mortality and extended low flows dry up eggs (Cowx & Fraser, 2000; Cowx et al., 2004).

5.3 | Other stressors beyond climate change influencing fish populations

The modelling approach is a simplified representation of the ecological interactions as it does not include all the factors determining the presence and abundance of fish (such as water temperature and habitat suitability). Modelling was carried out for natural streamflow with the intent to examine climate impacts, but this exercise cannot be considered as realistic forecasting without paying attention to other important pressures.

5.3.1 | Habitat suitability

As fish have varying habitat preferences and life cycles, changes in hydraulic variables can different impacts on fish species. Guse et al. (2015) found that habitat suitability contributed to fish declines due to climate change, but it is strongly species-specific and suitability can even increase for some of them.

According to van Vliet et al. (2013), fish will encounter significant increases in frequency and magnitude of events where their maximum temperature tolerances were exceeded due to climate change. The same study showed that fish habitats are likely to change in the near future, and in consequence affect species distribution.

Simulations from a study carried out in France suggested that by 2100, the mean annual stream flow is projected to decrease by approximately 15% and near-surface air temperature to increase on average by approximately 1.2°C. This might result in the majority of cool- and warm-water fish species expanding their geographical range, while the cold-water species will experience a reduction in their distribution (Tisseuil et al., 2012).

In the VOB, a robust increase in the annual mean daily minimum and maximum temperature by 1.9–3.8°C in the far future up to 2100 (areal-means of the ensemble mean values) was projected (Piniewski, Szcześniak, Kardel, et al., 2017). As air temperature can be considered a proxy for water temperature, the impact of temperature on the distribution of fish species in VOB might be significant.

5.3.2 | Man-made alterations to the flow regime

This study does not include alterations to flow regime caused by human activity in river basins. Channelisation, building dams and water abstraction can contribute and interact with climate change causing further alterations of in-stream ecosystems (Döll & Zhang, 2010; Gibson et al., 2005). Changes in flow regime resulting from climate change occur gradually, unlike sudden changes that originate from water withdrawal or dam construction (Gibson et al., 2005). Additionally, Bunn and Arthington (2002) stated that there is a difficulty in distinguishing the direct effects of modified flow regimes from impacts resulting from land use change or local anthropogenic pressures.

According to the International Commission on Large Dams, Poland has 69 structures classified as large dams, that is with a height of 15 m or greater from lowest foundation to crest or a dam between 5 and 15 m impounding more than three million cubic metres (ICOLD CIGB 2018). In terms of the number of large dams, Poland is in the middle of the list among European countries. The presence of dams and other man-made disturbances in Poland negatively impacts the capability of fish to migrate for spawning and disturbs the flow regime, which causes further loss of suitable habitats.

5.3.3 | Land use change

Habitat suitability for fish is expected to decrease due to the changing climate conditions, which could also have a more significant impact than land use change (Guse et al., 2015; Yan et al., 2016). Land use change has a stronger impact on nitrate concentrations (Guse et al., 2015) and land use change can enhance or mitigate the effect of climate change (Yan et al. (2016).

The major driver of land use change is agricultural expansion and urbanisation. Loss and gain of natural and semi-natural areas is considered a good indicator of land use change. Converting land from its natural state to more anthropogenic systems has potentially harmful impacts on biodiversity and ecosystems. According to OECD, Poland gained 7% of natural and semi-natural vegetated land and lost less than 3% of those lands between 1992 and 2015. During that time, 2% of (semi-) natural vegetated areas were converted to croplands. Another 2% was converted from cropland to artificial surfaces (OECD 2018). On the basis of the above-mentioned information, it could be concluded that land use change should not be a driving factor for changes in the streamflow of rivers in the VOB.

5.4 | Adaptation capability of fish

Environmental alterations caused by climate change are projected to impact fish community composition, range, distribution, survival, phenology, evolutionary adaptations, genetic selection and number of reproductive cycles (EPA (U.S. Environmental Protection Agency), 2008). The adaptive capacity of fish to changing hydrologic regimes and rising water temperatures varies among species (van Vliet et al., 2013). The rate and magnitude at which adaptation occurs is another variable. Fish physiology, biological rhythms and distribution depend on environmental variables, such as temperature, hydromorphological conditions and water quality. Climatic disruptions impact these factors and cause major changes for fish species. Changes in physiological characteristics in response to a rise in water temperature have consecutively resulted in changes in growth, reproduction and seasonal rhythms. Some species might move up river when movement is not obstructed by other factors such as dams and weirs, which would result in extending their range. These migrations can lead to modifications in the composition of communities, species richness, and in the number of dominant species (Baptist, Poulet & Séon-Massin, 2014). Additionally, freshwater fish extinctions can be linked to climate change (Poff, Olden & Strayer, 2012), and alterations to the natural streamflow regime may favour non-native fish (Propst, Gido & Stefferud, 2008).

Data on the adaptation capacity to climate change in the three fish species chosen for this study are not available. It could be expected that the suite of threats analysed above will all serve to jeopardise pike, chub and Atlantic salmon's chances of adapting to the new threats arising from climate change.

5.5 | Transferability and applicability of the modelling approach in river management

The current approach is well suited for larger scales, such as river basin-scale or country-scale. It is both an advantage and a setback that it does not require field sampling or complex modelling cascades. The transferability of this approach to other catchments is manageable.

Although this study does not judge whether the exceedance of the set threshold for IHA parameters will have a positive or negative influence on given fish species (as this is a complex issue), the conclusion is clear: climate change will affect fish migration and spawning. This issue cannot be ignored, and its consequences require further research and the generated model is a suitable tool. Collectively, this study allows for improved understanding of linkages between climate change induced alteration to streamflow and the risk of losing suitable environmental conditions for fish spawning and migration in Poland. Such insight may guide water management plans and strategies to assist fish resilience to hydrological alterations.

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REFERENCES

Abbaspour, K. C., Johnson, C. A., & van Genuchten, M. T. (2004). Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zone Journal*, *3*(4), 1340. https://doi.org/10.2136/vzj2004.1340

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, *19*, 2247–2260. https://doi.org/10.5194/hess-19-2247-2015

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association*, *34*(1), 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Arthington, A. H. (2012). *Environmental flows: Saving rivers in the third mil-lennium*. Los Angeles, CA: University of California Press. https://doi.org/10.1525/california/9780520273696.001.0001

Baptist, F., Poulet, N., & Séon-Massin, N. (2014). *Freshwater fish and climate change. Current situation and adaptation strategies*. Publisher: Onema, Editor: Onemal, SBN: 970-10-91047-38-8

Berezowski, T., Szcześniak, M., Kardel, I., Michałowski, R., Okruszko, T., Mezghani, A., & Piniewski, M. (2016). CPLFD-GDPT5: High-resolution gridded daily precipitation and temperature data set for two largest Polish river basins. *Earth System Science Data Discussions*, *8*, 127–139. https://doi.org/10.5194/essd-8-127-2016

Błachuta, J., Rosa, J., Wiśniewolski, W., Zgrabczyński, J., Bartel, R., Białokoz, W., … Zgrabczyńska, M. (2010). *Ocena potrzeb i priorytetów udrożnienia ciągłości morfologicznej rzek w kontekście osiągnięcia dobrego stanu i potencjału części wód w Polsce* (pp. 56). Warszawa, Poland: Krajowy Zarząd Gospodarki Wodnej.

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, *30*(4), 492–507. https://doi.org/10.1007/s00267-002-2737-0

Cowx, I. G., & Fraser, D. (2000). *Monitoring the Atlantic Salmon Salmo salar. Conserving Natura 2000 Rivers Monitoring Series*. Peterborough.

Cowx, I. G., Welcome, R. L., Noble, R. A. A., Nunn, A. D., Halls, A., & Harvey, J. P. (2004). *Flow and level criteria for coarse fish and conservation species. R&D technical report to the environment agency (W6-096)* (pp. 156). Bristol, UK: Environment Agency.

Dhungel, S., Tarboton, D. G., Jin, J., & Hawkins, C. P. (2016). Potential effects of climate change on ecologically relevant streamflow regimes. *River Research and Applications*, *32*(9), 1827–1840. https://doi.org/10.1002/rra.3029

Döll, P., & Zhang, J. (2010). Impact of climate change on freshwater ecosystems: A global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences*, *14*(5), 783–799. https://doi.org/10.5194/hess-14-783-2010

EPA (U.S. Environmental Protection Agency). (2008). *Climate change effects on stream and river biological indicators : A preliminary analysis*. Global Change Research Program, National Center for Environmental Assessment, Washington, DC, EPA/600/R-(March), 119.

Fredrich, F., Ohmann, S., Curio, B., & Kirschbaum, F. (2003). Spawning migrations of the chub in the River Spree, Germany. *Journal of Fish Biology*, *63*(3), 710–723. https://doi.org/10.1046/j.1095-8649.2003.00184.x

Gibson, C. A., Meyer, J. L., Poff, N. L., Hay, L. E., & Georgakakos, A. (2005). Flow regime alternations under changing climate in two river basins: Implications for freshwater ecosystems. *River Research and Applications*, *21*, 849–864. https://doi.org/10.1002/rra.855

Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, *377*(1–2), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003

Guse, B., Kail, J., Radinger, J., Schröder, M., Kiesel, J., Hering, D., … Fohrer, N. (2015). Eco-hydrologic model cascades: Simulating land use and climate change impacts on hydrology, hydraulics and habitats for fish and macroinvertebrates. *Science of the Total Environment*, *533*, 542–556. https://doi.org/10.1016/j.scitotenv.2015.05.078

Huang, S., Kumar, R., Flörke, M., Yang, T., Hundecha, Y., Kraft, P., … Krysanova, V. (2017). Evaluation of an ensemble of regional hydrological models in 12 large-scale river basins worldwide. *Climatic Change*, *141*(3), 381–397. https://doi.org/10.1007/s10584-016-1841-8

ICOLD CIGB. (2018). *General synthesis number of Dams by country members*. Retrieved from http://www.icold-cigb.net/article/GB/world_register/general_synthesis/number-of-dams-by-country-members [date accessed 23 July 2018].

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L., … Yiou, P. (2014). EURO-CORDEX: New high-resolution climate change projections for European impact research. *Regional Environmental Change*, *14*(2), 563–578. https://doi.org/10.1007/s10113-013-0499-2

Jonsson, B., & Jonsson, N. (2009). A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout Salmo trutta, with particular reference to water temperature and flow. *Journal of Fish Biology*, *75*, 2381–2447. https://doi.org/10.1111/j.1095-8649.2009.02380.x

Karr, J. R. (1981). Assessment of biotic integrity using fish communities. *Fisheries*, *6*(6), 21–27. https://doi.org/10.1577/1548-8446(1981) 006 < 0021:AOBIUF>2.0.CO;2

Kottelat, M., & Freyhof, J. (2007). *Handbook of European freshwater fishes*. Berlin, Germany: Publications Kottelat, Cornol and Freyhof.

Kruk, A., Ciepłucha, M., Zięba, G., Błońska, D., Tybulczuk, S., Tszydel, M., … Penczak, T. (2017). Spatially diverse recovery (1986–2012) of fish fauna in the Warta River, Poland: The role of recolonizers' availability after large-area degradation. *Ecological Engineering*, *102*, 612–624. https://doi.org/10.1016/J.ECOLENG.2017.01.019

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Oki, T., … Shiklomanov, I. (2009). The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal*, *53*(1), 2–10. https://doi.org/10.1623/hysj.53.1.3

Laizé, C. L. R., Acreman, M. C., Dunbar, M. J., Houghton-Carr, H., Florke, M., & Schneider, C. (2010). *Monthly hydrological indicators to assess impact of change on river ecosystems at the pan- European scale: Preliminary results*. British Hydrological Society Third International Symposium Role of Hydrology in Managing Consequences of a Changing Global Environment, Newcastle University, Newcastle.

Lindberg, D. E. (2011). *Atlantic salmon (Salmo salar) migration behavior and preferences in smolts, spawners and kelts*. Introductory Research Essay, Department of Wildlife, Fish, and Environmental Studies, Swedish University of Agricultural Sciences, (14).

Merilä, J., & Hoffmann, A. A. (2016). *Evolutionary impacts of climate change summary and keywords evolutionary impacts of climate change evolutionary impacts of climate change*. https://doi.org/10.1093/acrefore/9780199389414.013.136

Mezghani, A., Dobler, A., Haugen, J. E., Benestad, R. E., Parding, K. M., Piniewski, M., … Kundzewicz, Z. W. (2017). CHASE-PL Climate Projection dataset over Poland – bias adjustment of EURO-CORDEX simulations. *Earth System Science Data Discussions*, *95194*, 905–925. Retrieved from https://doi.org/10.4121/uuid:e940ec1a-71a0-449e-bbe3-29217f2ba31d https://doi.org/10.5194/essd-9-905-2017

Morid, R., Delavar, M., Eagderi, S., & Kumar, L. (2016). Assessment of climate change impacts on river hydrology and habitat suitability of Oxynoemacheilus bergianus. Case study: Kordan River, Iran. *Hydrobiologia*, *771*(1), 83–100. https://doi.org/10.1007/s10750-015-2617-2

Noble, R. A. A., Cowx, I. G., & Starkie, A. (2007). Development of fish-based methods for the assessment of ecological status in English and Welsh rivers. *Fisheries Management and Ecology*, *14*(6), 495–508. https://doi.org/10.1111/j.1365-2400.2007.00574.x

OECD (2018). *Monitoring Land cover change*. Retrieved from http://www.oecd.org/env/indicators-modelling-outlooks/brochure-land-cover-change-v2.pdf [accessed 23 July 2018].

Papadaki, C., Soulis, K., Muñoz-Mas, R., Martinez-Capel, F., Zogaris, S., Ntoanidis, L., & Dimitriou, E. (2015). Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the south-western Balkans. *Science of the Total Environment*, *540*, 418–428. https://doi.org/10.1016/j.scitotenv.2015.06.134

Papadimitriou, L. V., Koutroulis, A. G., Grillakis, M. G., & Tsanis, I. K. (2016). High-end climate change impact on European runoff and low flows – exploring the effects of forcing biases. *Hydrology and Earth System Sciences*, *20*, 1785–1808. https://doi.org/10.5194/hess-20-1785-2016

Paparrizos, S., & Matzarakis, A. (2016). Assessment of future climate change impacts on the hydrological regime of selected Greek areas with different climate conditions. *Hydrology Research*, *48*(5), 1327–1342; https://doi.org/10.2166/nh.2016.018

Piniewski, M., Okruszko, T., & Acreman, M. C. (2014). Environmental water quantity projections under market-driven and sustainability-driven future scenarios in the Narew basin, Poland. *Hydrological Sciences Journal*, *59*(3–4), 916–934. https://doi.org/10.1080/02626667.2014.888068

Piniewski, M., Szcześniak, M., Kardel, I., Berezowski, T., Okruszko, T., Srinivasan, R., … Kundzewicz, Z. W. (2017). Modelling water balance and streamflow at high resolution in the Vistula and Odra basins. *Hydrological Sciences Journal*, *62*(8), 1266–1289. https://doi.org/10.1080/02626667.2017.1321842

Piniewski, M., Szcześniak, M., Kundzewicz, Z. W., Mezghani, A., & Hov, Ø. (2017). Changes in low and high flows in the Vistula and the Odra basins: Model projections in the European-scale context. *Hydrological Processes*, *31*, 2210–2225. https://doi.org/10.1002/hyp.11176

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., … Stromberg, J. C. (1997). The natural flow regime: A paradigm for river conservation and restoration. *BioScience*, *47*(11), 769–784. https://doi.org/10.2307/1313099

Poff, N. L., Olden, J. D., & Strayer, D. L. (2012). Climate change and freshwater fauna extinction risk. In L. Hannah (Ed.), *Saving a million species* (pp. 309–336). Washington, DC: Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-182-5_17

Power, M., Sun, A., Parker, M., Dietrich, W., & Wootton, J. (1995). Hydraulic food-chain models: An approach to the study of food web dynamics in large rivers. *BioScience*, *45*, 159–167. https://doi.org/10.2307/1312555

Propst, D. L., Gido, K. B., & Stefferud, J. A. (2008). Natural flow regimes, nonnative fishes, and native fish persistence in arid-land river systems. *Ecological Applications : A Publication of the Ecological Society of America*, *18*(5), 1236–1252. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/18686584 https://doi.org/10.1890/07-1489.1

R Development Core Team. (2008). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. https://doi.org/isbn 3-900051-07-0

Resh, V., Brown, A., Covich, A., Gurtz, M., Li, H., Minshall, G., … Wissmar, R. (1988). The role of disturbance in stream ecology. *Journal of the North American Benthological Society*, *7*, 433–455. https://doi.org/10.2307/1467300

Richter, B. D., Baumgartner, J. V., Braun, D. P., & Powell, J. (1998). A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research & Management*, *14*(4), 329–340. https://doi.org/10.1002/(SICI)1099-1646(199807/08)14:4<329:AID-RRR505>3.0.CO;2-E

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, *10*(4), 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x

Roset, N., Grenouillet, G., Goffaux, D., Pont, D., & Kestemont, P. (2007). A review of existing fish assemblage indicators and methodologies. *Fisheries Management and Ecology*, *14*(6), 393–405. https://doi.org/10.1111/j.1365-2400.2007.00589.x

Roudier, P., Andersson, J. C. M., Donnelly, C., Feyen, L., Greuell, W., & Ludwig, F. (2016). Projections of future floods and hydrological droughts in Europe under a+2°C global warming. *Climatic Change*, *135*(2), 341–355. https://doi.org/10.1007/s10584-015-1570-4

Schneider, C., Laizé, C. L. R., Acreman, M. C., & Flörke, M. (2013). How will climate change modify river flow regimes in Europe? *Hydrology and Earth System Sciences*, *17*(1), 325–339. https://doi.org/10.5194/hess-17-325-2013

Shiklomanov, I. A., & Rodda, J. C. (2003). *World water resources at the beginning of the Twenty-First Century*. Cambridge, UK: Cambridge University Press.

Solomon, D. J., & Sambrook, H. T. (2004). Effects of hot dry summers on the loss of Atlantic salmon, *Salmo salar*, from estuaries in South West England. *Fisheries Management and Ecology*, *11*(5), 353–363. https://doi.org/10.1111/j.1365-2400.2004.00403.x

The Nature Conservancy. (2009). *Indicators of Hydrologic Alteration Version 7.1 User's Manual*.

Thompson, J., & Archfield, S. (2015). *EflowStats: Returns Hydrologic Indicator stats for a given set of data*.

Thompson, J. R., Laizé, C. L. R., Green, A. J., Acreman, M. C., & Kingston, D. G. (2014). Climate change uncertainty in environmental flows for the Mekong River. *Hydrological Sciences Journal*, *59*(3–4), 935–954. https://doi.org/10.1080/02626667.2013.842074

Tisseuil, C., Vrac, M., Grenouillet, G., Wade, A. J., Gevrey, M., Oberdorff, T., … Lek, S. (2012). Strengthening the link between climate, hydrological and species distribution modeling to assess the impacts of climate change on freshwater biodiversity. *Science of The Total Environment*, *424*(2012), 193–201. https://doi.org/10.1016/j.scitotenv.2012.02.035

van Vliet, M. T. H., Ludwig, F., & Kabat, P. (2013). Global streamflow and thermal habitats of freshwater fishes under climate change. *Climatic Change*, *121*(4), 739–754. https://doi.org/10.1007/s10584-013-0976-0

Wang, X., Yang, T., Wortmann, M., Shi, P., Hattermann, F., Lobanova, A., & Aich, V. (2016). Analysis of multi-dimensional hydrological alterations under climate change for four major river basins in different climate zones. *Climatic Change*, *141*(3), 483–498. https://doi.org/10.1007/s10584-016-1843-6

Wenger, S. J., Isaak, D. J., Luce, C. H., Neville, H. M., Fausch, K. D., Dunham, J. B., … Williams, J. E. (2011). Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(34), 14175–14180. https://doi.org/10.1073/pnas.1103097108

Wilby, R. L., & Dessai, S. (2010). Robust adaptation to climate change. *Weather*, *65*(7), 180–185. https://doi.org/10.1002/wea.543

Xenopoulos, M. A., Lodge, D. M., Alcamo, J., Marker, M., Schulze, K., & Van Vuuren, D. P. (2005). Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, *11*(10), 1557–1564. https://doi.org/10.1111/j.1365-2486.2005.01008.x

Yan, R., Huang, J., Wang, Y., Gao, J., & Qi, L. (2016). Modeling the combined impact of future climate and land use changes on streamflow of Xinjiang Basin, China. *Hydrology Research*, *47*(2), 356–372. Retrieved from http://hr.iwaponline.com/content/47/2/356

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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Table S1 The list of gauging stations used for calibration/validation.

Code	River	Gauge	SWAT reach	Area [km2]	Mean flow [m^3/s]	SD [m^3/s]
Benchmark catchments (calibration and temporal validation)						
BdT-BKI	Bystrzyca	Borki	1302	687.1	2.71	2.05
Bie-SZT	Biebrza	Sztabin	107	846	4.05	3.28
Brd-TUC	Brda	Tuchola	172	2462.2	19.39	5.39
Bro-NKA	Brok	Nowe Kaczkowo	682	730.2	2.87	5.2
Brz-KAR	Brzozówka	Karpowicze	169	649.8	2.93	3.15
BTa-KWI	Biała	Koszyce Wielkie	2397	956.9	10.5	27.1
Buk-RJA	Bukowa	Ruda Jastkowska	2031	650.8	3.75	4.31
CNi-MOR	Czarna Nida	Morawica	1961	754.6	4.29	8.01
Cze-ZAN	Czerna Wielka	Żagań	1401	899	4.06	3.53
CzM-DWA	Czarna (Maleniecka)	Dąbrowa	1612	941.3	6.03	6.79
CzW-JAN	Czarna (Włoszczowska)	Januszewice	1844	588.9	3.77	4.82
Dra-DRO	Drawa	Drawno	357	1259.8	8.78	3.26
Drw-ROD	Drwęca	Rodzone	207	1701.1	10.35	5.34
Drz-ODR	Drzewiczka	Odrzywół	1512	1004.1	4.99	4.25
Dun-NTK	Biały Dunajec	Nowy Targ-Kowaniec	2580	681.1	15.83	20.16
Elk-PRY	Ełk	Przechody	160	1452.5	9.59	6.42
Gra-GRA	Grabia	Grabno	1521	810.7	4.4	5
Huc-GOW	Huczwa	Gozdów	1919	1215	5.11	5.63
Ilz-KAZ	Iłżanka	Kazanów	1605	950	2.29	2.85
Ina-GOL	Ina	Goleniów	216	2162	13.17	8.54
Jas-JAS	Jasiółka	Jasło	2470	512.8	7	13.7

Jeg-WOZ	Jegrznia	Woźnawieś	153	851.5	4.03	3.31
Jez-PIA	Jeziorka	Piaseczno 2	1174	846.2	2.51	3.42
Kna-POR	Krzna	Porosiuki	1126	1210.2	4.73	4.21
Kos-JAG	Kostrzyn	Jagodne	1089	577.2	2.94	4.65
Kru-UKT	Krutynia	Ukta	129	634.6	3.93	1.26
Les-KAM	Lesnaya	Kamenets	946	1920	6.84	5.35
Lis-KUL	Liswarta	Kule	1768	1557	8.35	7.41
Liw-ZAL	Liwiec	Zaliwie	1064	1028.8	4.13	5.39
Lob-WYR	Łobzonka	Wyrzysk	427	635	2.21	1.71
Lua-PLE	Lubsza	Pleśno	1187	813	3.1	3.7
Lub-ZAW	Lubaczówka	Zapałów	2290	854.2	4.93	4.67
Lug-VVO	Luga	Volodimir-Volynskiy	1834	1250	5.61	3.82
Mie-MIC	Mierzawa	Michałów	2099	558.5	2.67	1.86
Mla-SZR	Mławka	Szreńsk	522	622	2.9	2.68
Mle-GOR	Mleczka	Gorliczyna	2323	529	3.65	6.63
MPa-STW	Mała Panew	Staniszcze Wielkie	2042	1107.4	6.83	8.01
Mys-DOL	Myśla	Dolsk	604	765.2	1.9	1.33
Nca-DOE	Nidzica	Dobiesławice	2245	643.2	2.68	2.26
Net-BNN	Netta	Białobrzegi	83	980	6.47	3.8
Nka-NKA	Narewka	Narewka	592	635.3	2.54	2.62
NKL-KLO	Nysa Kłodzka	Kłodzko	2142	1083.7	13.95	16.4
Nur-BRA	Nurzec	Brańsk	656	1226.6	4.26	5.64
Ola-OLA	Oława	Oława	1857	956.7	3.94	3.42
Ole-NIW	Oleśnica	Niechmirów	1561	591.6	2.78	3.24
Olz-CIE	Olza	Cieszyn	2503	453.5	9.96	17.41
Omu-BIB	Omulew	Białobrzeg Bliższy	454	1875.8	8.37	4.9

Orc-MMA	Orzyc	Maków Mazowiecki	598	1948.1	7.1	6.7
Orz-CZO	Orz	Czarnowo	587	529.2	1.49	2.18
Osa-LIS	Osa	Lisnowo	252	550.5	2.15	1.73
Osl-ZAG	Osława	Zagórz	2573	505.2	9.13	15.25
Oso-RSL	Osobłoga	Racławice Sląskie	2212	490.9	3.85	6.73
Pop-SSA	Poprad	Stary Sącz	2574	2071	28.72	37.38
Por-SUL	Pór	Sułów	1925	571.4	3.39	1.82
Pro-MIR	Prosna	Mirków	1598	1255	5.76	5.36
Psi-BOJ	Psina	Bojanów	2355	519.8	1.76	1.95
Pwa-ZAB	Pilawa	Zabrodzie	367	1375.1	6.48	2.29
Rab-STR	Raba	Stróża	2479	644.1	11.66	21.21
Rac-SAR	Raciążnica	Sarbiewo	718	583.9	1.96	3.07
Rad-ROK	Radomka	Rogożek	1428	2060.4	7.76	7.39
Rat-VOL	Rata	Volytsya	2196	680	7.43	6.4
Raw-KES	Rawka	Kęszyce	1142	1190.6	4.43	2.39
San-ZAT	San	Zatwarnica	2620	490.5	14.04	19.53
Sci-GOW	Ścinawka	Gorzuchów	2094	511.2	4.76	5.82
Skr-PAR	Skrwa	Parzeń	769	1534.2	6.25	7.8
Soa-CZE	Sołokia	Czervonograd	2106	914	6.6	6.47
Sol-ZYW	Sola	Żywiec	2514	784.8	17.94	30.92
Szk-CHY	Szkło	Charytany	2321	747.6	4.17	4.32
Szr-BIS	Szreniawa	Biskupice	2271	681.6	3.27	2.67
Tan-HAR	Tanew	Harasiuki	2088	2033.7	12.71	9.79
Wca-ZAK	Wierzyca	Zapowiednik	14	794.3	6.24	2.31
Wel-KOW	Wełna	Kowanówko	756	2597.1	7.11	7.05
Wel-KUI	Wel	Kuligi	284	764.1	4.92	1.63

Wia-KRO	Wiar	Krówniki	2460	788.9	8.02	15.34
Wil-CYG	Wilga	Cyganówka	1243	536.6	2.47	3.55
Wka-ZOW	Wisłoka	Żółków	2494	581.2	8.5	17.83
Wkr-BRU	Wkra	Brudnice	484	900.4	4.51	3.31
Wsn-NIE	Wisznia	Nienowice	2373	1191.5	7.25	12.02
Wwa-ZBY	Widawa	Zbytowa	1729	720.7	2.59	3.06
Zgl-WRU	Zgłowiączka	Włocławek-Ruda	781	1463.8	3.95	3.53
Spatial validation catchments						
Bie-BUR	Biebrza	Burzyn	353	6900.4	36.14	28.01
Bob-ZAG	Bóbr	Żagań	1390	4254.3	33.95	29.98
Bug-WLO	Bug	Włodawa	1387	14410	52.84	35.89
Bzu-SOC	Bzura	Sochaczew	1016	6281.4	18	16.25
Dra-DRA	Drawa	Drawiny	579	3287	21.26	5.56
Drw-ELG	Drwęca	Elgiszewo	500	4959.4	28.22	11.46
Dun-NSA	Dunajec	Nowy Sącz	2548	4341	66.3	83.16
Liw-LOC	Liwiec	Łochów	848	2465.5	9.48	8.88
Nar-STR	Narew	Strękowa Góra	362	7180.6	29.89	21.23
Nar-ZAM	Narew	Zambski Kościelne	688	28268.1	132.88	79.08
Nid-PIN	Nida	Pińczów	2084	3352.5	16.95	15.7
NyL-GUB	Nysa Łużycka	Gubin	1170	3973.6	27.93	20.61
Odr-CHA	Odra	Chałupki	2428	4666.2	39.8	60.61
Odr-GOZ	Odra	Gozdowice	658	109729	504.07	263.6
Odr-SCI	Odra	Ścinawa	1582	29584	176.18	148.56
Odr-SLU	Odra	Słubice	928	53382	286.81	203.26
Pil-SUL	Pilica	Sulejów	1592	3908.6	21.94	13.84
Pis-DOB	Pisa	Dobrylas	322	4061.2	22.1	8.11

Pro-BOG	Prosna	Bogusław	1242	4303.5	14.33	13.1
San-RAD	San	Radomyśl	1997	16823.8	129.82	111.51
War-DZI	Warta	Działoszyn	1742	4089	22.02	11.02
War-GOR	Warta	Gorzów Wielkopolski	675	52404.3	193.26	93.69
War-KON	Warta	Konin	1017	13351	69.21	43.08
War-POZ	Warta	Poznań	923	25910.9	94.89	53.83
War-SIE	Warta	Sieradz	1482	8139.6	41.3	26.7
War-SKW	Warta	Skwierzyna	773	32054	136.97	94.03
Wis-SAN	Wisła	Sandomierz	1996	31846.5	271.38	241.13
Wis-TCZ	Wisła	Tczew	74	194376	1046.19	636.1
Wis-TRY	Wisłok	Tryńcza	2275	3516	25.15	29.76
Wis-WAR	Wisła	Warszawa	1087	84539.5	551.93	378.17

Table S2 List of available GCM-run-RCM combinations from EURO-CORDEX composing the multi-model ensemble.

Code	GCM	RCM
01	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17
02	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4
03	ICHEC-EC-EARTH	CLMcom-CCLM4-8-17
04	ICHEC-EC-EARTH	SMHI-RCA4
05	ICHEC-EC-EARTH	KNMI-RACMO22E
06	ICHEC-EC-EARTH	DMI-HIRHAM5
07	IPSL-IPSL-CM5A-MR	SMHI-RCA4
08	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17
09	MPI-M-MPI-ESM-LR	SMHI-RCA4

Tab. S3 Summary and comparison of characteristics related to streamflow of the three chosen fish species (Northern pike, chub and Atlantic salmon).

Characteristic	Northern pike (Esox lucius)	Chub (Squalius cephalus)	Atlantic salmon (Salmo salar)
Type of life cycle	Potamodroumus	Potamodroumus	Anadromous
Migrations	Non-migratory	Migration to the nearest spawning streams is usually in a distance up to 50 km	Long distance
Time of spawning	Spring (March – May)	Spring (March - June)	Spawning migrations occur in autumn (September – October) and spawning takes place in the winter (November – December)
Egg deposition	In flooded areas and on submerged vegetation and macrophytes	On gravel substratum	On gravel substratum
Spawning stimulant	Increasing discharge	Does not require hydrological extremes as spawning clues	Literature contains contradictory information whether the increasing or decreasing streamflow is a migratory cue and an opportunity for moving upstream
Negative impact on spawning success	Lack of high flows and abnormally high discharges or flash floods, rapid fall rates of streamflow	Rapid fall in streamflow	Drought during the upstream migration, low flows cause many obstructions to be impassable. High flows can wash out eggs and alevins.
Positive impact on spawning success	Low variability in flow, high base flow and steady fluctuation between high and low flow	Low base flows	Likely migrates only during specific parts of the hydrograph: during the rising and falling limbs
References	Brylińska 1991; Kottelat & Freyhof 2007; Piniewski et al. 2014, Błachuta et al., 2010, Mann 1996; Ovidio & Philippart 2003; Cowx et al., 2004.	Brylińska 1991; Cowx et al., 2004; Kottelat & Freyhof, 2007; Mann, 1996.	Brylińska 1991; Jonsson & Jonsson 2009; Mills, 1991; Błachuta et al., 2010; Lindberg 2011; Webb, Gibbins, Moir, & Soulsby, 2001; Jensen, Hvidsten, & Johnsen, 1998; Solomon & Sambrook 2004; Cowx et al., 2004; Cowx & Fraser, 2000

A text summary of the streamflow requirements of pike, chub and Atlantic salmon is available in Text S1 along with references.

Tab. S4 Chosen IHA parameters for the three fish species.

No.	**Northern pike**	**Chub**	**Atlantic salmon**
1	March median flows	March median flows	September median flows
2	April median flows	April median flows	October median flows
3	May median flows	May median flows	November median flows
4	Maxima, 7-day median (March - May)	June median flows	December median flows
5	Number of high pulses within each water year (March - May)	Number of low pulses within each water year (March-June)	Number of low pulses within each water year (September-October)
6	Median duration of high pulses (days) (March - May)	Median duration of low pulses (days) (March-June)	Median duration of high pulses (days) (November-December)
7	Fall rates: Median of all negative differences between consecutive daily values (March - May)	Fall rates: Median of all negative differences between consecutive daily values (March-June)	Median duration of low pulses (days) (September-October)

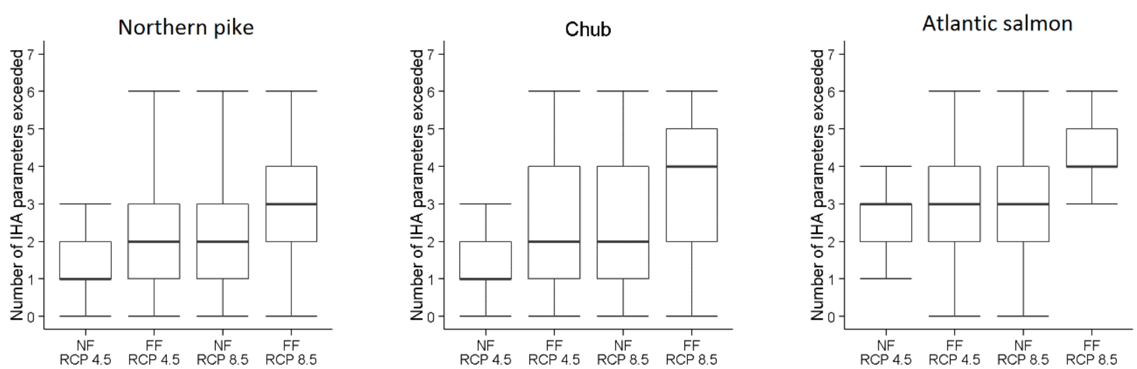

Fig. S1 Spread of the data on number of IHA parameters that exceeded the set threshold of acceptable change in nine climate models within consideration of the two RCP scenarios and time horizons.

Text S1 Summary of streamflow regime requirements of pike, chub and Atlantic salmon .

Pike (*Esox lucius*) flow requirements

Pike are non-migratory spring spawners (in Poland from March to May). In order to assess the modelled streamflow conditions during the spawning season, March-May median flows were chosen as suitable IHA parameters for analysis. Pike deposit eggs in flooded areas and on submerged vegetation and macrophytes (Brylińska 1991; Kottelat and Freyhof 2007; Piniewski *et al.* 2014, Błachuta et al., 2010, Mann 1996). Increasing discharge seems to stimulate spawning (Ovidio and Philippart 2003). Lack of high flows negatively influence the spawning success of pike. However, abnormally high discharges or flash floods can wash away adult and juvenile fish. This intolerance to extreme conditions is why the 7-day maximal median, median duration and number of high pulses in the period of March-May was selected for pike. Rapid fall rate can lead to stranding pike in its spawning grounds and increase mortality. Hence it is another parameter to be considered. Pike were reported to inhabit ground-water fed rivers with low variability in flow, high base flow and steady fluctuation between high and low flow (Cowx et al., 2004).

Chub (*Squalius cephalus*) flow requirements

Chub (*Squalius cephalus)* spawning season in Poland takes place from March until June (Brylińska 1991) and the median flow for these months are considered as IHA parameters. Migration to the nearest spawning streams is usually up to 50 km. Chub prefer low base flows as they lay eggs on gravel substratum and do not require hydrological extremes as spawning clues. On the other hand, a rapid fall in streamflow can leave those fish stranded in cut off shallow pools (Cowx et al., 2004; Kottelat and Freyhof, 2007; Mann, 1996), so additional suitable parameters for this fish are: median duration, number of low pulses in March-June, as well as fall rates.

Atlantic salmon (*Salmo salar*) flow requirements

Atlantic salmon carry out spawning migrations in autumn so the parameter of median flows for months of September up to October were taken under consideration. Spawning takes place in the winter and the median flows for November and December were included in the analysis (Brylińska 1991; Jonsson and Jonsson 2009; Mills, 1991; Błachuta et al., 2010). Atlantic salmon are sensitive to large fluctuations of flow. Increased flows cue migratory behavior and gives these fish an opportunity for moving upstream (Lindberg 2011; Webb, Gibbins, Moir, and Soulsby, 2001). Other studies suggest that they preferred falling flow phases for making an ascent (Jensen, Hvidsten, and Johnsen, 1998; Jonsson and Jonsson 2009). Atlantic salmon likely migrate only during specific parts of the hydrograph: during the rising and falling limbs. A drought during the upstream migration period will delay or reduce the number of spawning fish (Jonsson and Jonsson 2009; Solomon and Sambrook 2004). Additionally low flows cause many obstructions to be impassable for salmonids during their migration (Cowx et al., 2004). Due to this immobility during low flow scenarios the number and median duration of low pulses during the Atlantic salmon migration to spawning grounds in September and October was chosen for assessment. In contrast, high flows can wash out eggs and alevins and contribute towards mortality (Cowx and Fraser, 2000; Cowx et al., 2004), so it was important to include the median duration of high pulses in the analysis of the Altaltic Salmon spawning season, November-December (Cowx et al., 2004).

A tabular summary and comparison of characteristics related to streamflow requirements of pike, chub and Atlantic salmon is available in Table S3.

References:

Błachuta, J., Rosa J., Wiśniewolski, W., Zgrabczyński, J., Bartel, R., Białokoz, W., Borzęcka, I., Chybowski, Ł., Depowski, R., Dębowski, P., Domagała, J., Drożdzyński, K., Hausa, P., Kukuła, K., Kubacka, D., Kulesza, K., Ligęza, J., Ludwiczak, M., Pawłowski, M., Picińska-

Faltynowicz, J., Lisiński, K., Witkowski, A., Zgrabczyński, D., Zgrabczyńska, M. (2010). Ocena potrzeb i priorytetów udrożnienia ciągłości morfologicznej rzek w kontekście osiągnięcia dobrego stanu i potencjału części wód w Polsce. Krajowy Zarząd Gospodarki Wodnej, Warszawa, pp.56.

Brylińska, M. (1991). *Ryby słodkowodne Polski : praca zbiorowa*. Warszawa: Państwowe Wydawn. Nauk, pp.521.

Cowx, I. G., & Fraser, D. (2000). *Monitoring the Atlantic Salmon Salmo Salar*. *Conserving Natura 2000 Rivers Monitoring Series*. Peterborough.

Cowx, I.G., Welcome, R.L., Noble, R.A.A., Nunn, A.D., Halls, A. & Harvey, J.P. (2004) Flow and Level Criteria for Coarse Fish and Conservation Species. R&D Technical Report to the Environment Agency (W6-096). Bristol, UK: Environment Agency, 156 pp.

Jensen, A., Hvidsten, N., & Johnsen, B. (1998). *Effects of Temperature and Flow on the Upstream Migration of Adult Atlantic Salmon in Two Norwegian Rivers*. *Fish Migration and Fish Bypasses*. Oxford, England: Fishing News Books. Retrieved from http://scholarworks.umass.edu/fishpassage_book_chapters/77

Jonsson, B., & Jonsson, N. (2009). A review of the likely effects of climate change on anadromous Atlantic salmon Salmo salar and brown trout Salmo trutta, with particular reference to water temperature and flow. *Journal of Fish Biology*. https://doi.org/10.1111/j.1095-8649.2009.02380.x

Kottelat, M., & Freyhof, J. (2007). *Handbook of European freshwater fishes*. Berlin: Publications Kottelat, Cornol and Freyhof.

Lindberg, D.-E. (2011). Atlantic salmon (Salmo salar) migration behavior and preferences in smolts, spawners and kelts. *Introductory Research Essay, Department of Wildlife, Fish, and Environmental Studies, Swedish University of Agricultural Sciences*, (14).

Mann, R. H. K. (1996). Environmental requirements of European non-salmonid fish in rivers. *Hydrobiologia*, *323*(2), 3–235. Retrieved from https://link.springer.com/content/pdf/10.1007/BF00007848.pdf

Mills, D. (1991). *Ecology and Management of Atlantic Salmon*. London: Chapman and Hall.

Ovidio, M., & Philippart, J. C. (2003). Long range seasonal movements of northern pike (Esox lucius L.) in the barbel zone of the River Ourthe (River Meuse basin, Belgium), Aquatic telemetry: advances and applications. Proceedings of the Fifth Conference on Fish Telemetry held in Europe. Ustica, Italy, 9-13 June 2003.

Piniewski, M., Okruszko, T., & Acreman, M. C. (2014). Environmental water quantity projections under market-driven and sustainability-driven future scenarios in the Narew basin, Poland. *Hydrological Sciences Journal*, *59*(3–4), 916–934. https://doi.org/10.1080/02626667.2014.888068

Solomon, D. J., & Sambrook, H. T. (2004). Effects of hot dry summers on the loss of Atlantic salmon, Salmo salar, from estuaries in South West England. *Fisheries Management and Ecology*, *11*(5), 353–363. https://doi.org/10.1111/j.1365-2400.2004.00403.x

Webb, J. H., Gibbins, C. N., Moir, H., & Soulsby, C. (2001). Flow Requirements of Spawning Atlantic Salmon in an Upland Stream: Implications for Water-Resource Management. *Water and Environment Journal*, *15*(1), 1–8. https://doi.org/10.1111/j.1747-6593.2001.tb00296.x

11. Article 3

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Original Research Article

Future of birds nesting on river islands in the conditions of hydrological variability caused by climate change

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Islands

ABSTRACT

The mew gull (*Larus canus*), little tern (*Sternula albifrons*) and black-headed gull (*Chroicocephalus ridibundus*) are threatened in Poland by the loss of breeding habitats due to changes in the hydrological regime of rivers and the frequency and length of inundation. Analysis of daily flows generated from the SWAT model allowed us to obtain the values of hydrological characteristics expressed as Indicators of Hydrological Alteration (IHA) and find the relationship with collected data on nesting success on islands and sandbanks in the Middle Vistula from 2004 until 2018. For each bird species, a set of adjusted IHA was calculated for future scenarios (2021-2050 and 2071-2100). The projections were prepared on the basis of EURO-CORDEX and contain two scenarios of changes in greenhouse gas concentrations: RCP4.5 and RCP8.5. Catastrophic breeding seasons quantification was carried out to assess the number of years that will have unsuitable hydrological breeding conditions in the projected climate change. The mew gull noted the lowest nesting success (during 2004-2018) but it seems that hydrology is not the principal factor causing it. This species will experience an increase in high flows due to climate change in the far future scenarios. The black-headed gull is projected not to be affected by an increase in the percentage of catastrophic breeding seasons due to climate change. The little tern seems to be the most affected by projected climate change due to an increase in high flows and, in consequence, an increasing percentage of catastrophic breeding seasons. The results confirmed the importance of hydrologic change for avian nesting success.

1. Introduction

Streamflow is regarded as the "master variable" that impacts the abundance and distribution of riverine species (Power et al., 1995). Subtle changes in the spatio-temporal heterogeneity of streamflow can influence the distribution and abundance of certain taxa (Bunn and Arthington, 2002). This feeds into the ecohydrology concept, which focuses on the interactions between ecological and hydrological processes (Zalewski et al., 1997). It was found that river flow variability, especially high (flood) and low (drought) streamflow conditions, influence the spatio-temporal distribution and abundance of river birds (Royan et al., 2015, 2014, 2013). Flooding has the most profound impact as it affects birds' survival, habitat occupancy, abundance, foraging activities, breeding success and

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timing (Royan et al., 2014). Quantification of the relationships amid river flow variability and riparian ecology is a pressing and significant research challenge (Royan et al., 2013). This becomes especially important due to the persistent threat of flow regime modification occurring due to climate change (Schneider et al., 2013). New strategies and tools are needed to predict the climate change effects on the response of ecological systems and how mitigation or transformation activities can be initiated (Janauer, 2016).

Climate change will put large numbers of bird species at risk of extinction with estimates ranging from 2 to 72 percent depending on the region, climate scenario and potential for birds to shift to new habitats (Wormworth and Mallon, 2006). Climate change causes mismatches in the availability of food resources; the timing of flooding events or snow cover and other factors that can seriously affect the migration and reproduction of bird populations. As a consequence, the breeding mortality increases e.g. by washing nests away (Poiani, 2006) and changes the species range of occurrence (Carey, 2009; Wormworth and Mallon, 2006). A number of studies detected climate change impacts on birds phenology, migration patterns, geographic range, life history traits (survival, maturation or breeding), population size, composition and abundance (Crick, 2004; Jenouvrier, 2013; Shi et al., 2006; Trautmann, 2018; Walther et al., 2002; Wormworth and Mallon, 2006). Persistent climate change is likely to affect birds at many levels, such as causing changes in their body size, the introduction of invasive species and new diseases (Pautasso, 2012).

Several studies focus on investigating island area, exposure above water and availability for nesting birds over the breeding season and how it affects nesting colonies productivity, abundance or the number of successful breeding cycles (e.g., Atamas and Tomchenko, 2015; Dugger et al., 2002; Habel, 2018; Smith and Renken, 1985; Tracy-Smith et al., 2012). Only studies carried out by Royan et al. in 2015, 2014, 2013 approached predicting how riparian bird species distribution will be influenced by climate-induced changes in river flow and assessing their vulnerability. Lenhart et al., (2013) used the Indicators of Hydrologic Alteration (IHA), daily streamflow data and evaluated the historical channel change using aerial photographs to investigate the impact of hydrologic change on sandbar nesting availability for freshwater turtles. A common approach for assessing how future flow regimes may differ from the current ones is forcing a process-based hydrological model with climate change projections from climate models (Krysanova et al., 2016). To our knowledge, there were no studies linking this climate-hydrology chain with long term field data on nesting success of birds.

Against this background, the objective of this study is to (1) quantify relationships between streamflow variability and the nesting success of the black-headed gull *Chroicocephalus ridibundus*, mew gull *Larus canus* and little tern *Sternula albifrons* and (2) project how climate change-induced hydrological change is going to impact these three species in the future (up to the year 2100). This is achieved by linking the streamflow characteristics (Indicators of Hydrologic Alteration) obtained from the SWAT hydrological model with data from monitoring the nesting success (NS) of birds for the period 2004-2018. The second objective is accomplished by using future streamflow projections and a modelling chain to assess the impact of climate change on IHA and the occurrence of catastrophic breeding seasons (CBS). Understanding how birds react to hydrological variability and climate change-induced hydrological change is of great importance for ensuring the long-term protection of their habitats. This is of particular significance in Natura 2000 areas, whose task is to preserve specific types of natural habitats and species that are considered to be valuable and endangered throughout Europe. This study focuses on the Middle Vistula in Poland, which is almost entirely a Natura 2000 site. This research is interdisciplinary as it encompasses ornithology and hydrology. The methodology of this research stems from avian nesting success data collected over the course of 15 years and progresses to establish a link with river hydrology through bird's vulnerability periods. Then streamflow modelling is incorporated together with climate change scenarios to obtain results on climate change impact on hydrological characteristics (IHA) important for three bird species and the occurrence of years that will have unsuitable hydrological breeding conditions (CBS).

2. Material and methods

2.1. Study area

The Vistula (Wisła) river flows through Central and Eastern Europe, has its source in the Carpathian Mountains and drains to the southern Baltic Sea. The whole basin has an area of 193,831 km^2, of which 87% is located in Poland. The remaining parts of the basin lie in Belarus, Ukraine and Slovakia. The Vistula River length is 1047 km. The Vistula basin is located in the temperate climatic zone with cold winters and warm summers. An east to west temperature gradient is shaped by continental influence in the east and a maritime influence in the west.

This study was carried out for the middle course of the Vistula River (Middle Vistula), which is 256 km long and begins from the mouth of the San river and ends at the mouth of the Narew river (Fig. 1). The habitats under investigation are river islands on a 239 km stretch of the Vistula River (between the 383 and 622 kilometers of the river). This section of the Vistula River is a Natura 2000 Special Protection Area (PLB140004 and PLB140006). The study sites are sand islands, sandbars, sandbars on wooded islands, river spits and sand islands accreted to the shore. The characteristics of the river and its islands change with a gradient of increasing streamflow. All the studied islands are located upstream of the Włocławek dam so the hydrology is not under its direct impact (first study site no. 22 is located 115 km upstream from the dam and approximately 60 km upstream from the impoundment).

One characteristic of rivers in this region of Europe is a moderate seasonal variability of streamflow, with the highest flows usually occurring in March and April, and the lowest flows in September and October. In the Vistula catchment, there are four flood generation mechanisms: intense and/or long-lasting rain, snowmelt, ice-related phenomena and storm surge (Cyberski et al., 2010). The

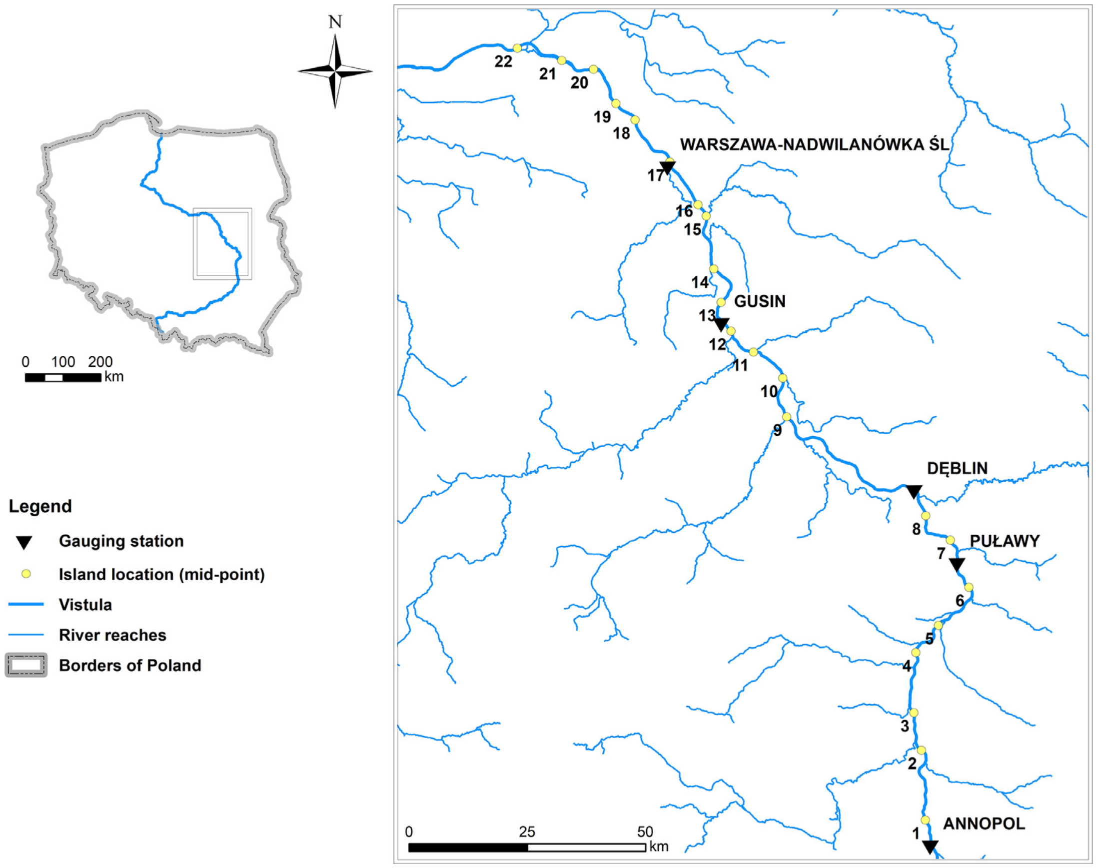

Fig. 1. Island locations and gauging stations along the Middle Vistula.

mean annual runoff of 171 mm for the Vistula is among the lowest in Europe (Shiklomanov and Rodda, 2003).

2.2. Ornithological data

2.2.1. Ornithological data collection

Ornithological data was collected from 2004 until 2018 in 22 locations along the middle course of the Vistula River (Fig. 1, Table A.1). Each location is an approximately 3 km stretch of the river that contains islands and sand bars which are suitable nesting grounds for the black-headed gull *Chroicocephalus ridibundus*, mew gull *Larus canus* and little tern *Sternula albifrons*. Those three species were chosen as representatives of ground-nesting birds that breed on river islands because they use different habitat types and heights for nesting. Each studied section of the Vistula River was monitored every few days from the beginning of April each year until the end of the breeding season. When the first egg was laid, a nest was marked with the numbered stick and checked every 3-5 days until fledging or breeding failure. This allowed investigators to track the history of each nest, including breeding phenology, nesting success and causes of the failure.

2.2.2. Species nesting requirements and nesting success

The studied bird species vary in preferences regarding nesting substrate and vegetation, breeding period and timing, egg incubation and chicks fledging time, nesting site fidelity, and ability to repeat breeding in case of unfavorable conditions. These preferences were compiled in Table 1.

This study uses the term nesting success (NS) as the average number of fledged chicks raised by bird pairs nesting on a given 3 km section of the river in a given breeding season. Nesting success was observed yearly for each species in each of the 22 locations (Fig. 1). This NS measure is most accurate and valuable because (a) it involves tracking the fate of the brood throughout the breeding season: from hatching to feathering (gaining the ability to fly) and (b) allows to obtain precise information from each nest under observation during the breeding season about the number of hatchlings that have acquired the ability to fly.

2.2.3. Vulnerability periods

Analyzing the periods when the birds are arriving at nesting grounds, laying eggs, incubating and rearing chicks (from hatching to fledging) allowed us to establish vulnerability periods that are critical for a successful breeding season. Laying eggs consists of the period between laying the first egg in a brood and completing the egg laying process. Incubating takes place between laying the last egg and the hatching of the first chick in the brood. Rearing chicks is the time between the hatching of all chicks in a brood until all of them reach a capability to fly. Vulnerabil-

Table 1
Comparison of species requirements regarding nesting and breeding in the Middle Vistula in Poland.

Species	Legal protection*	Breeding site fidelity	Characteristics of preferred nesting locations in Middle Vistula	Preferred vegetation in nesting locations in Middle Vistula	Repeated breeding on islands of the Middle Vistula	Timing of egg-laying on the islands of Middle Vistula	Incubation	Time needed to achieve chick stage**	Literature
Mew gull *Larus canus*	Strictly protected, and requires active conservation	High natal site fidelity. Usually return to the immediate vicinity of last year's nesting sites.	Prefers nesting sites along island shores, where territories most often border onto the water. Occupies islands of moderate or low height.	Prefers sandy sites with clumps of herbaceous vegetation or, less often, places overgrown with high and dense grass and/or bare sandy beaches.	One brood per year. If a clutch is lost, it can be replaced a few times which is a common occurrence.	Begins in the last 10 days of April and continues until the end of May, with a peak between 1 and 10 May.	24–27 days	30–40 days	(Bukacińska, 1999; Bukaciński, 1998; Bukaciński and Bukacińska, 2015a, 2003, 1994; Różycki, 2014)
Black-headed gull *Chroicocephalus ridibundus*	Strictly protected	Most likely not strongly tied to a place. Attachment to the nesting place requires more careful studies.	Chooses high, flat islands in the river's current, as well as islands with sand without vegetation on the low sandbanks. Often picks dry areas and located several hundred meters from the water	Prefers areas with dense grass, as well as in places with herbaceous vegetation set in clumps, less often occupies sand without vegetation	One brood per year. In years with a large rise of the Vistula River waters in April or May (e.g. 2010 and 2014) a substantial number of birds repeats breeding. The peak of repeated egg laying depend on the term of water rising, and single nests with eggs can still be found in the second half of July.	Egg laying takes place from the second decade of April to the end of May, with the peak between the third decade of April and the second decade of May.	21–27 days	35–42 days	(Bukacińska and Bukaciński, 2004, 1993; Bukaciński and Bukacińska, 2015b, 1995, 1994, 1993a, 1993b)
Little tern *Sternula albifrons*	Strictly protected, including a ban on taking pictures, filming and observation that could flush or disturb the birds, and requires active conservation	Lack of natal and nest site fidelity. Highly mobile even within one breeding season.	Most often establishes colonies fairly close to the water, it occupies almost exclusively very low sandy islands and sandbanks.	Occupies areas without vegetation or with very small plant cover (not exceeding 10%), sometimes with rubble brought by the water.	One brood per year. If the clutch is lost, it can be replaced. Unlike the majority of gulls and terns, the replacement clutch can be laid even hundreds of kilometers away from the location of the first clutch.	Breeding season lasts from mid-May until the end of June, with the peak of egg-laying between the end of May to mid-June.	18–23 days	19–23 days	(Bukaciński and Bukacińska, 2015c, 1994)

* Under the Ordinance of the Minister of the environment of 16 December 2016 on the conservation of animal species (Journal of Laws of the Republic of Poland 2016 item 2183).
** Days from hatching

Table 2
Vulnerability periods of birds (with break down of breeding stages) in the Middle Vistula.

Species	Mew gull (*Larus canus*)	Black-headed gull (*Chroicocephalus ridibundus*)	Little tern (*Sternula albifrons*)
Laying eggs	21.04 – 31.05	11.04 - 20.05	11.05 – 20.06
Incubation	25.04 – 20.06	20.04 - 31.05	15.05 – 30.06
Rearing chicks	21.05 – 30.06	10.05 - 10.06	11.06 – 10.07
Vulnerability period	**21.04 - 30.06**	**11.04 - 10.06**	**11.05- 10.07**

ity periods are species-specific and consist of the time span required to successfully produce a new generation (Table 2, Fig. 3). Vulnerability periods in this study were established on the basis of Table 1 and the authors' observations for the Middle Vistula conditions.

2.3. Hydrologic modelling in SWAT

In this study, we used an existing, extensively calibrated and validated Soil and Water Assessment Tool (SWAT) model for the Vistula basin described in Piniewski et al., (2017b) and built upon it. SWAT is a process-based, semi-distributed, continuous-time model which simulates hydrology on a catchment scale with a daily time step (Arnold et al., 1998). The daily climate data from 1951 to 2018 that was used as input was obtained from a gridded daily precipitation and temperature data set with a resolution of 5 km (CHASE- PL Forcing Data CPLFD- GDPT5) (Berezowski et al., 2016). The analysis of the low and high flow simulations from the SWAT model used in this study indicated that the model performance for high flows was noticeably better than for low flows (R^2 equal to 0.9 vs 0.61 for the calibration period) (Piniewski et al., 2017c). This proves that the model is suitable for spatial analysis of climate change impacts on hydrological indicators and extremes in the Vistula basin.

The subbasins and corresponding reaches from the SWAT model were paired with 22 bird nesting locations in the Middle Vistula. In four cases, two nesting locations were situated in the same subbasin, which left us with 18 subbasins. We focused on analyzing the amount of streamflow in m^3/s simulated at the outlet of each subbasin. The model setup used in this study assumes constant land use and did not include water management and man-made disturbances, which enabled the assessment of the pure effect of climate change on streamflow, which is typical for most hydrological impact studies.

2.4. Model performance

Five hydrological gauging stations in the Middle Vistula were paired with subbasins from the SWAT model. The stations are called Warszawa-Nadwilanówka, Gusin, Dęblin, Puławy and Annopol. Goodness-of-fit (GoF) functions for comparison of simulated and observed hydrological time series were obtained from the hydroGOF (version 0.4-0) R package. Data from the time period of January 1st, 2004 until December 31st, 2018 were compared. Model performance was assessed on the basis of Nash-Sutcliffe efficiency (NSE), Kling-Gupta Efficiency (KGE), percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measured data (RSR).

2.5. Climate change scenarios

The climate projections used in this study consist of an ensemble of nine bias-corrected EURO-CORDEX (Jacob et al., 2014) combinations of Global and Regional Climate Models under two Representative Concentration Pathways (RCPs) of greenhouse gas concentration trajectories: 4.5 and 8.5 (Table A.2). The original EURO-CORDEX simulations were bias-corrected using the quantile mapping method, the CPLFD- GDPT5 dataset (Berezowski et al., 2016) as reference data, and transformed onto a 5 by 5-km grid. Climate parameters were simulated for the reference period (1971- 2000) and for two future time horizons: near future (NF, 2021- 2050) and far future (FF, 2071-2100). The underlying data are available free of charge for research purposes as the CHASE-PL Climate Projections: 5-km Gridded Daily Precipitation and Temperature Dataset (CPLCP-GDPT5) (Mezghani et al., 2017).

The projected mean annual temperature in Poland is expected to rise by approximately 1.1°C in the NF and 2°C in the FF in the RCP 4.5 scenario. A strong seasonal variation is visible with the highest changes in winter (2.5°C in FF) and the lowest in summer (1.7°C in FF). For the RCP 8.5 scenario, the temperature increase rate seems to accelerate in the second half of the century, reaching a mean of 3.6°C in FF, whereas in NF, it is similar to RCP 4.5 (1.3°C versus 1.1°C).

The projections for annual precipitation in Poland showed an increase in the future for all seasons (with the highest increase in winter and spring). In the RCP 4.5 emission scenario, the annual mean precipitation is projected to rise by approximately 6% in NF and 10% in FF, while for RCP 8.5, the projections show a 16% increase in FF. Both for precipitation and temperature, changes are more significant in the far future time horizon and RCP 8.5 (Piniewski et al., 2017a).

Future average daily streamflow data (m^3/s) was derived by forcing the SWAT model with the CPLCP- GDPT5 data set. The first 3 years of each 30- year simulation period were removed from the analysis as they constituted the warm-up period of the SWAT model. Analysis nodes were the outlets of 2,633 SWAT reaches distinguished in the model set- up, of which 18 were the outlets used in this study. For each node, 45 time series with daily flow values were available (nine climate models, one reference period and two future periods under two RCPs).

2.6. Adjusted IHA parameters

In order to define the flow characteristics, a set of Indicators of Hydrological Alteration (IHA) adjusted to the needs of this study was used. The IHA method contains

33 parameters in five groups of hydrologic features: magnitude, timing, frequency, duration and rate of change (The Nature Conservancy, 2009). IHA recognize that all features of the streamflow regime are ecologically important and capture almost the entire range of all available hydrological indicators (Laizé et al., 2010). IHA were obtained on the basis of modelled streamflow data. Adjustments of IHA were carried out in the R language (R Development Core Team, 2008). A total of 13 adjusted IHA were calculated per bird. The developed code is available on the GitHub platform: https://github.com/jo-dzian/Birds_hydrology

Before calculating IHA parameters from groups 1 and 2, streamflow for each island location was standardized by dividing by mean flow calculated over the entire 2004-2018 period in order to make the locations with different flow sizes comparable. IHA from groups 1 and 2 are originally expressed in m^3/s, but after the standardization they become dimensionless (Tavassoli et al., 2014).

2.6.1. IHA Parameter Group 1

This group traditionally describes the magnitude of monthly water conditions. It was decided that the most crucial for this study are the mean streamflow values during periods of laying eggs, incubating and rearing chicks (different for each of the 3 species) specified in Table 2.

2.6.2. IHA Parameter Group 2

Group 2 describes the magnitude and duration of annual extreme water conditions. Vulnerability period minima and maxima were calculated for 1-day mean, 3-day mean and 7-day mean for each bird. In order to do it correctly 1,3,7-day rolling means were calculated for the calendar year and afterwards values were extracted for the vulnerability period and used to find the minima and maxima among the 1,3,7-day means. Zero flow days do not occur in the Vistula River and annual maxima and minima for 30-day and 90-day means would exceed or consume most of the vulnerability period, so those indicators were not included in the analysis. Base flow was also dismissed due to the inadequate representability of the vulnerability period.

2.6.3. IHA Parameter Group 3

The Julian date of each annual 1-day maximum and 1-day minimum was found in order to assess the timing (dates within a year) of annual extreme water conditions. The next step was checking if the extreme event happened within the vulnerability period of a given bird. The Julian day of the start and end of the vulnerability period was extracted and then compared to the Julian day of the extreme event in the given year. If the event occurred within the vulnerability period, it was given a score of 1 and, if it did not, a score of 0. It was decided that, as long as the extreme event occurs within the vulnerability period (without the distinction at which exact moment), it has an impact on the nesting success. Each year was analyzed and given a score, which was then summarized for the entire period. For leap years, the Julian dates of the vulnerability period were appropriately adjusted.

2.6.4. IHA Parameter Group 4

Indices from group 4 analyse the frequency and duration of high and low pulses. The 0.05, 0.25, 0.75 and 0.95 percentile was obtained from the streamflow data. A sum of days above the 75-th and 95-th percentile during the vulnerability period each year for each subbasin was obtained to analyse the duration of high pulses. A sum of days below the 0.25 and 0.05 percentile during the vulnerability period each year for each subbasin was obtained to analyse the duration of low pulses.

2.6.5. IHA Parameter Group 5

This group analyses the rate and frequency of water condition changes. Indicators included in this group are: rise rates, fall rates and number of hydrologic reversals. They characterize the number and mean or median rate of positive (increase) and negative (decrease) flow changes on two consecutive days. The authors did not find a suitable method to adjust the indices in this group to represent the vulnerability period in comparison to the whole calendar year.

2.7. Assessment of adjusted IHA change over time and climate projections

2.7.1. Tier 1

The correlation between all the adjusted IHA parameters (from modelled streamflow data) and observed nesting success during the years 2004-2018 (baseline period) was calculated in order to choose a set of the most relevant indicators for each bird species that represent the effect of streamflow variability on the nesting success. Pearson's R coefficient of correlation and level of statistical significance expressed as a p-value were assessed.

2.7.2. Tier 2

The IHA method was implemented to assess hydrological alteration of streamflow regime parameters between two defined periods: reference and far or near future at a given location (Richter et al., 1998, 1996). The chosen set of yearly means of most relevant adjusted IHA were calculated for nine climate models in the reference period and two future periods under two RCPs in each of the 18 subbasins for three bird species with different vulnerability periods. Afterwards, means were calculated from the 18 subbasins and nine models and presented for each bird species within the two time horizons and RCPs. For group 4, the number of days above the 75-th and 95-th percentile in NF and FF is compared to the 0.75 and 0.95 percentile calculated for the reference scenario.

The percentage change between the reference period (1971-2000) and for two future time horizons (2021–2050 and 2071–2100) with climate change projections allowed us to study the projected impact of climate change on adjusted IHA relevant for the nesting success of black-headed gull *Chroicocephalus ridibundus*, mew gull *Larus canus* and little tern *Sternula albifrons*. The resulting box plots were presented against a +/- 30% threshold of acceptable change. Exceeding the threshold indicates a significant difference from the reference period. This threshold value was extracted from studies by Laizé et al. (2010);

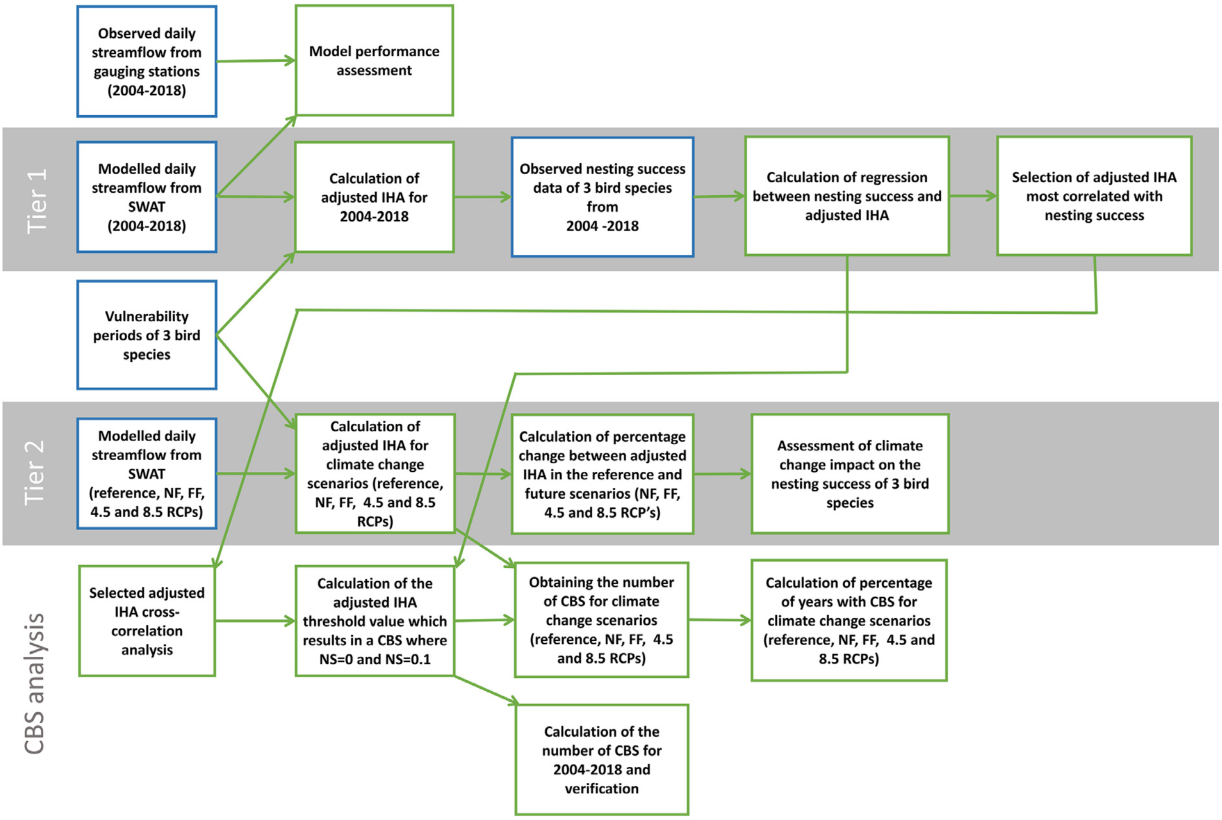

Fig. 2. Workflow of data analysis (blue boxes indicate input data, green obtained results)

Schneider et al. (2013); Thompson et al. (2014);and Wang et al. (2016). Exceeding the threshold of ±30%, indicated the vulnerability of different birds to changes in most crucial streamflow parameters. The calculation workflow for both tiers is presented in Fig. 2.

2.8. *Occurrence of a catastrophic breeding season*

This analysis was carried out for the adjusted IHA with the highest and second highest correlation to NS (according to the baseline period analysis in Tier 1). By preparing a correlation matrix, it was tested if the pairs of adjusted IHA are cross-correlated. The linear regression equations of the relationship between adjusted IHA and NS from the baseline period of 2004-2018 from tier 1 were transformed to obtain the adjusted IHA threshold value. This results in a catastrophic breeding season (CBS), which was defined as the year in which NS value was very low. Two thresholds were tested: NS=0 and NS=0.1. A verification was carried out for the baseline with the use of the adjusted IHA threshold values to assess if the CBS are going to be flagged accurately. It was identified in how many years of the reference and future scenarios (including two RCP scenarios and nine EURO-CORDEX models) this threshold will be exceeded and therefore will be identified as CBS. The results are presented as percentage of years with CBS. The calculation workflow for CBS analysis is presented in Fig. 2.

3. Results

3.1. *Model performance*

A hydrograph for Warszawa Nadwilanówka and GoF functions for all the gauging station and subbasin pairs are available in supplementary material Fig A.1 and Table A.3. Model performance expressed as the NSE value was on average 0.62 while PBIAS ranged from -5.9 to 3.4; the KGE and RSR were on average 0.8 and 0.61, respectively. According to Kouchi et al. (2017) and Moriasi et al. (2015, 2007), who established guidelines for watershed model evaluation, the NSE performance rating is satisfactory. The PBIAS, KGE and RSR ratings for streamflow are good which, overall, was assessed as appropriate for further analysis. As can be observed in the hydrograph for the three birds' vulnerability periods in Fig A.2, the modelled streamflow tends to be underestimated (lower) than the observed streamflow.

3.2. *Annual variability during the period of 2004-2018*

3.2.1. *Nesting success*

Modelled streamflow data for the baseline period was used to analyze the relationship between streamflow characteristics and observed nesting success in the baseline period of 2004-2018. A graphical comparison of the yearly hydrographs during the vulnerability period of each of the three bird species and its nesting success is available in

Fig. 3 and Fig. A.3. All three bird species were negatively affected by the flood in the year 2010, which caused almost a complete loss of brood. A high streamflow peak also occurred during the vulnerability period of all three birds in 2013 and 2014, causing a very low nesting success (median below 0.25). In 2013, an extremely high flow at the beginning of the breeding season reduced the NS of black-headed gull, while the NS for the two other species was probably reduced by another high flow event during the end (mew gull) and middle (little tern) of the breeding season. In 2005 and 2006, the black-headed gull noted a median nesting success of 0.75 and 0.67 while mew gull and little tern suffered an almost complete loss of brood (nesting success median below 0.25). This might be caused by a high peak at the end (mew gull) and in the middle (little tern) of the vulnerability periods of those birds, while this peak did not occur during the vulnerability period of the black-headed gull. Within the last three years (2016-2018), little tern most likely experienced very favorable conditions, which resulted in higher median nesting success in comparison with the remaining two birds species. Hydrographs for vulnerability periods in years 2004, 2007, 2008, 2011, 2012, 2016, 2017, 2018 do not show any extreme high flow events, which most likely, positively affected the nesting success of the three bird species during those years. Over the 15-year-long period, mew gull had the lowest nesting success (average 0.19) while black-headed gull had the highest (average 0.61) and the little tern was in the middle (average 0.41).

3.2.2. Adjusted IHA

The results of the mean number of days during the vulnerability period when flows are lower than the yearly 0.05 percentile (gr.4_P0.05) showed zeros for all three bird species. The Julian date of each annual 1-day minimum (gr.3_vp_min) never occurred during the vulnerability period of the bird species during the 15-year period. Both of those adjusted IHA were dismissed from further analysis as it was impossible to assess their impact and correlation with nesting success (Table 3). Yearly mean values of the adjusted IHA parameters during the baseline period 2004-2018 are presented for all three birds in Fig. A.4 and a commentary in Appendix B. The differences in the results for the three bird species visible in Fig. A.4 stem directly from the varied vulnerability periods and hydrological conditions.

3.3. Selection of adjusted IHA with the highest correlation with nesting success

The correlation graphs between the adjusted IHA (from modelled streamflow data) and observed nesting success during the years 2004-2018 (baseline period) are available in Fig. A.5 (IHA chosen for further analysis) and Fig. A.6 (IHA not chosen for further analysis). Investigating the correlation allowed for a set of the most relevant indicators for each bird species to be chosen. Most variables have a negative association because as the IHA value increases, the NS value decreases. The positive association occurs only between gr.4_P0.25 and the NS of the black-headed gull and the little tern (Fig. A.6).

Table 3
Adjusted IHA parameters chosen for further analysis.

Adjusted IHA code	Adjusted IHA explanation	Mew gull	Black-headed gull	Little tern
gr.1_mean_LE	mean streamflow during laying eggs	✓		✓
gr.1_mean_Incub	mean streamflow during incubation	✓	✓	✓
gr.1_mean_RC	mean streamflow during rearing chicks	✓	✓	✓
gr.2_day01_min	one day rolling mean of streamflow minimum during vulnerability period			
gr.2_day01_max	one day rolling mean of streamflow maximum during vulnerability period			
gr.2_day03_min	three day rolling mean of streamflow minimum during vulnerability period			
gr.2_day03_max	three day rolling mean of streamflow maximum during vulnerability period	✓	✓	✓
gr.2_day07_min	seven day rolling mean of streamflow minimum			
gr.2_day07_max	seven day rolling mean of streamflow maximum			
gr.3_vp_min	Yearly minimum flow falling within the vulnerability period (1= Yes, 0=No)			
gr.3_vp_max	Yearly maximum flow falling within the vulnerability period (1= Yes, 0=No)		✓	
gr.4_P0.95	Mean number of days during the vulnerability period when flows exceed the 0.95 percentile		✓	
gr.4_P0.75	Mean number of days during the vulnerability period when flows exceed the 0.75 percentile	✓		✓
gr.4_P0.25	Mean number of days during the vulnerability period when flows were lower than the yearly 0.25 percentile			
gr.4_P0.05	Mean number of days during the vulnerability period when flows where lower than the yearly 0.05 percentile			

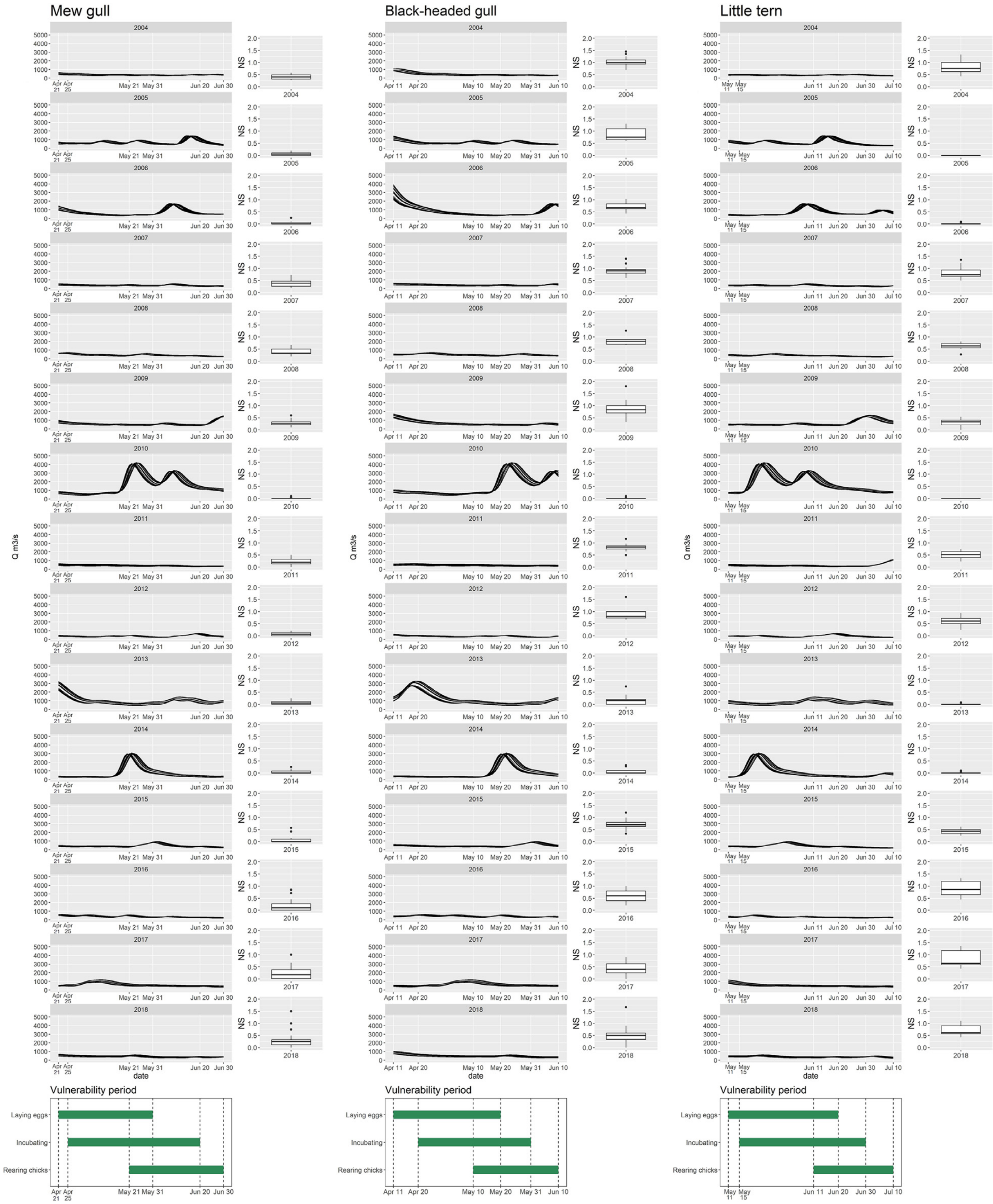

Fig 3. Comparison of the hydrographs (line plot) from 18 subbasins during the vulnerability period (Gantt chart) of each bird and illustration how it impacts the nesting success (box plot) of mew gull, black-headed gull and little tern.

For the mew gull, the highest correlation of -0.43 occurs between gr.2_day01_max as well as gr.2_day03_max and nesting success. For the black-headed gull, the highest correlation of -0.71 occurs between gr.1_mean_Incub and nesting success. The highest correlation of -0.77 occurs for the little tern between the nesting success and gr.4_P0.75. During the analysis, it was decided to keep the adjusted IHA with a correlation higher than -0.37 for the mew gull and-0.62 for the black-headed gull and the little tern (Fig A.5, Fig A.6).

All three bird species showed a high correlation between gr.2_day01_max, gr.2_day03_max and gr.2_day07_max and nesting success. Those three indicators are very similar so it was decided to pick just one that would represent well the whole group 2. As a study carried out by Royan et al. (2013) found that birds displayed positive and quadratic relationships with three day maximums, it was decided to keep this indicator. Five indicators remained for further assessment for each of the birds (Table 3).

3.4. Impact of projected climate change on nesting success

The developed procedure focuses on indicating changes by setting a +/- 30% threshold of tolerable deviation from the baseline scenario. Box-plots presented in Fig. 4 show the percentage changes in adjusted IHA values for 18 subbasins in NF 4.5, FF 4.5, NF 8.5, FF 8.5 in 9 models in comparison to the reference period. Median percentage change values of adjusted IHA for those scenarios are available in Table A.4. Absolute values of adjusted IHA in the reference and future periods are available in Fig. A.7. According to Fig. 4 for analysed bird species, the percentage change between the reference and future scenarios for group 1 adjusted IHA (gr.1_mean_LE, gr.1_mean_Incub, gr.1_mean_RC) increases with time horizon and RCP. An exception occurred only for scenario 4.5, gr1.mean_LE for mew gull and scenario 4.5, gr.1_Incub for black-headed gull, but does not exceed the 30% threshold. For the mew gull and black-headed gull, median percentage change values of gr.2_day03_max decrease in NF scenarios in relation to the reference period and increase in FF, while for the little tern, there is a constant increase with time horizon and RCP. Median percentage change of gr.2_day03_max does not exceed the 30% threshold for the three bird species.

Gr.3_vp_max was only analysed for the black-headed gull; its median percentage change decreases in NF scenarios (down to -35.6% in NF 8.5 exceeding the threshold) and then increases to 7.4% in FF (both RCP 4.5 and 8.5) in relation to the reference period. Median percentage change of gr.4_P0.95 in relation to reference period for the black-headed gull increases only in FF 8.5. For the mew gull and little tern, gr.4_P0.75 median percentage change increases over time and RCP scenario in comparison to the reference period. For the little tern, median percentage change exceeds 30% in both FF scenarios (32.9% in 4.5 and 37.5% in 8.5). As indicated by the span of the box plot outliers, the uncertainty of the results is particularly high in the FF 8.5 scenarios for the mew gull and little tern.

The above analysis is based on all 18 subbasins that are paired with 22 island locations on a 239 km stretch of the Vistula River. To distinguish the spatial pattern along the river, Fig. A.8 shows a comparison of the results for percentage changes in highest correlated with NS adjusted IHA values for the three birds in three subbasins: most down- and upstream and a middle one. For the mew gull and black-headed gull, there is no clear difference between subbasins. For the little tern, the percentage changes in the adjusted IHA values are increasing the more downstream the subbasin is, and exceed the +/-30% threshold for the most downstream subbasin (in FF 4.5, NF 8.5 and FF 8.5).

3.5. Occurrence of catastrophic breeding seasons

The selected pairs of adjusted IHA with the highest and second highest correlation to NS (according to the baseline period analysis in Tier 1) for the mew gull and little tern have the lowest cross-correlation among adjusted IHA but it is not the case for the black-headed gull (Fig. A.9). According to Table A.3, the strength of the relationship (R value) between the adjusted IHA with the highest correlation to NS is weak for the mew gull (gr.2_day03_max) and strong for the black-headed gull (gr.1_mean_Incub) and the little tern (gr.4_P0.75). For adjusted IHA with the second highest correlation to NS, the relationship remains weak for the mew gull (gr.4_P0.75) and becomes moderate for the black-headed gull (gr.2_day03_max) and little tern (gr.2_day03_max). Table A.3 contains the regression equations and established adjusted IHA threshold values which result in a CBS when NS equals 0 or 0.1.

The adjusted IHA threshold values which result in a CBS when NS equals 0 or 0.1 were tested against the baseline period and the results are presented in Table 4. The year 2010 was identified as CBS for all three birds and NS values, which was correct as during that year extreme flooding occurred. Years picked up as CBS remain the same for the black-headed gull and the little tern but the number of years increases for mew gull with increasing NS value.

According to the results during the reference period, the highest % of years with CBS occurred for the little tern (median 18.5%), this occurred approximately half as often for the mew gull (median 7.4%) and the black-headed gull was the least affected (median 3.7%). The percentage of years with CBS for the adjusted IHA with the highest correlation to NS (according to the baseline period analysis in Tier 1) calculated for NS=0.1 increases with RCP and time scenarios for the little tern reaching 29.6% in FF 4.5 and FF 8.5. For the black-headed gull, the percentage of the years with CBS remain the same in the reference period, NF 4.5, FF 4.5 and NF 8.5 (median 3.7%) and increase in FF 8.5 to 11.1%. The projections for the mew gull show that in the NF the percentage of years with CBS will decrease to 3.7% and increase in FF scenarios to 7.4% in FF 4.5 and 14.8% in FF 8.5 (Fig. 5, Table A.6).

In order to test if the set threshold values of adjusted IHA which result in a CBS for NS=0.1 were sensitive enough, additional thresholds were obtained for NS=0 and the results are presented in Fig. A.10. For the threshold calculated for NS=0, the highest percentage of years with CBS in the future scenarios can be noted for the little tern (14.8% to 22.2%). For the mew gull and black-headed gull they amount to 3.7% in the reference period and 0%

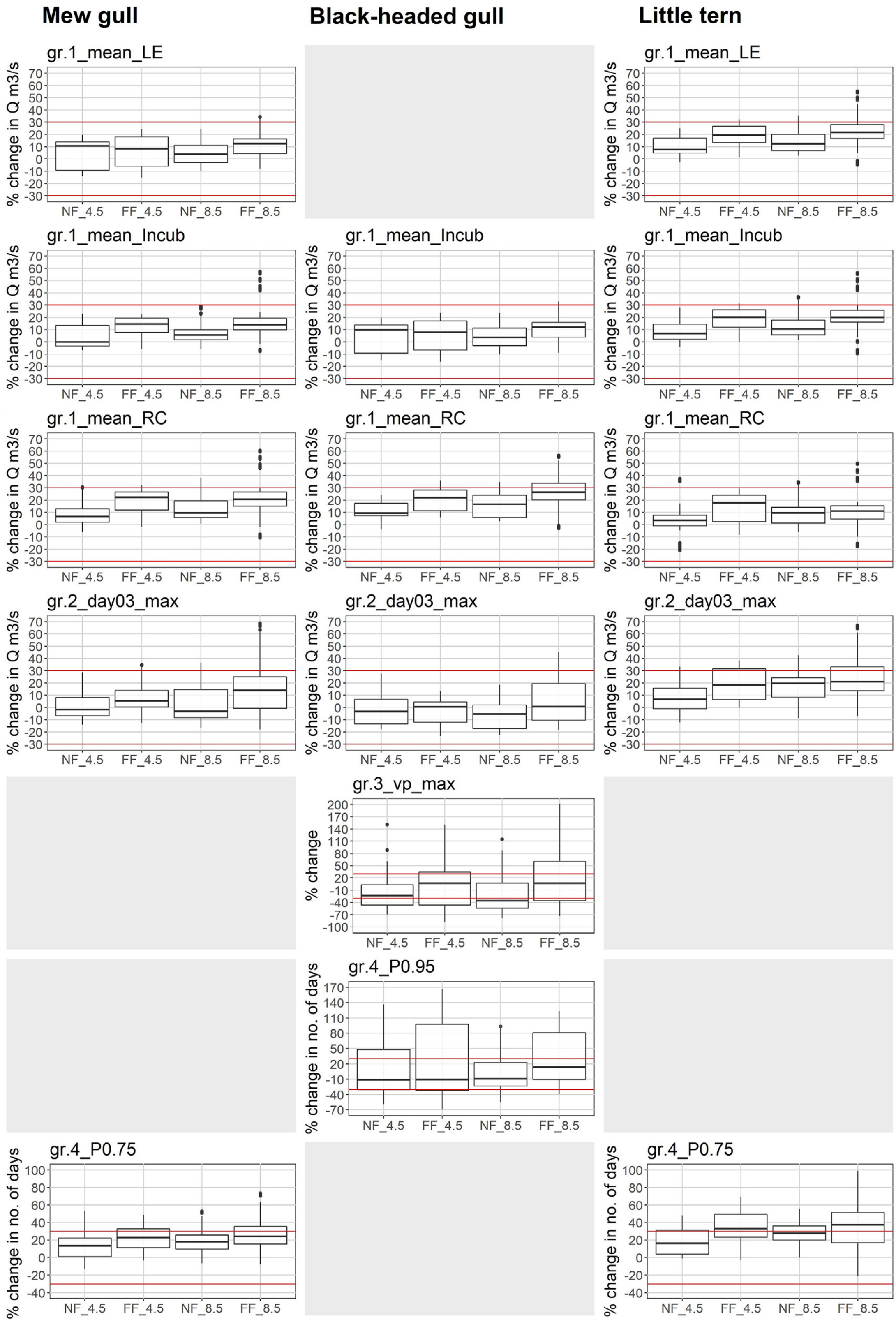

Fig. 4. Percentage changes in adjusted IHA values for 18 subbasins in near future (NF), far future (FF) and climate change projections (RCP 4.5 and 8.5) in 9 models in comparison to reference period (1971- 2000). Red line indicates the +/-30% threshold and a thick line in the box-plot the median value.

Table 4
Years during the baseline period detected as CBS according to NS value.

Bird species	Adjusted IHA	Years with CBS (NS=0) during baseline	Years with CBS (NS=0.1) during baseline
Mew gull	gr.2_day03_max	2010	2010, 2013, 2014
Black-headed gull	gr.1_mean_Incub	2010	2010
Little tern	gr.4_P0.75	2010, 2013	2010, 2013

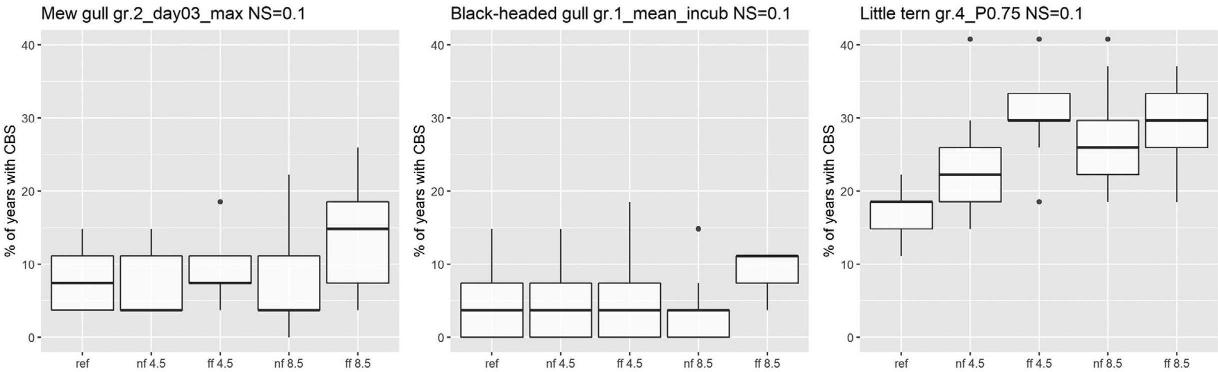

Fig. 5. Projected percentage of years with a catastrophic breeding season (CBS) for the mew gull, black-headed gull and little tern: adjusted IHA with the highest correlation to NS obtained for NS=0.1.

in the future scenarios (except NF 4.5 for the black-headed gull where it is 3.7%) (Fig. A.10, Table A.6). An additional analysis was carried out for the second highest correlated adjusted IHA to NS (according to the baseline period analysis in Tier 1) for NS=0 and NS=0.1 in Fig. A.10. Changing the indicators caused the mew gull to have the highest projected percentage of years with CBS in the reference (29.6%) and future scenarios (29.6% to 40.7%). Adjusted IHA from group 4 seems to be the most sensitive to changes in the percentage of years with CBS (Fig. A.10, Table A.6).

4. Discussion

4.1. Impact on mew gull, black-headed gull and little tern

Due to the fact that for 15 years (2004-2018) comprehensive studies and observations of the ecology and breeding behavior of gulls and terns have been carried out in the Middle Vistula, combined with individual marking of adult birds and chicks; we were able to use the most precise NS measurement possible (average number of feathered chicks / pair). The faith of the bird brood was traced during the baseline period from the moment of hatching until leaving the nest and allowed to precisely assess the actual number of chicks that fledged and gained the ability to fly. There was no need to use other indirect and less precise measures such as Mayfield method of estimating nest success, which is based on calculating the probability of chick survival to a certain age on the basis of their actual mortality at a younger age and adopted general assumptions (Mayfield, 1961).

The analysis focused on the breeding season, which for all three species of birds takes place during spring and happens to coincide with the occurrence of the highest flows during the year. As proven by the collected NS data during the baseline period, the NS of all three birds is negatively affected by extremely high flow events and flooding such as those that occurred in 2014 and 2010. The number of colonies and nesting pairs of birds significantly decreases under high flood conditions due to delayed exposure of their breeding habitats and increases under low-water conditions when sandy islands and river spits expand their area in the form of temporary sandbanks (Atamas and Tomchenko, 2015). The timing of high flow events also plays a key role as due to different vulnerability periods; some events only affect one or two of the analysed species. A good example of such a situation is the hydrological conditions that occurred in 2005 and 2006 where the black-headed gull was not affected by a high flow event that occurred later on in the season and resulted in low NS (median below 0.25) for the mew gull and little tern.

Years with a steady hydrograph (such as 2004, 2007, 2008, 2011, 2012, 2016, 2017, 2018) resulted in higher NS in comparison to years with high flow events. It was found by Bukaciński et al. (2018) that, between 2015 and 2018, the water level in the Middle Vistula was more stable and lower in April-June in comparison to prior years and the breeding failure caused by floods was on average at its lowest for 30 years. This seemed to be especially beneficial for the little tern as, during 2016-2018, this species had a higher median nesting success in comparison to the remaining two birds. Over the baseline period of 2004-2018, the mew gull had the lowest nesting success (average 0.19) while the black-headed gull had the highest (average 0.61) and the little tern was in the middle (average 0.41).

Among the three species, the mew gull showed the least correlation between adjusted IHA and NS, which suggests that there are other factors more significant than hydrology that impact that species' NS. The black-headed gull and little tern showed a moderate and strong correlation between NS and adjusted IHA which points to a conclusion that hydrology is an important factor affecting their breeding.

The value of percentage change of adjusted IHA for the mew gull indicates a prevailing increase in the future in comparison to the reference scenario, but without exceeding the 30% threshold. Increases in gr.1 indicators are displayed for the black-headed gull but for the remaining indicators their values are lower than reference in NF and higher in FF. The value of gr.3_vp_max in NF 8.5 goes below the -30% threshold. The percentage changes in adjusted IHA values for the little tern increase with time and RCP scenario, and for gr.4_P0.75 even exceed the 30% threshold of acceptable change in FF. Climate change will have the most profound impact on the little tern due to an increase of high flow characteristics, an irregular impact on the black-headed gull and a slight impact on the mew gull. The little tern also seems to be most affected by the location of the island as adjusted IHA percentage changes between the reference and future scenarios are higher in downstream locations.

The percentage of years with CBS is projected to fluctuate for the mew gull, as in NF it decreases and in FF 8.5 increases in comparison to the reference period. The percentage of years with CBS remains the same throughout the time horizons and climate change scenarios (except for FF 8.5 when it slightly increases) for the black-headed gull. The adjusted IHA gr.4_P0.75 analysed for the little tern shows the highest change and increase in CBS. A conclusion can be drawn that, in the Middle Vistula, the little tern will be under the highest pressure from increasing percentage of years with CBS, the mew gull will experience an increase in the FF and the black-headed gull is projected not to be impacted by significant changes. These results confirmed the importance of hydrologic change for avian nesting success.

Future streamflow projections used in this study are based on model-derived estimates of future climate and they are associated with high uncertainties. Two RCPs and nine climate models produced 18 scenarios for each time horizon (NF, FF). The uncertainty resulting from the use of the nine climate models was addressed by preparing the results as box plots (Fig. 4 and Fig. 5) to show the range of results. The model setup doesn't take into account existing river barriers that influence streamflow and assumes that the land use and water management does not change over time, which downplays important factors but also allows to study the pure effect of climate change on river hydrology. Additionally, there are limitations to using linear regression to establish the relationship between NS and adjusted IHA; replacing it with more advanced models would provide more detailed results. It must be emphasized that the presented work is a conceptual model based on streamflow projections, and further verification research is needed.

4.2. Other factors impacting the breeding success

Factors impacting the breeding success of birds change over time. From 1985-1994, the most limiting factor for the breeding of gulls and terns along the Vistula River were (1) weather conditions (sudden temperature drops in April and May, sand storms and strong insolation), (2) predation by the hooded crow *Corvus corone cornix* and the Eurasian magpie *Pica pica*, (3) frequent high flows, and (4) uncontrolled livestock grazing (Bukaciński et al., 2018; Bukaciński and Bukacińska, 2003, 1995, 1994). In the 1990s, new threats appeared such as outbreaks of black flies (blood-sucking dipteran from the *Simuliidae* family) and large floods (Bukaciński and Bukacińska, 2000, 1997). At the start of 2000s, the predation pressure of the American mink *Neovision vision* (an invasive species) and the red fox *Vulpes vulpes* started increasing rapidly. In the years 2005-2014, the threats to island avifauna included (1) growing predation pressure by the American mink and red fox and an appearance of subsequent invasive species: the raccoon dog *Nyctereutes procyonoides* and raccoon *Procyon lotor,* (2) rising pressure from birds such as the northern goshawk *Accipiter gentilis*, Eurasian eagle-owl *Bubo bubo*, crows and magpies, (3) loss of optimal breeding habitats for terns and the mew gull as a result of decreased livestock grazing (in comparison to the years 1995-2004), (4) operation of hydro-technical measures (weirs, groynes, bank protection structures, etc.), (5) presence of tourists, particularly motorists on quads, motorcycles and off-road vehicles on islands and sandy shoals, and (6) feral dogs and cats hunting on the islands (Bukaciński et al., 2020, 2018; Bukaciński and Bukacińska, 2008). However, it was also during this time period that the pressure of the black fly outbreaks decreased. Periods of drought can also be dangerous for birds as they promote vegetation succession and reduce areas suitable for breeding habitats, especially for terns and mew gulls. Low flows allow easy access to islands for people, mammalian predators and feral cats and dogs (Bukaciński et al., 2018; Bukaciński and Bukacińska, 2015b, 2015c, 2015a).

4.3. River and island morphology change over time

Areas of the Middle Vistula River that are unregulated or have a slightly modified riverbed- and therefore still maintain its character of a natural, lowland braided river with sandy islands and braid bars within the main channel- create key breeding sites for mew gull, black-headed gull and little tern (Bukaciński et al., 2020). This study analyses islands on a 239 km stretch of the Vistula River. The character of the river and its islands changes with a gradient of increasing streamflow. Flow regime variability, which includes extreme high and low flows, impacts the morphology and regulates the physico-chemical and biotic properties of rivers, and, in consequence, drives the community dynamics of riverine-floodplain ecosystems (Bunn and Arthington, 2002). The island type is determined by the hydraulic parameters of the channel, specifically the hydraulic radius. River island and sandbar features can be described with an emerged surface area at a specific water level, average height measured from the water surface, the wetted perimeter of the emerged part, and longitudinal slope measured from the tail (lower part) to the front (higher part) (Habel, 2018). Additionally, physical sandbar characteristics include a substrate, particle size distribution, temperature and plant coverage and type

(Lenhart et al., 2013). The morphology of the islands may change multiple times a year depending on the dominating water levels occurring at a given time. The substrate that builds the islands is constantly moving downstream at different rates depending on the hydrological regime and channel properties (Babiński, 1992).

This study does not take into account the change of river morphology over the time span of the future scenarios (NF, 2021- 2050 and FF, 2071- 2100) in relation to the reference or baseline scenario. The scope of this study did not focus on modelling morphological changes over time and is concentrated on hydrological indicators. Therefore, it was assumed the 22 island location will still exist in the Middle Vistula Valley in future scenarios. Future studies on this topic would benefit from including 2D hydrodynamic flood inundation models to assess island availability for breeding of birds due to changes in water level and river morphology.

4.4. Nesting habitats and behavior of individual species

The three analysed bird species (mew gull, black-headed gull, little tern) differ in terms of preference of nesting habitats characteristics, such as type of vegetation, island substrate, island height, and distance from the water. Each of the bird species tends to occupy a different section of river islands, which impacts their susceptibility to flooding. The little tern tends to choose the lower sections of the islands for nesting, the black-headed gull chooses the upper sections and the mew gull is flexible in terms of their preferences. All three bird species produce one brood per year but, in extreme cases where the clutch is lost, it can be replaced (see also Table 1). The mew gull exhibits high natal site fidelity (Bukaciński and Bukacińska, 2015a, 2003), little tern is highly mobile (Bukaciński and Bukacińska, 2015c) and data related to natal site fidelity of black-headed gull is not clear (Bukaciński and Bukacińska, 2015b). According to Fig. A.8, the little tern is the most impacted by location suitability as the percentage changes in adjusted IHA values increase the more downstream the subbasin (and exceed 30% threshold of acceptable change in FF scenarios), while for the two other birds there are no changes. Since little tern is highly mobile and flexible in terms of choosing a nesting location, it could be a beneficial trait under climate change conditions.

4.5. Species response to climate change

According to (Holt, 1990) there are three possible responses of species to climate change: adaptation (evolutionary change or physiological acclimatization), movement or extirpation. Bird species can actively search for the geographic position of their ecological niches which sustain their livelihoods (Holt, 1990; Peterson et al., 2001). Changes in birds species' range due to climate change were already confirmed (Li et al., 2015; Peterson et al., 2001). Sparks et al. (2002) found that there is good evidence that birds are changing the timing of their nesting seasons, and that their egg size, hatching success, and nesting success is changing due to warmer springs. Species can also be capable of evolutionary change or have a wide range of physiological tolerances in response to shifting environmental conditions. A recent study on birds by (Radchuk et al., 2019) assessed that those changes are insufficient and are not occurring fast enough in order to keep up with the ongoing climate change which is already threatening the viability of species. Migratory and island birds are among the most vulnerable to climate change and factors that exacerbate this threat are poor dispersal capability, low population numbers, restricted or patchy habitat, and narrow climatic range. According to a study by Bartosz et al. (2012), gulls and terns are among the birds most sensitive to climate change in Poland.

This study did not focus on the potential of change in species' distribution range or their ability to adapt to the changing hydrological conditions but rather on the potential risk of extirpation, which occurs when adaptation and movement fails. It is possible that within the baseline period, where the nesting success data was collected, those birds were already affected by climate change and therefore could have been adapting. We observe that, currently, gulls and terns arrive earlier at their breeding grounds on the Middle Vistula and delay the start of breeding if their colonies' sites (islands, sandbars) are flooded (Bukaciński and Bukacińska, unpublished data). In the case of long-lasting water increases in May, mew gulls try to adapt to these unfavorable conditions by undertaking breeding attempts in trees, even at a height of several meters above the ground, although so far usually without breeding success (Bukaciński and Bukacińska, 2015a, unpublished data). It is difficult to distinguish and separate natural behavior from already occurring adaptation or species range shift due to climate change; it was not the scope of this study.

4.6. Protection and management implications

Knowledge about climate change impacts on species on a large scale is important for biodiversity conservation and preparation of management programs (Li et al., 2015). Investigating the interdependency and interconnectedness between water flow and the behavior of aquatic organisms can provide a better insight into river status, often called "river health" (Rowiński et al., 2022). Large rivers with islands and sandbars within the channel serve as breeding and resting places for many bird species and their existence and stability is therefore crucial (Bukaciński et al., 2020). Modern-day rivers are under a lot of pressure from hydrological changes, river channelization and regulation, building and maintaining dikes and dams. Areas surrounding rivers are impacted by agriculture intensification, land use change, and urbanization. The introduction of hydro-engineering structures decreases the channel width, causes natural islands and sandbars to be replaced by flat, lower by 0.5 m diagonal bars which are lacking natural hiding places such as shrubs and three trunks (Bukaciński et al., 2013; Habel, 2018). Flow regulation and channelization in many large rivers have reduced sandbar habitats availability and their restoration is a priority (Tracy-Smith et al., 2012). Improved management and restoration approaches focusing on specific stages of birds' life cycles could benefit ground-nesting bird species, many of which are threatened with extinction (Bukaciński et al., 2017; Dombrowski et al., 2021).

5. Conclusions

This study focuses on vulnerable species and habitats: three strictly protected bird species (mew gull, little tern and black-headed gull) nesting in the Middle Vistula River which is a Natura 2000 Special Protection Area. Alterations to birds nesting habitats and streamflow regimes due to climate change most likely will pose new challenges and will increase the need for adaptation and conservation measures. This research is an important contribution in helping to understand how streamflow could shape the nesting success of ground-nesting bird species under climate change-induced conditions. The availability of long-term nesting success data of the three bird species made this study feasible and allowed connections to be made between it and the past streamflow extremes whose occurrence is unpredictable. Analysis of percentage changes in adjusted IHA and percentage of years with CBS is a practical framework for assessing levels of vulnerability among a group of bird species and could be further used for evaluating conservation needs and targeting efforts at priority species. Through the development of adjusted IHA and CBS analysis, this study revealed that the little tern is the most vulnerable among the three species. It is important to take into account that, for some species, hydrology is not the dominant cause for low nesting success, as was found for the mew gull. The black-headed gull is projected to be least affected by climate change according to our study. Although this study focused on the Middle Vistula, the findings from this study are likely relevant to other temperate climate, large, lowland rivers. The utilized modelling approach generated a new insight into hydroecological interactions and created a foundation for further work on studying the impact of hydrological variability on water dependent taxa.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

Authors state that the research was conducted according to ethical standards.

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Appendices

Appendix A

Table A1–A6 and Figure A1–A10.

Table A1
Island locations according to Vistula River waterway kilometers. 0 km marks where Przemsza river drains to Vistula in the South of Poland and 941.3 km is the Vistula estuary to the Baltic sea.

Island location number	Vistula River kilometer
1	383-385
2	394-396
3	402-404
4	411-413
5	415-420
6	428-432
7	440-442
8	443-445
9	455-457
10	463-468
11	471-475
12	479-483
13	488-490
14	496-500
15	539-541
16	547-551
17	558-563
18	571-574
19	579-583
20	593-596
21	602-604
22	617-622

Table A2
List of available GCM-run-RCM combinations from EURO-CORDEX composing the multi-model ensemble.

Code	GCM	RCM
01	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17
02	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4
03	ICHEC-EC-EARTH	CLMcom-CCLM4-8-17
04	ICHEC-EC-EARTH	SMHI-RCA4
05	ICHEC-EC-EARTH	KNMI-RACMO22E
06	ICHEC-EC-EARTH	DMI-HIRHAM5
07	IPSL-IPSL-CM5A-MR	SMHI-RCA4
08	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17
09	MPI-M-MPI-ESM-LR	SMHI-RCA4

Table A3
Goodness of Fit between the observed and simulated streamflow values for five gauging stations in the Middle Vistula.

Gauging station	NSE	KGE	PBIAS	RSR
Warszawa Nadwilanówka	0.58	0.75	2.7	0.65
Gusin	0.61	0.8	-2.3	0.62
Dęblin	0.65	0.82	-5.9	0.59
Puławy	0.64	0.81	3.2	0.6
Annopol	0.64	0.82	3.4	0.6

Table A4
Median percentage change in adjusted IHA values for 18 subbasins in near future (NF), far future (FF) and climate change projections (RCP 4.5 and 8.5) in 9 models in comparison to reference period (1971-2000). Color red indicates values above the +\-30% threshold.

Scenario	gr.1_mean_LE		gr.1_mean_Incub			gr.1_mean_RC			gr.2 day03_max			gr.3_vp_max	gr.4_P0.95	gr.4_P0.75	
	Mew gull	Little tern	Mew gull	Black-headed gull	Little tern	Mew gull	Black-headed gull	Little tern	Mew gull	Black-headed gull	Little tern	Black-headed gull	Black-headed gull	Mew gull	Little tern
NF 4.5	10.6	7.8	-0.3	9.8	6.7	6.5	9.4	3.4	-1.8	-3.4	6.6	-23.3	-11.3	13.6	16.4
FF 4.5	8.5	19.6	14.5	7.9	20.1	22.2	21.9	17.9	5.3	0.4	18.3	7.4	-11.1	22.7	32.9
NF 8.5	4.0	12.5	5.5	3.6	10.3	9.6	16.6	9.6	-3.1	-5.4	19.7	-35.6	-9.1	17.9	27.9
FF 8.5	12.5	21.7	13.9	12.0	20.0	20.6	26.5	11.1	13.9	0.6	21.0	7.4	13.6	24.1	37.5

Table A5
Summary of adjusted IHA with the highest and second highest correlation with NS for each bird, transformed regression equations, IHA value thresholds resulting in catastrophic breeding season.

Bird species	Adjusted IHA	R value for adjusted IHA correlation to NS	Strength of relationship (R)	Transformed regression equation for obtaining NS	IHA value threshold resulting in catastrophic breeding season (NS=0)	IHA value threshold resulting in catastrophic breeding season (NS=0.1)
Mew gull	gr.2_day03_max	-0.43	weak	0.312 - 0.044x	7.011	4.761
	gr.4_P0.75	-0.42	weak	0.269 - 0.004x	64.646	40.602
Black-headed gull	gr.1_mean_Incub	-0.71	strong	1.187 - 0.471x	2.521	2.309
	gr.2_day03_max	-0.67	moderate	0.948 - 0.117x	8.102	7.248
Little tern	gr.4_P0.75	-0.77	strong	0.675 - 0.014x	49.242	41.942
	gr.2_day03_max	-0.68	moderate	0.741 - 0.121x	6.132	5.304

Table A6
Median of projected percentage of years with catastrophic breeding season (CBS) when NS=0 and 0.1 for mew gull, black-headed gull and little tern. Calculations prepared for adjusted IHA with the highest and second highest correlation to NS.

Mew gull				
Scenario	gr.2_day03_max NS=0	gr.2_day03_max NS=0.1	gr.4_P0.75 NS=0	gr.4_P0.75 NS=0.1
ref	3.7	7.4	3.7	29.6
NF 4.5	0	3.7	11.1	29.6
FF 4.5	0	7.4	14.8	40.7
NF 8.5	0	3.7	11.1	40.7
FF 8.5	0	14.8	14.8	40.7
Black-headed gull				
Scenario	gr.1_mean_Incub NS=0	gr.1_mean_Incub NS=0.1	gr.2_day03_max NS=0	gr.2_day03_max NS=0.1
ref	3.7	3.7	0	0
NF 4.5	3.7	3.7	0	3.7
FF 4.5	0	3.7	0	0
NF 8.5	0	3.7	0	0
FF 8.5	0	11.1	0	0
Little tern				
Scenario	gr.4_P0.75 NS=0	gr.4_P0.75 NS=0.1	gr.2_day03_max NS=0	gr.2_day03_max NS=0.1
ref	7.4	18.5	0	3.7
NF 4.5	14.8	22.2	3.7	7.4
FF 4.5	22.2	29.6	3.7	7.4
NF 8.5	18.5	25.9	0	3.7
FF 8.5	18.5	29.6	3.7	11.1

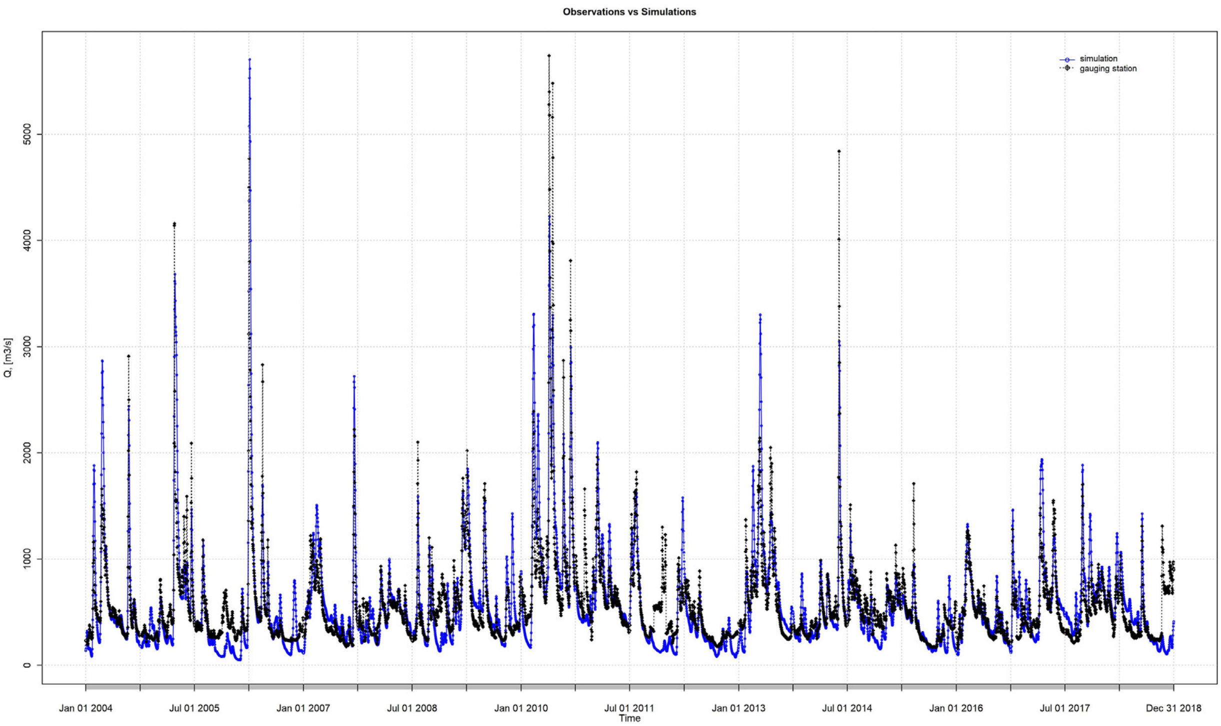

Fig. A1. Graphical Goodness of Fit between the observed and simulated streamflow values in the Warszawa Nadwilanówka gauging station (blue – simulation, black- gauging station).

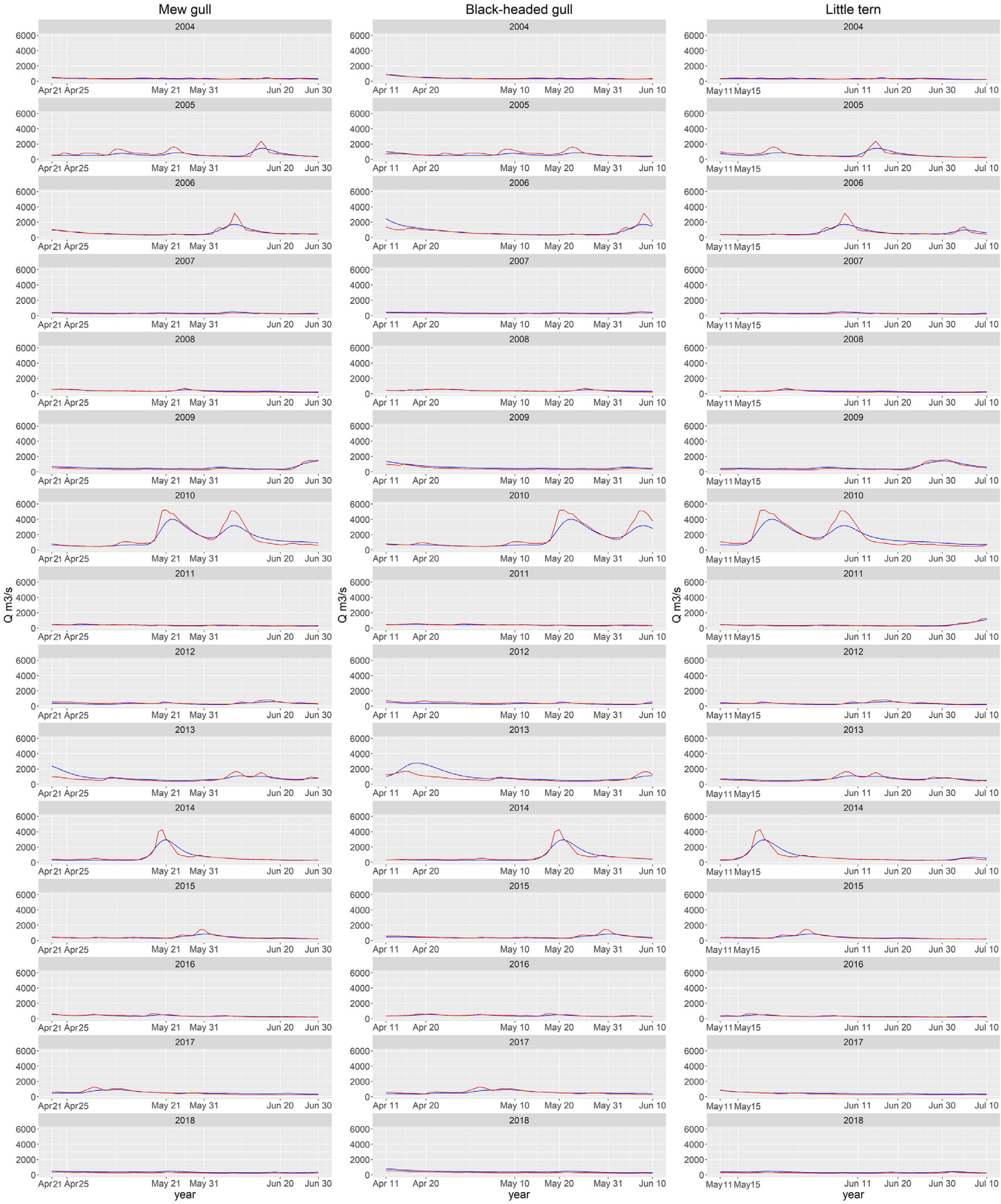

Fig. A2. Simulated (blue) and observed (red) streamflow in Puławy gauging station on Vistula River during the vulnerability periods of mew gull, black-headed gull and little tern

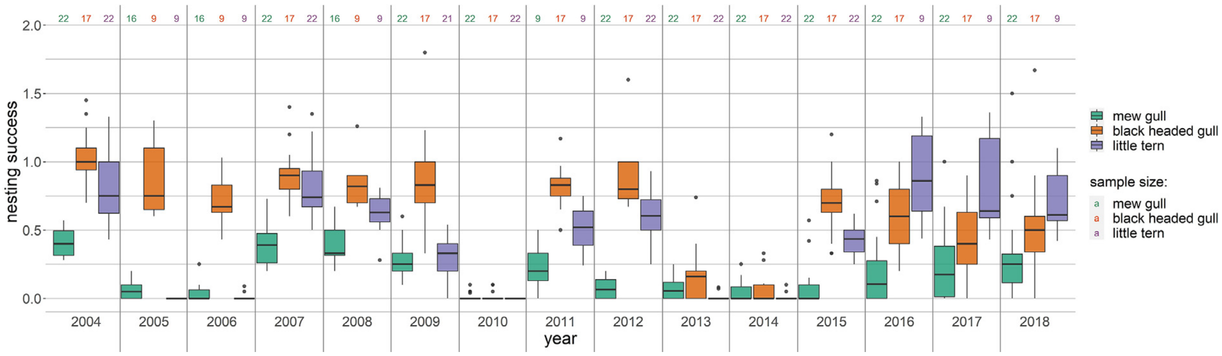

Fig. A3. Nesting success from 22 locations during the baseline period of 2004-2018 of black-headed gull, mew gull and little tern. Numbers above the box plot indicate the sample size (number of analyzed locations with data).

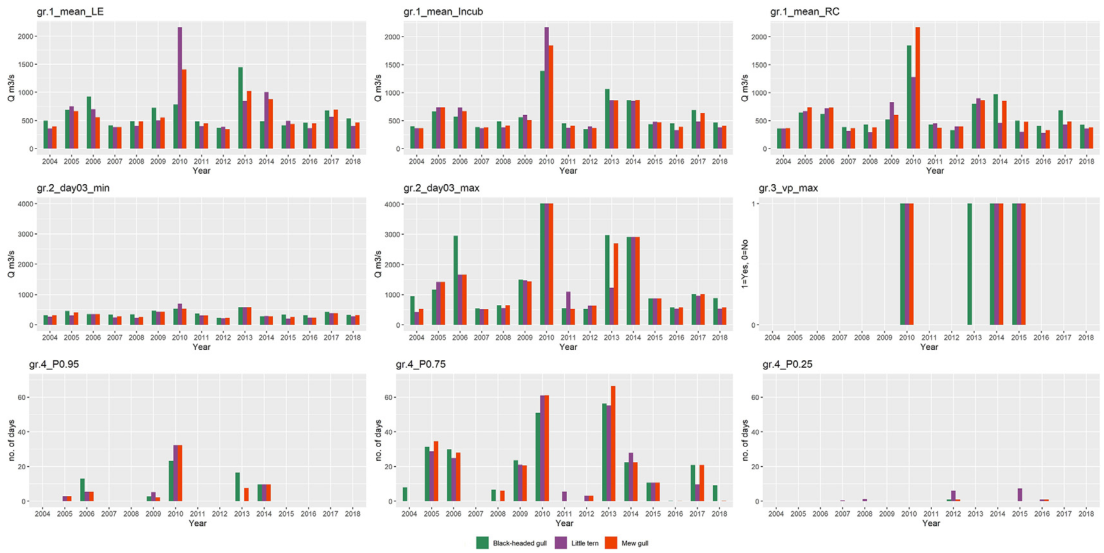

Fig. A4. Mean yearly adjusted IHA results from 18 subbasins for modelled streamflow during the baseline period (2004-2018) for black-headed gull, mew gull and little tern.

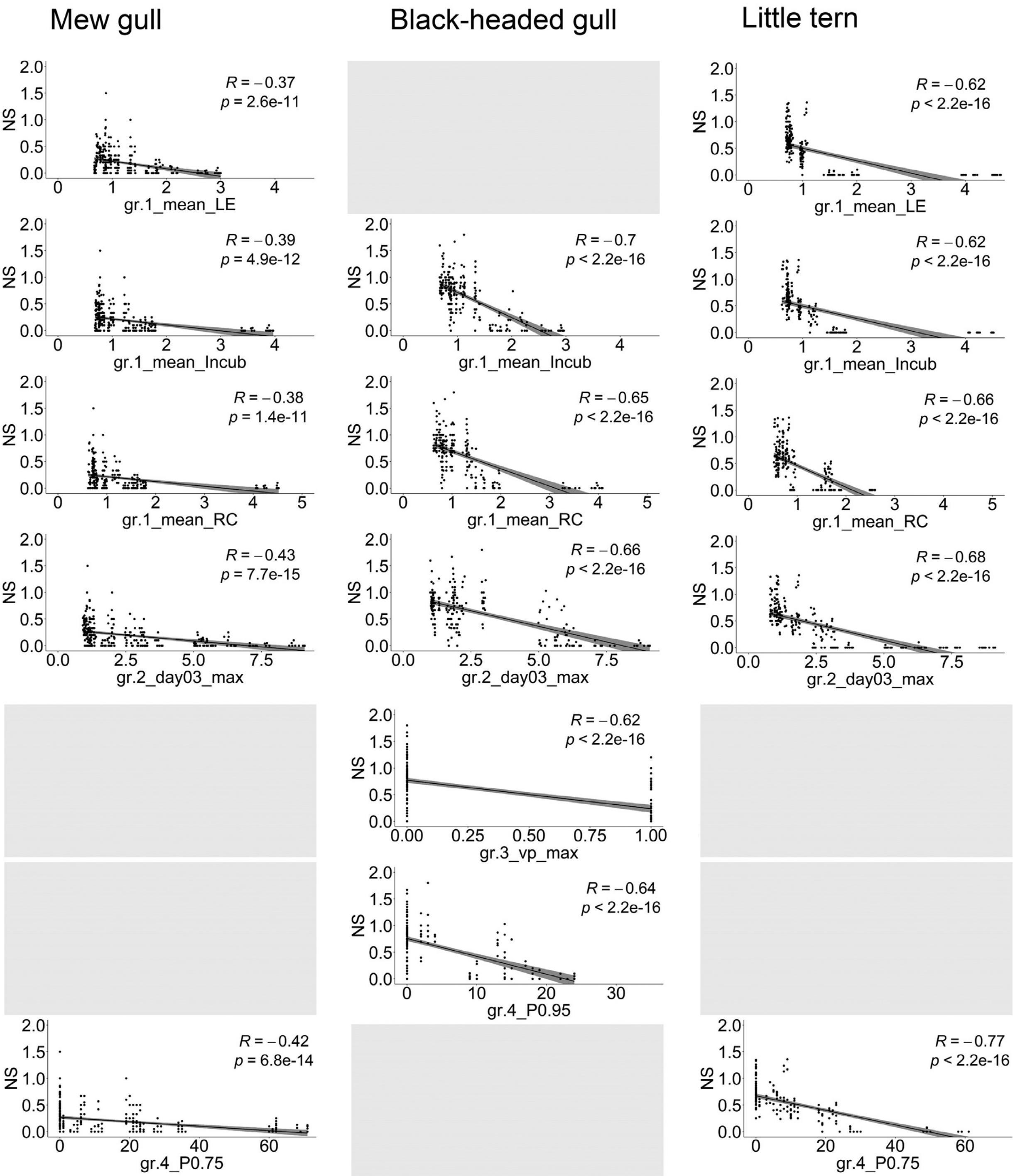

Fig. A5. Correlation between NS (nesting success) and adjusted IHA indicators for the baseline period (2004 – 2018) prepared for IHA indicators chosen for further analysis.

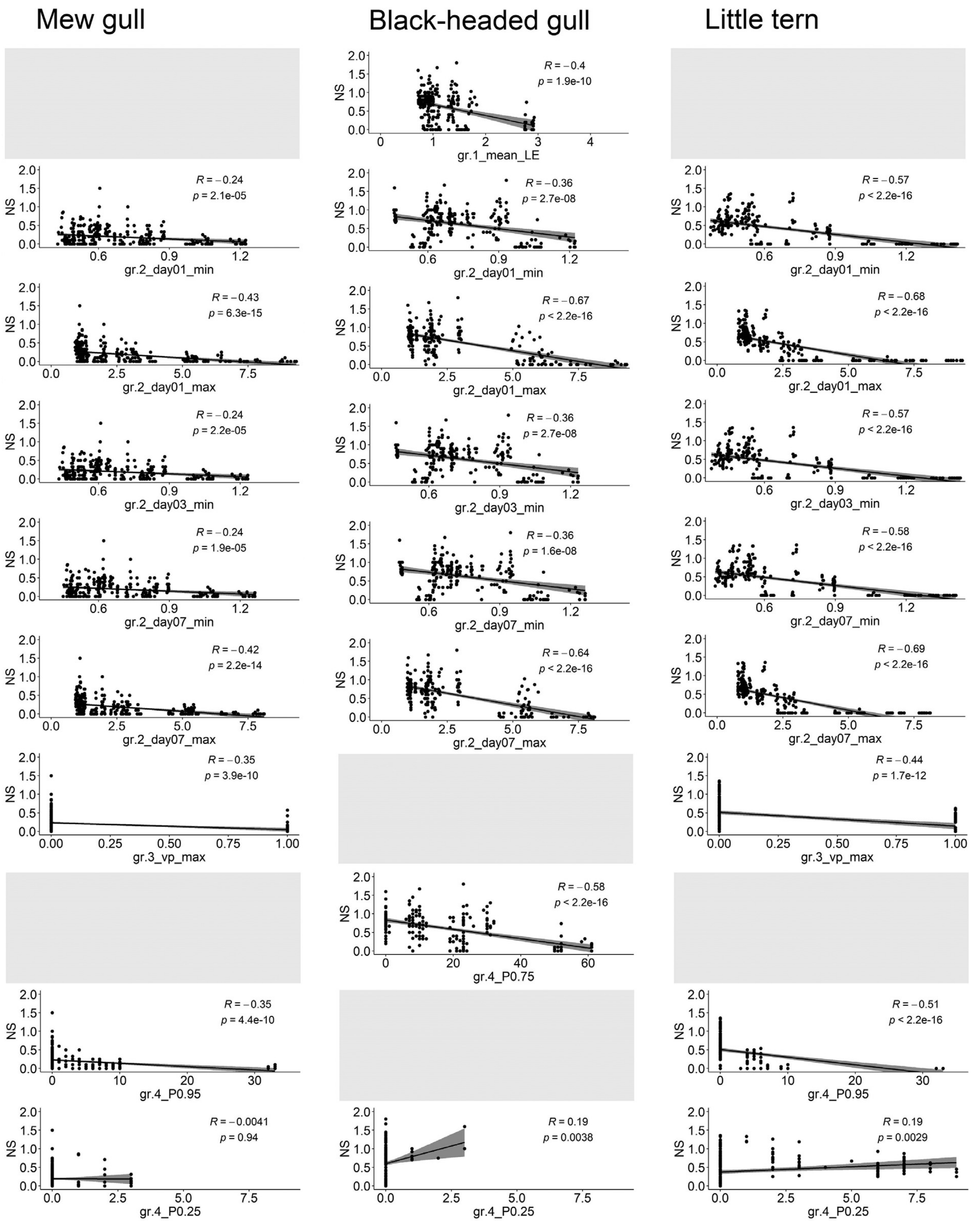

Fig. A6. Correlation between NS (nesting success) and adjusted IHA indicators for the baseline period (2004 – 2018) prepared for IHA indicators not chosen for further analysis.

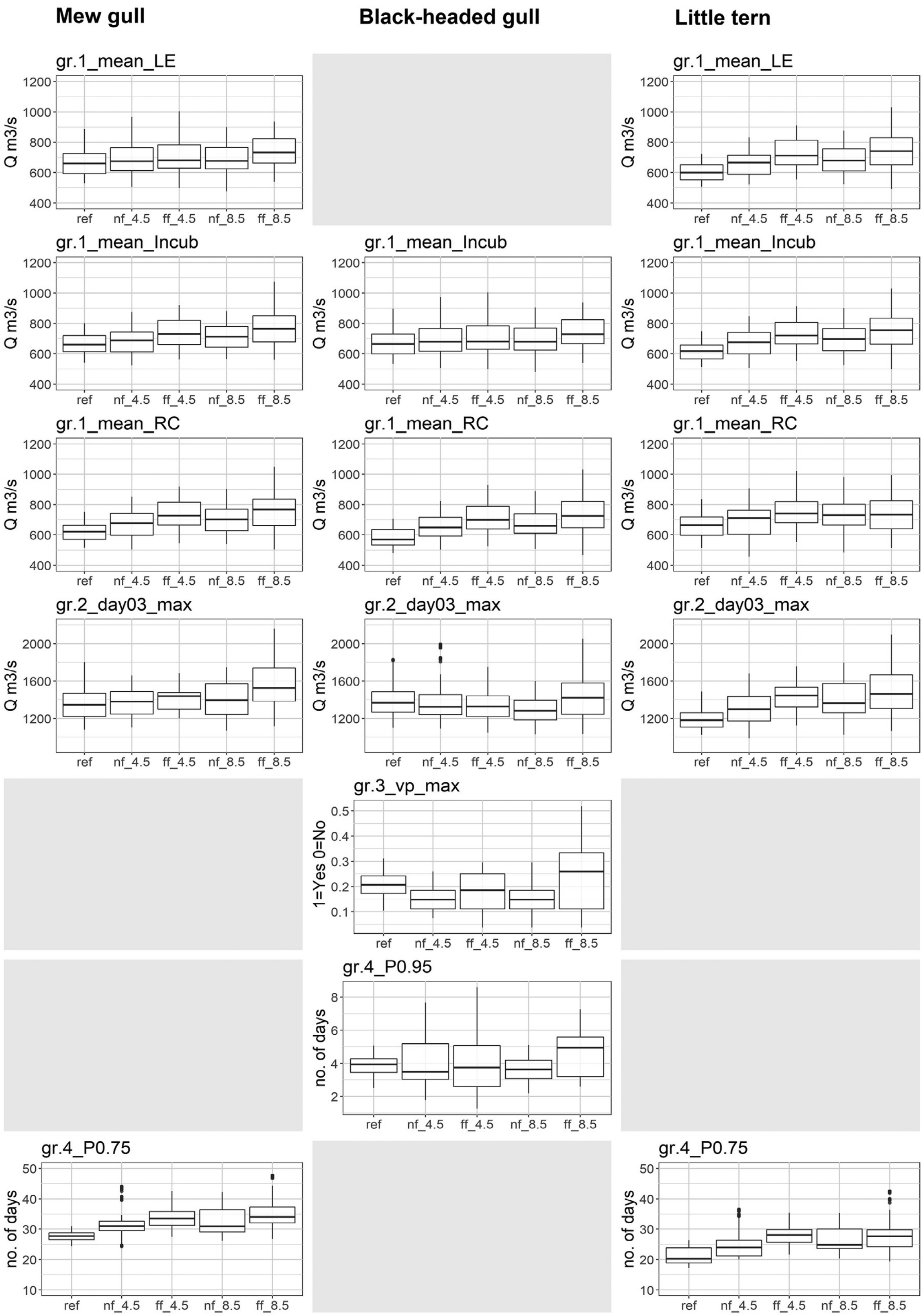

Fig. A7. Absolute change of adjusted IHA values for 18 subbasins in the reference period (ref), near future (NF), far future (FF) and climate change projections (RCP 4.5 and 8.5).

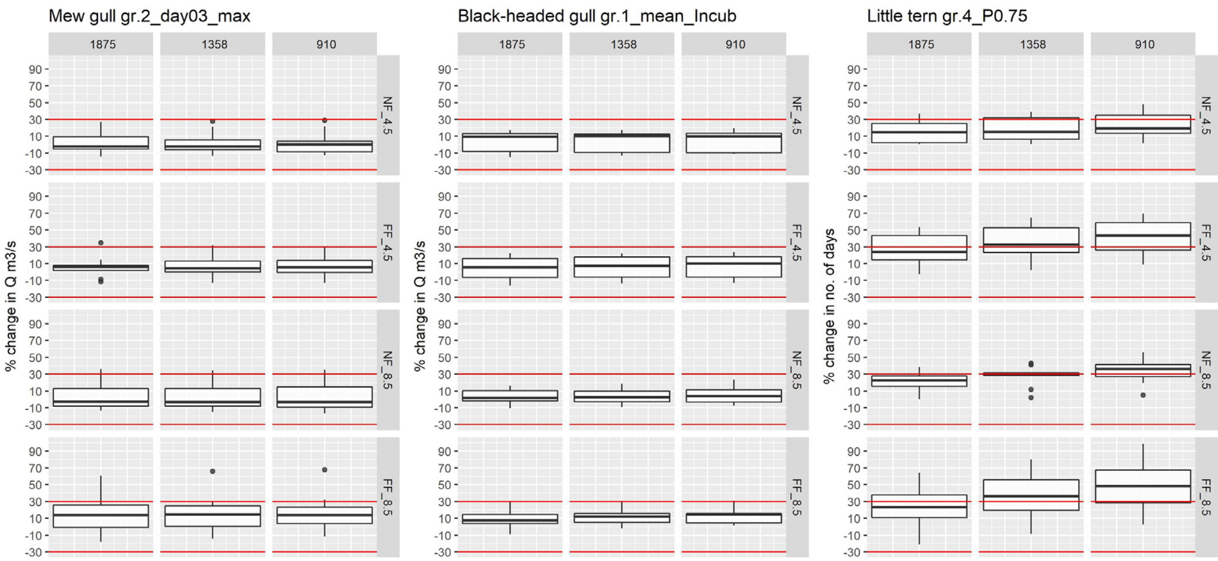

Fig. A8. Comparison of IHA results for three subbasins located in the upper (1875), middle (1358) and lower (910) section of the research area on the Vistula River.

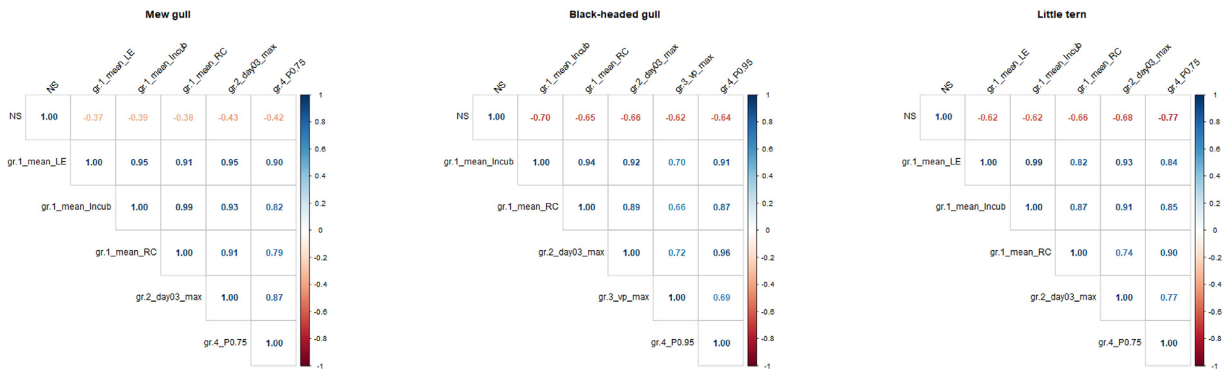

Fig. A9. Correlation matrix of adjusted IHA and NS for the baseline period.

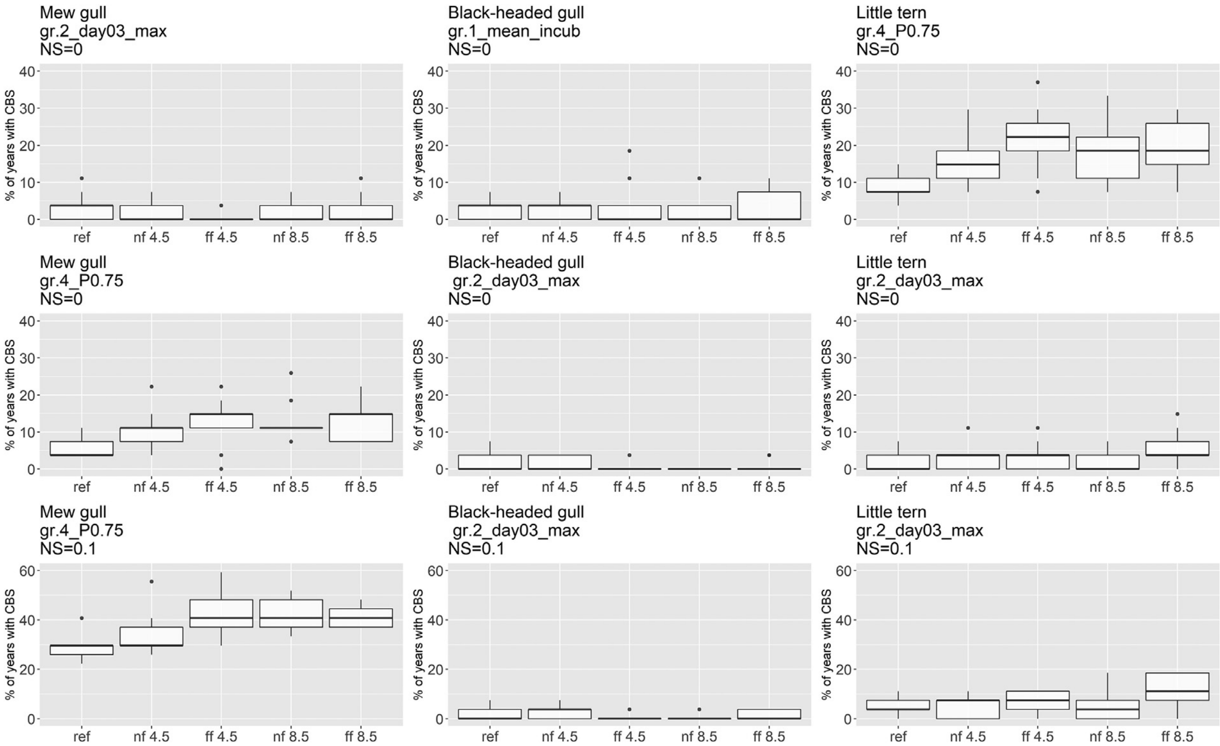

Fig. A10. Projected percentage of years with catastrophic breeding seasons (CBS) for mew gull, black-headed gull and little tern: adjusted IHA with the highest correlation to NS for CBS with NS=0 (top), adjusted IHA with the second highest correlation for CBS with NS=0 (middle) and NS=0.1 (bottom).

Appendix B

According to Fig. A.4 the highest mean streamflow during laying eggs (gr.1_mean_LE) and during incubation (gr.1_mean_Incub) occurred in 2010 and among the three birds was the highest for little tern and smallest for black-headed gull. The order was different in 2010 for mean streamflow during rearing chicks (gr.1_mean_RC) where highest streamflow was during mew gulls vulnerability period and lowest during little terns. Highest three day rolling mean of streamflow minimum during vulnerability period (gr.2_day03_min) occurred for all three birds in 2010 and 2013 while the lowest was in 2012. Three day rolling mean of streamflow maximum during vulnerability period (gr.2_day03_max) exceeded 2000m^3/s during VP of black-headed gull in 2006, 2010, 2013 and 2014, while for mew gull this occurred in 2010, 2013 and 2014 and for little tern only in 2010 and 2014. Yearly maximum flow fell within the vulnerability period (gr.3_vp_max) of all three bird species in 2010, 2014 and 2015, for black-headed gull additionally in 2013. Days during the vulnerability period when flows exceed the yearly 0.95 percentile (gr.4_P0.95) occurred only during 6 years out of the 15 year analysis period (2005, 2006, 2009, 2010, 2013, 2014). Mean number of those days was the highest for all birds in 2010. Mean number of days during the vulnerability period when flows exceed the yearly 0.75 percentile (gr.4_P0.75) was highest for all three birds in 2010 and 2013. There were more than 5 days during the vulnerability period when flows were lower than the yearly 0.25 percentile (gr.4_P0.25) only for little tern during 2012 and 2015.

References

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. J Am Water Resour Assoc 34, 73–89. doi:10.1111/j.1752-1688.1998.tb05961.x.

Atamas, N.S., Tomchenko, O.v., 2015. The Influence of Spring Flood Water Levels on the Distribution and Numbers of Terns (On the Example of the Lower Desna River). Vestn Zool 49, 439–446. doi:10.1515/vzoo-2015-0051.

Babiński, Z., 1992. The present-day fluvial processes of the Lower Vistula river. Geographical Studies 157.

Bartosz, R., Bukowska, M., Chylarecki, P., Ignatowicz, A., Puzio, A., Wilińska, A., 2012. Ocena wpływu zmian klimatu na różnorodność biologiczną oraz wynikające z niej wytyczne dla działań administracji ochrony przyrody do roku 2030.

Berezowski, T., Szcześniak, M., Kardel, I., Michałowski, R., Okruszko, T., Mezghani, A., Piniewski, M., 2016. CPLFD-GDPT5: High-resolution gridded daily precipitation and temperature data set for two largest Polish river basins. Earth Syst. Sci. Data 8, 127–139. doi:10.5194/essd-8-127-2016.

Bukacińska, M., 1999. Wpływ opieki rodzicielskiej na sukces lęgowy u mewy pospolitej (Larus canus) PhD Thesis. Instytut Ekologii PAN.

Bukacińska, M., Bukaciński, D., 2004. Larus ridibundus (L., 1766) – śmieszka. In: Gromadzki, M. (Ed.), Ptaki. Cz. 2. Poradniki Ochrony Siedlisk i Gatunków Natura 2000 – Podręcznik Metodyczny. Ministerstwo Środowiska, Warszawa, pp. 160–165.

Bukacińska, M., Bukaciński, D., 1993. The Effect of Habitat Structure and Density of Nests on Territory Size and Territorial Behaviour in the Black-headed Gull (Larus ridibundus L.). Ethology 94, 306–316. doi:10.1111/J.1439-0310.1993.TB00447.X.

Bukaciński, D., 1998. Adaptacyjne znaczenie terytorializmu u mewy pospolitej Larus canus PhD Thesis. Instytut Ekologii PAN.

Bukaciński, D., Bukacińska, M.Monografia, in: STOP, 2015a. Mewa siwa Larus canus. In: Kluczowe Gatunki Ptaków Siewkowych Na Środkowej Wiśle: Biologia, Ekologia, Ochrona i Występowanie. STOP, Warszawa, p. 44.
Bukaciński, D., Bukacińska, M., 2015b. Śmieszka Chroicocephalus ridibundus. Monografia. In: Kluczowe Gatunki Ptaków Siewkowych Na Środkowej Wiśle: Biologia, Ekologia, Ochrona i Występowanie. STOP, Warszawa, p. 68.
Bukaciński, D., Bukacińska, M., 2015c. Rybitwa białoczelna Sternula albifrons. Monografia. In: Kluczowe Gatunki Ptaków Siewkowych Na Środkowej Wiśle: Biologia, Ekologia, Ochrona i Występowanie. STOP, Warszawa, p. 40.
Bukaciński, D., Bukacińska, M., 2008. Threatened bird species of the middle Vistula River islands: status, necessity for protection and proposed activities. In: Uchmański, J. (Ed.), Theoretical and Applied Aspects of Modern Ecology. Wydawnictwo UKSW, Warszawa, pp. 219–239 10.21697/SEB.2020.18.5.30.
Bukaciński, D., Bukacińska, M., 2003. Larus canus Common Gull. In: Parkin, D. (Ed.), Birds of the Western Palearctic Update 5. Oxford University Press, pp. 13–47.
Bukaciński, D., Bukacińska, M., 2000. The impact of mass outbreaks of black flies (Simuliidae) on the parental behaviour and breeding output of colonial common gulls (Larus canus). Ann Zool Fennici 37, 43–49.
Bukaciński, D., Bukacińska, M., 1997. Masowy pojaw meszek Simulidae przyczyna strat w legach w koloniach mewy pospolitej Larus canus na srodkowej Wisle. Notatki Ornitologiczne 38, 167–168.
Bukaciński, D., Bukacińska, M., 1995. The factors limiting breeding success in the Black-headed Gull (Larus ridibundus) in different habitat types on the middle course of the Vistula River, Poland. Archiv für Hydrobiologie 9, 221–228 Suppl. 101 Large Rivers.
Bukaciński, D., Bukacińska, M., 1994. Czynniki wpływające na zmiany liczebności i rozmieszczenie mew, rybitw i sieweczek na Wiśle środkowej. Notatki Ornitologiczne 35, 79–97.
Bukaciński, D., Bukacińska, M., 1993a. Colony site and nest-site selection in the Black-headed Gull (Larus ridibundus) at the middle course of the Vistula River. Ring 15, 208–215.
Bukaciński, D., Bukacińska, M., 1993b. The changes in numbers and distribution of the Black-headed Gull breeding population on the Vistula River in the years 1962–1993. Ring 15, 159–164.
Bukaciński, D., Bukacińska, M., Buczyński, A., 2020. Wetland birds of middle Vistula River during breeding season: the impact of human activities on the distribution, abundance and richness of species. Studia Ecologiae et Bioethicae 18, 335–348. doi:10.21697/seb.2020.18.5.30.
Bukaciński, D., Bukacińska, M., Buczyński, A., 2018. Threats and the active protection of birds in a riverbed: postulates for the strategy of the preservation of the middle Vistula River avifauna. Studia Ecologiae et Bioethicae 16, 5–23. doi:10.21697/seb.2018.16.4.01.
Bukaciński, D., Bukacińska, M., Burzyński, A., 2013. The impact of hydrotechnical facilities on island avifauna: a case study of the middle Vistula River. Studia Ecologiae et Bioethicae 11, 93–109 10.21697/seb.2013.11.4.07.
Bukaciński, D., Keller, M., Buczyński, A., Bukacińska, M., 2017. Awifauna lęgowa koryta środkowej Wisły w roku 2009 - zmiany liczebności i rozmieszczenia w ciągu ostatnich 36 lat. In: Keller, M., Kot, H., Dombrowski, A., Rowiński, P., Chmielewski, S., Bukaciński, D. (Eds.), Ptaki Środkowej Wisły. M-ŚTO, Pionki, pp. 97–127.
Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manage 30, 492–507. doi:10.1007/s00267-002-2737-0.
Carey, C., 2009. The impacts of climate change on the annual cycles of birds. Philosophical Transactions of the Royal Society B: Biological Sciences 364, 3321–3330. doi:10.1098/rstb.2009.0182.
Crick, H.Q.P., 2004. The impact of climate change on birds. Ibis 146, 48–56.
Cyberski, J., Grześ, M., Gutry-Korycka, M., Nachlik, E., Kundzewicz, Z.W., 2010. History of floods on the River Vistula. Hydrological Sciences Journal 51. doi:10.1623/hysj.51.5.799.
Dombrowski, A., Chmielewski, S., Bukaciński, D., Antczak, K., Murawski, M., Pagórski, P., 2021. Znaczenie koryt największych rzek dorzecza środkowej Wisły dla awifauny lęgowej-zmiany po dwóch dekadach. Ornis Polonica 62, 89–100.
Dugger, K.M., Ryan, M.R., Galat, D.L., Renken, R.B., Smith, J.W., 2002. Reproductive success of the interior least tern (Sterna Antillarum) in relation to hydrology on the Lower Mississippi River. River Res Appl 18, 97–105. doi:10.1002/rra.634.
Habel, M., 2018. Effects of flow regulation and river channelization on sandbar bird nesting availability at the Lower Vistula River. Ecological Questions 29, 43–53. doi:10.12775/EQ.2018.028.
Holt, R.D., 1990. The microevolutionary consequences of climate change. Trends Ecol Evol 5, 311–315. doi:10.1016/0169-5347(90)90088-U.
Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg Environ Change 14, 563–578. doi:10.1007/s10113-013-0499-2.
Janauer, G.A., 2016. Ecohydrology, floodplain water bodies, European legal provisions and the future. Ecohydrology & Hydrobiology 16, 58–65. doi:10.1016/J.ECOHYD.2015.09.001.
Jenouvrier, S., 2013. Impacts of climate change on avian populations. Glob Chang Biol 19, 2036–2057. doi:10.1111/gcb.12195.
Kouchi, D.H., Esmaili, K., Faridhosseini, A., Sanaeinejad, S.H., Khalili, D., Abbaspour, K.C., 2017. Sensitivity of Calibrated Parameters and Water Resource Estimates on Different Objective Functions and Optimization Algorithms. Water (Basel) 9, 384. doi:10.3390/w9060384.
Krysanova, V., Kundzewicz, Z.W., Piniewski, M., 2016. Assessment of climate change impacts on water resources. In: Singh, V.P. (Ed.), Handbook of applied hydrology. McGraw-Hill Education, New York, p. 148 1-148.12.
Laizé, C.L.R., Acreman, M.C., Dunbar, M.J., Houghton-Carr, H., Florke, M., Schneider, C., 2010. Monthly hydrological indicators to assess impact of change on river ecosystems at the pan- European scale: preliminary results. British Hydrological Society Third International Symposium Role of Hydrology in Managing Consequences of a Changing Global Environment. Newcastle University, Newcastle.
Lenhart, C.F., Naber, J.R., Nieber, J.L., 2013. Impacts of hydrologic change on sandbar nesting availability for riverine turtles in eastern minnesota. USA. Water (Switzerland) 5, 1243–1261. doi:10.3390/w5031243.
Li, X., Clinton, N., Si, Y., Liao, J., Liang, L., Gong, P., 2015. Projected impacts of climate change on protected birds and nature reserves in China. Sci Bull (Beijing) 60, 1644–1653. doi:10.1007/s11434-015-0892-y.
Mayfield, H., 1961. Nesting success calculated from exposure. Wilson Bull 73, 255–261.
Mezghani, A., Dobler, A., Erik Haugen, J., Benestad, R.E., Parding, K.M., Piniewski, M., Kardel, I., Kundzewicz, Z.W., 2017. CHASE-PL Climate Projection dataset over Poland - Bias adjustment of EURO-CORDEX simulations. Earth Syst Sci Data 9, 905–925. doi:10.5194/essd-9-905-2017.
Moriasi, D.N., Arnold, J.G., Liew, M.W. Van, Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. MODEL EVALUATION GUIDELINES FOR SYSTEMATIC QUANTIFICATION OF ACCURACY IN WATERSHED SIMULATIONS, Transactions of the ASABE.
Moriasi, D N, Gitau, M W, Pai, N., Daggupati, P., Gitau, Margaret W, Member, A., Moriasi, Daniel N, 2015. HYDROLOGIC AND WATER QUALITY MODELS: PERFORMANCE MEASURES AND EVALUATION CRITERIA. Trans ASABE 58, 1763–1785. doi:10.13031/trans.58.10715.
Pautasso, M., 2012. Observed impacts of climate change on terrestrial birds in Europe: An overview. Italian Journal of Zoology 79, 296–314. doi:10.1080/11250003.2011.627381.
Peterson, A.T., Sánchez-Cordero, V., Soberón, J., Bartley, J., Buddemeier, R.W., Navarro-Sigüenza, A.G., 2001. Effects of global climate change on geographic distributions of Mexican Cracidae. Ecol Modell 144, 21–30. doi:10.1016/S0304-3800(01)00345-3.
Piniewski, Mikołaj, Mezghani, A., Szcześniak, M., Kundzewicz, Z.W., 2017a. Regional projections of temperature and precipitation changes: Robustness and uncertainty aspects. Meteorologische Zeitschrift 26, 223–234. doi:10.1127/metz/2017/0813.
Piniewski, M., Szcześniak, M., Kardel, I., Berezowski, T., Okruszko, T., Srinivasan, R., Vikhamar Schuler, D., Kundzewicz, Z.W., 2017b. Hydrological modelling of the Vistula and Odra river basins using SWAT. Hydrological Sciences Journal 62, 1266–1289. doi:10.1080/02626667.2017.1321842.
Piniewski, Mikołaj, Szcześniak, M., Kundzewicz, Z.W., Mezghani, A., Hov, Ø., 2017c. Changes in low and high flows in the Vistula and the Odra basins: Model projections in the European-scale context. Hydrol Process 31, 2210–2225. doi:10.1002/hyp.11176.
Poiani, A., 2006. Effects of Floods on Distribution and Reproduction of Aquatic Birds. Adv Ecol Res 39, 63–83. doi:10.1016/S0065-2504(06)39004-6.
Power, ME., Sun, A., Parker, M., Dietrich, WE., Wootton, JT, 1995. Hydraulic food-chain models: an approach to the study of food web dynamics in large rivers. Bioscience 45, 159–167.

Radchuk, V., Reed, T., Teplitsky, C., van de Pol, M., Charmantier, A., Hassall, C., Adamík, P., Adriaensen, F., Ahola, M.P., Arcese, P., Miguel Avilés, J., Balbontin, J., Berg, K.S., Borras, A., Burthe, S., Clobert, J., Dehnhard, N., de Lope, F., Dhondt, A.A., Dingemanse, N.J., Doi, H., Eeva, T., Fickel, J., Filella, I., Fossøy, F., Goodenough, A.E., Hall, S.J.G., Hansson, B., Harris, M., Hasselquist, D., Hickler, T., Joshi, J., Kharouba, H., Martínez, J.G., Mihoub, J.B., Mills, J.A., Molina-Morales, M., Moksnes, A., Ozgul, A., Parejo, D., Pilard, P., Poisbleau, M., Rousset, F., Rödel, M.O., Scott, D., Senar, J.C., Stefanescu, C., Stokke, B.G., Kusano, T., Tarka, M., Tarwater, C.E., Thonicke, K., Thorley, J., Wilting, A., Tryjanowski, P., Merilä, J., Sheldon, B.C., Pape Møller, A., Matthysen, E., Janzen, F., Dobson, F.S., Visser, M.E., Beissinger, S.R., Courtiol, A., Kramer-Schadt, S., 2019. Adaptive responses of animals to climate change are most likely insufficient. Nat Commun 10, 1–14. doi:10.1038/s41467-019-10924-4.

R Development Core Team, 2008. R: A language and environment for statistical computing. https://doi.org/ISBN 3-900051-07-0

Richter, B.D., Baumgartner, J.v., Braun, D.P., Powell, J., 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research & Management 14, 329–340. doi:10.1002/(SICI)1099-1646(199807/08)14:4<329::AID-RRR505>3.0.CO;2-E.

Richter, B.D., Baumgartner, J.v., Powell, J., Braun, D.P., 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. Conservation Biology 10, 1163–1174. doi:10.1046/j.1523-1739.1996.10041163.x.

Rowiński, P.M., Okruszko, T., Radecki-Pawlik, A., 2022. Environmental hydraulics research for river health: recent advances and challenges. Ecohydrology & Hydrobiology 22, 213–225. doi:10.1016/J.ECOHYD.2021.12.003.

Royan, A., Hannah, D.M., Reynolds, S.J., Noble, D.G., Sadler, J.P., 2014. River birds' response to hydrological extremes: New vulnerability index and conservation implications. Biol Conserv 177, 64–73. doi:10.1016/j.biocon.2014.06.017.

Royan, A., Hannah, D.M., Reynolds, S.J., Noble, D.G., Sadler, J.P., 2013. Avian community responses to variability in river hydrology. PLoS One 8, 1–10. doi:10.1371/journal.pone.0083221.

Royan, A., Prudhomme, C., Hannah, D.M., Reynolds, S.J., Noble, D.G., Sadler, J.P., 2015. Climate-induced changes in river flow regimes will alter future bird distributions. Ecosphere 6, 1–10. doi:10.1890/ES14-00245.1.

Różycki, A.Ł., 2014. Fenologia rozrodu i produkcja jaj mew: uwarunkowania i konsekwencje w warunkach środkowej Wisły. Uniwersytet w Białymstoku.

Schneider, C., Laizé, C.L.R., Acreman, M.C., Flörke, M., 2013. How will climate change modify river flow regimes in Europe? Hydrol. Earth Syst. Sci 17, 325–339. doi:10.5194/hess-17-325-2013.

Shi, J., Li, D., Xiao, W., 2006. A review of Impacts of Climate Change on Birds: Implications of Long Term Studies. Zool Res 27, 637–646.

Shiklomanov, I.A., Rodda, J.C., 2003. World water resources at the beginning of the Twenty-First Century. Cambridge University Press, Cambridge.

Smith, J.W., Renken, B., 1985. Least Tern Nesting Habitat In The Mississippi River Valley Adjacent To Missouri. J Field Ornithol 62, 497–504.

Sparks, T., Crick, H., Elkins, N., Moss, R., Moss, S., Mylne, K., 2002. Birds, weather and climate. Weather 57, 399–410.

Tavassoli, H.R., Tahershamsi, A., Acreman, M., 2014. Classification of natural flow regimes in Iran to support environmental flow management. Hydrological Sciences Journal 59, 517–529. doi:10.1080/02626667.2014.890285.

The Nature Conservancy, 2009. Indicators of Hydrologic Alteration Version 7.1 User's Manual.

Thompson, J.R., Laizé, C.L.R., Green, a.J., Acreman, M.C., Kingston, D.G., 2014. Climate change uncertainty in environmental flows for the Mekong River. Hydrological Sciences Journal 59, 935–954. doi:10.1080/02626667.2013.842074.

Tracy-Smith, E., Galat, D.L., Jacobson, R.B., 2012. Effects Of Flow Dynamics On The Aquatic-Terrestrial Transition Zone (ATTZ) Of Lower Missouri River Sandbars With Implications For Selected Biota. River Res Appl 28, 793–813. doi:10.1002/rra.1492.

Trautmann, S., 2018. Climate Change Impacts on Bird Species. Bird Species 217–234. doi:10.1007/978-3-319-91689-7_12.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature doi:10.1038/416389a.

Wang, X., Yang, T., Wortmann, M., Shi, P., Hattermann, F., Lobanova, A., Aich, V., 2016. Analysis of multi-dimensional hydrological alterations under climate change for four major river basins in different climate zones. Clim Change 141, 483–498. doi:10.1007/s10584-016-1843-6.

Wormworth, J., Mallon, K., 2006. Bird Species and Climate Change: The Global Status Report version 1.0.

Zalewski, M., Janauer, G.A., Jolánkai, G., 1997. Ecohydrology A New Paradigm for the Sustainable Use of Aquatic Resources. Technical Documents in Hydrology 7 Paris.

12. Author statements

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Szkoły Głównej Gospodarstwa Wiejskiego w Warszawie

Oświadczenie o współautorstwie

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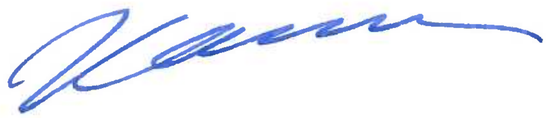

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Wyrażam zgodę na udostępnianie mojej pracy w czytelniach Biblioteki SGGW.

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(czytelny podpis autora)