Modelling of climate change impact on flow conditions in the lowland anastomosing river

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Progressive degradation of freshwater ecosystems worldwide forces actions for their conservation. Nowadays protection strategies need to step beyond the traditional approach of management of protected areas, as they have to deal with protection or recovery of natural flow regimes, disrupted by effects of future climate conditions. Climate change affects the hydrosphere at catchment scale altering hydrological processes which in turn impact hydrodynamics at the river reach scale. Therefore, conservation strategies should be based on mathematical models, which allow understanding of ecosystem functions and their interactions across different spatial and temporal scales. This study focuses on the anastomosing river system in north-eastern Poland, where in recent decades significant loss of the anabranches has been observed. The objective was to assess the impact of projected climate change on average flow conditions in the anastomosing section of the River Narew. Soil and Water Assessment Tool for the Narew catchment was coupled with the HEC-RAS one-dimensional unsteady flow model. The study looked into projected changes for two future time horizons 2021–2050 and 2071–2100 under the Representative Concentration Pathway 4.5, using an ensemble of nine EURO-CORDEX model scenarios. Results show that at the catchment scale, average daily discharge was predicted to increase. However, reach scale simulations indicated a low decrease in 2021-2050 and slight increase for 2071-2100. Hydraulic modelling indicated extremely low flow velocities in the anastomosing arm (<0.1 m/s) nowadays and under future projections which is preferable for in-stream vegetation development and their gradual sedimentation and closure. The perspective of further degradation on anastomosing system in coming decades requires actions to be undertaken by freshwater ecosystem managers.

1. Introduction

The climate change is considered to be one of the greatest challenges nowadays and preventing it is a key strategic priority for the European Union. It is expected that it will amplify current pressures on natural resources, but also create new ones (IPCC, 2014). Riverine ecosystems, which provide a diverse range of services, upon which humans are dependent, are listed amongst the most sensitive to climate change of all ecosystems (Ormerod, 2009). Thus, it is obvious that effective water management is crucial to successful climate change adaption (Ostfeld et al., 2012). Climate change affects riverine ecosystems directly, by determining hydrological processes (where precipitation, temperature and evaporation are the key drivers), and indirectly, by changing the human use of river catchments, riparian zones and floodplains (IPCC, 2014; Ormerod, 2009). In the face of progressive degradation of riverine ecosystems worldwide (Millennium Ecosystem Assessment, 2005), communities and governments are forced to consider strategies for conservation management. Such strategies need to step beyond the traditional approach of management of protected areas, as they have to deal with protection or recovery of natural flow regimes, disrupted by effects of future climate change, which is considerably uncertain (Kingsford, 2011).

Conservation strategies and particular measures preventing from further decline in the health of aquatic ecosystems should be based on mathematical models, which allow understanding of ecosystem functions and their interactions across different spatial and temporal scales (Jähnig et al. 2012). Catchment-scale hydrological changes driven by climate change strongly impact conditions at finer scales i.e. in-stream hydraulics in river reaches (Kiesel et al., 2013). Attempts to model the impact of climate change on water resources at watershed scale have been conducted in a number of studies (Napoli et al., 2017; Krysanova et al. 2016; Kundzewicz et al., 2018, Kharel and Kirilenko, 2018, Tamm et al., 2018), however, such large scale models still lack of components that allow to fully describe links between catchment-scale hydrological processes and in-stream hydraulics and morphology. Therefore, an integrated modelling framework (IMF) has been proposed by Jähnig et al. (2012) aimed at providing the environmental data and describing highly complex interactions between atmosphere, hydrosphere and biosphere across different spatial scales. So far, such IMF approach has been successfully applied in numerous studies: Guse et al. (2015) simulated land use and climate change impact on hydraulics and habitat suitability for fish and macroinvertebrates; Kail et al. (2015) assessed the effect of different pressures on abiotic habitat conditions and the biota of rivers; Visser et al. (2019) proposed a coupled hydrological and hydroecological modelling framework to assess the impact of climate change on hydroecological response. The scope of presented studies demonstrate the open-ended character of IMF which allows tackling diverse region and site-specific problems concerning riverine ecosystems.

One of the examples of such issues described by Lewin et al. (2010) and Walter and Merritts (2008) is the loss of multichannel anastomosing rivers from most of temperate lowland floodplains because of direct and indirect human activities. Once very common, now they are rare in the developed world, which forces even greater importance of their conservation. Most of the studies concerning the origin and evolution of anastomosing rivers were qualitative in nature (Kleinhans et al., 2012; Makaske et al., 2017), and thus, more quantitative, model-based assessment is required. Previous studies on modelling the multi-channel river systems mostly concentrated on vegetation-flow interactions (Schuurman et al., 2013; Marcinkowski et al., 2018b) and sediment transport (Nicholas et al., 2013). However, none of the studies investigated the impact of climate change on flow conditions, be means of hydrological modelling, which is crucial in light of long-term conservation programs for riverine ecosystems protection.

This study concentrates on the anastomosing river system in north-eastern Poland, where in recent decades significant loss of the anabranches has been observed (Marcinkowski et al. 2018a). The mechanisms controlling the loss were reported by Marcinkowski et al. (2017a) and attributed mainly to changes in flow conditions (Marcinkowski and Grygoruk, 2017), determined by different factors at catchment and reach scale. In the strictest sense, they observed that low water levels in anabranches facilitated sediment deposition and the colonization of common reed, while reduced high flows minimized sediment mobilization. Encroaching vegetation reduced flow efficiency and channel capacity, which in turn created perfect conditions for further reed colonization. After a few years, the former anabranch was eventually overgrown by reeds and disappeared completely. Therefore, as indicated by Marcinkowski et al. (2017a) low flow conditions are of special concern due to the fact that anabranches loss is recognized to be the most intensive during the summer season. In other study Marcinkowski et al. (2019) conducted an ex-ante model-based assessment of conservation measures efficiency, proposed in the protection plan (Mioduszewski et al. 2014) of the anastomosing section of the river in the Narew National Park (NNP). They indicated that the only way to maintain the anastomosing character of the river requires highly invasive engineering solutions (channel dredging and building water dams). However, before any implementation of engineering solution, which might cause serious ecological consequences in the protected area, a look ahead into potential flow changes caused by climate change projections is required. It might turn out that predicted increased precipitation in this part of Europe (Jacob et al., 2014), could potentially reverse the anastomosing system degradation, by increasing low flows in anabranches - the main factor responsible for channel extinction.

Against this background, the objective of this paper is to assess the impact of projected climate change on average flow conditions in the anastomosing section of the River Narew, with the focus on low discharges in the main channel and the anabranches, which are threatened of extinction. Soil and Water Assessment Tool (SWAT) for the Narew catchment is used and coupled with the HEC-RAS one-dimensional unsteady flow model, built for the anastomosing section of the river (where channel extinction process is recognized to be in progress), including main channel and the anabranch. The study looks into projected changes for two future time horizons within 21st century (2021–2050 and 2071–2100) under the Representative Concentration Pathway (RCP) 4.5, using an ensemble of nine EURO-CORDEX model scenarios (Jacob et al., 2014).

2. Materials and Methods

2.1 Site description

The Upper Narew is the sub-catchment of the largest Polish river basin - the Vistula (Figure 1). It drains area of 4231 km^2 (of which 27% belong to Belarus) and is characterized by a flat relief with an average elevation of 152 m a.s.l. The prevailing type of soils in the catchment are sands and loamy sands, whereas heavy, impervious soils are rare. The land cover in the Upper Narew catchment is predominantly forested (43.6%) and agricultural (41%), whereas wetlands and grasslands occupy 16% of the area. The catchment is located in a temperate climatic zone with moderately warm summers (mean temperature in July 18°C), cool winters (mean temperature in January -2ºC), and an annual average precipitation total of ca. 600 mm.

The Upper River Narew stretch, which was investigated in this study (Fig 1C), is characterized by low-gradient (0.0002 m/m) and average flow of 15 m^3/s. It is situated in the Narew National Park (NNP) for which Natura 2000 sites (under both Bird and Habitat directives) were established. Within the NNP (6810 ha), the river is characterized by a complex network of small interconnected channels (Gradziński et al., 2003). Vegetation cover within the NNP is dominated by early growth sedge and reed communities. This particular stretch has been selected for the analysis, as according to Marcinkowski et al. (2017a) the channel extinction process was recognized to be in progress there for last few years. It is worth noting that in current conditions during the growing season on average nearly 98% of the flow is concentrated in the main channel (right-hand side reach on Fig 1C) and only 2% is distributed to left-hand side anabranch. Such extremely low flows and unevenly distributed discharge create favorable conditions for vegetation encroachment and channel sedimentation, which in turn lead to the gradual closure of the side channels, what is observed in the field for the last few years.

2.3 Integrated modelling framework

IMF applied in this study consists of catchment scale SWAT model and river reach scale HEC-RAS model. Hydrological SWAT model driven by climate change projections was used for daily discharge calculations for the baseline and future time horizons (NF and FF). In the study, flow condition changes were assessed at two different spatial scales: (1) at catchment scale mean monthly flows were calculated (for all SWAT sub-basins) showing the general impact of climate change on water resources in the area and (2) at reach scale daily hydrographs were calculated for the particular reach (from the SWAT project) overlapping with the HEC-RAS hydraulic model most upper cross-section. This way SWAT-based simulations of daily flow could be directly transferred and routed in the HEC-RAS stream network (Fig.1C) as the flow hydrograph input, which allowed to assess the impact of climate change on hydraulic conditions in the anastomosing section of the River Narew. Due to the main goal of this research in hydraulic model, daily hydrographs covered only the summer and autumn months, when low flows prevail and trigger anabranch loss. The HEC-RAS model daily results were next reach-averaged discharge and flow velocity analyzed. Additionally, to assess not only the magnitude but also the duration of low flow conditions, hydrographs derived from SWAT were statistically examined. Given that the channel loss process is triggered by low flow conditions (Marcinkowski et al., 2017a) a threshold value has been defined based on the daily discharge observations from Suraż gauging stations (1952-2017), expressed as Q_{80} (with 80% exceedance probability). Taking into account the threshold for low flow ($7m^3/s$), for each climate model in the baseline, NF and FF horizons, number of days lower than Q_{80} were summarized.

2.4 SWAT

SWAT is a process-based, continuous-time model which simulates the movement of water, sediment, and nutrients on a catchment scale (Arnold et al., 1998). It is a comprehensive tool suitable for investigating the interaction between climate, land use and water quantity. It enables simulation of long-term impacts of climate changes on water, sediment, and nutrient loads in catchments with varied topography, land use, soils and management conditions. Spatially, the catchment area is divided into sub-basins and further into Hydrologic Response Units (HRU), which are the smallest spatially explicit units. Water balance as well as sediment and nutrient loads for each HRU are calculated at the land phase. Runoff and is further aggregated to the sub-basin level and routed through the stream network to the main outlet in order to obtain the total runoff for the river basin. In this study, we build upon the existing SWAT model of the Upper Narew catchment (Marcinkowski et al., 2016). While the full description of model setup, calibration and validation was presented in the latter study, here we provide a brief overview, important in the context of the main goal of the present paper.

2.4.1 Model setup, calibration and validation

Delineation of the catchment based on the 10-m resolution DEM resulted in division of the catchment into 243 sub-basins. Intersection of land cover map, soil map, and slope classes resulted in creation of 4509 HRUs. Daily precipitation and air temperature (minimum and maximum) data (1951–2013) were acquired from 5 km resolution gridded, interpolated using kriging techniques, dataset (CPLFD-GDPT5) based on meteorological observations coming from the Institute of Meteorology and Water Management (IMGW-PIB; Polish stations) (Berezowski et al., 2016). The use of interpolated climate data in the SWAT model, as reported by Szcześniak and Piniewski (2015) increased the model performance for a case study in Poland.

Calibration phase was conducted in SWAT-CUP using the SUFI-2 algorithm (Sequential Uncertainty Fitting Procedure Version 2) where the Kling–Gupta efficiency (KGE) was used as an objective function (Gupta et al., 2009). In the calibration and validation of the daily discharge, ten flow gauges (data acquired from IMGW-PIB) were used. Calibration period was set to 1976–1985, and the validation period was 1986–1991. Marcinkowski et al. (2016) reported satisfactory values of goodness-of-fit measures across for all gauging stations (median KGE above 0.7). Figure 2 depicts the observed vs simulated daily discharge in the Suraż gauging station (cf. Fig. 1), which is at immediate upstream to the HEC-RAS model created for the anastomosing section of the River Narew.

2.4.2 Climate change scenarios

In this study, SWAT was driven by climate forcing data from the CHASE-PL Climate Projections: 5-km Gridded Daily Precipitation & Temperature Dataset (Mezghani et al., 2016), consisting of nine bias-corrected GCM-RCM runs (involving four different GCMs and four different RCMs) provided within the EURO-CORDEX experiment projected to the year 2100 under RCP4.5 (Piniewski et al., 2017). All bias-corrected values (quantile mapping method by Norwegian Meteorological Institute, (Gudmundsson et al., 2012)) of precipitation and air temperature were available for three time slices: 1971–2000 (historical period), 2021–2050 (near future - NF), and 2071–2100 (far future - FF).

Projected mean annual temperature in the Upper Narew catchment is expected to increase by approximately 1.2°C in NF and 2.1°C in FF following the RCP4.5 according to the ensemble mean. Comparing the seasonal variation, the highest change is expected to occur in winter (2.4°C) and lowest in summer (1.7°C) (Marcinkowski et al., 2017b).

Annual total precipitation is projected to increase by 5.6% in the NF and by 9.5% in the FF, on the annual basis. The seasonal patterns show a relatively high increase in winter and spring and mixed response (both increase and decrease cases) in summer and autumn. In the FF the spring precipitation increase is distinctly higher than in other seasons, exceeding 20% (Marcinkowski et al., 2017b) (Fig 3).

2.5 HEC-RAS

HEC-RAS is a well-known hydrodynamic model for one and two-dimensional hydraulic calculations and is often used in calculating both steady and unsteady, gradually varied flow (Dysarz et al., 2019, Horrit and Bates, 2002). In addition, the HEC-RAS system solves movable boundary sediment transport computations and water quality analysis. In 1D hydrodynamic component model solves the full 1D St Venant equations for unsteady open channel flow with the finite difference method and using a four point implicit box scheme (Brunner, 2016). In calculation the Manning's *n* roughness coefficients are used in description of resistance of river for water flow and these friction coefficients are left as a calibration parameter. HEC-RAS is intended to perform hydraulic calculations for a full network of natural and constructed channels. Depending on the type of reach junction (flow split or flow rejoin) in a river network one equation of continuity of flow or equation continuity of stage is used as an interior boundary equations.

2.5.1 Fieldwork and data collection

HEC-RAS model setup is strongly dependent on geometric and hydrological data. Geometric data consisted of river cross-sectional geometry collected at periodic, uniformly distributed (250 m intervals) stations along the selected, anabranching reach. Cross-sectional data was collected using Real-Time Kinematic GPS (GPS-RTK). Actual water surface profiles for investigated study reach at low flow rates was surveyed in the summer season. It was accomplished by surveying the water surface elevation at each cross-section using the GPS-RTK. Discharge was measured using a hand-held electromagnetic water flow meter at two river reaches (main channel and anabranch). The collected cross-sectional data, water surface level and discharge were used for model setup, calibration and validation.

2.5.2 Model setup calibration and validation

Hydrodynamic model of the Narew River water flow was performed in HEC-RAS model. In the hydrodynamic model, the river network was reproduced using four river reaches (cf. Fig. 1C). The NG segment covers the upper section of the river from the cross section located at 05 + 470 km to the split of flow at a channel junction to reaches NR and NL, which represent the main Narew channel and its anabranch, respectively. Both sections are then combined in the ND segment (cf. Fig. 1C). In the model, the NG reach has 400 m of length and was presented through 9 calculation cross-sections. The NR segment with a length of 3.69 km is represented by 75 cross sections, and the NL oxbow lake with a length of 4.715 km is described in the model with 95 cross-sections. The ND segment ending the analyzed river network is 1.365 m long and consists of 28 cross-sections. In the model, the average distance between calculation cross-sections is about 50 m. The upper boundary condition is formulated in the form of a flow hydrograph. The rating curve describes downstream boundary condition. The calibration and validation of the model was performed for vegetation period. The Manning's *n* roughness coefficients were calibrated for four river reaches. The "trial and error" method was used to obtain the smallest differences between the simulated and observed the water table and the measured and simulated mean water velocity at 9 measurement points in ND, NR and NL sections (cf. Fig. 1).

3. Results

3.1 Catchment scale hydrological response to climate change

SWAT model simulations indicate that at the catchment scale the median of projected changes in average water discharge, at the annual basis, is expected to increase in the catchment by 11% and 25% in the NF and FF, respectively. Seasonal patterns showed the most pronounced increase occurring in winter and spring, with the ensemble median reaching 17% and 35% for NF and FF, respectively. During summer and autumn significantly lower increase in discharge is observed, reaching 7% and 23% for the NF and FF, respectively (Fig 4). Additionally, more extreme and outlying values (both low and high) are noted for the future time horizons, compared to historical period.

3.1 HEC-RAS model performance

A simulated split flow at channel junction was compared with observed in the NR and NL reaches. In the calibration process for a discharge 7.4 m^3/s, the error of the flow distribution is 0.7% and 11% for section NR and NL respectively. The average error of the water table in the river reaches varies from 0.03 m to 0.05 m. The mean error of simulated water velocity is 6%, 7%, 14% for the ND, NR and NL segments respectively (Table 1). The model accuracy discussed above was obtained for the following set of Manning's coefficients: $n_{NG} = 0.028$; $n_{NR} = 0.028$; $n_{NL} = 0.1$; $n_{ND} = 0.035\ m^{-1/3}/s$. These values are similar to the roughness coefficients used in other models for the analyzed section of the Narew River (Marcinkowski et al., 2018b). Verification of the developed model was based on measurements of the water level and water velocity performed at a discharge 10.5 m^3/s. In this case, the errors for the flow distribution are 0.9% and 9% for the sections NR and NL respectively. The average error of the water table varies from 0.04 m to 0.07 m. The mean error of simulated water velocity is 7%, 3%, 9% for the

ND, NR and NL river reaches respectively (Table 2). The obtained errors allow to use of the model to simulate the unsteady flow in vegetation period. Then the developed hydrodynamic model was used to simulate the flow for the long historical period 1973-2000 and climate change scenarios for years 2070-2100. In these simulations, the upper boundary condition in the form of a flow hydrograph was calculated in the SWAT hydrological model.

3.2 Reach scale flow condition changes

At the reach scale the flow condition changes were calculated based on the SWAT model simulations for particular sub-basin, that spatially overlaps with the HEC-RAS hydraulic model. As indicated in Figure 5 the duration of low flows changes significantly comparing historical period and future horizons. However, the change is not uniform across the year and varies notably between each month and projected period. In general, for winter and spring season a clear drop in the duration of low flows in observed reaching 30% and 50% (ensemble median) for NF and FF, respectively. However, for summer and autumn months (August - October) for the NF slight increase in duration of low flows is noted (8%). Such trend subsides in FF where again the decrease is observed, but significantly lower than for winter, reaching only 20%.

Further analysis included assessment of low flow magnitude changes, modelled in HEC-RAS using daily flow hydrographs derived from SWAT for summer and autumn seasons. Reach-averaged discharge and flow velocity is presented separately for the main channel and the anabranch. Simulations derived from SWAT indicate that in NF for both discharge rate and mean flow velocity slight drop is noted (8% for ensemble median). However, the direction of change shifts for FF, when a slight decrease is observed (5% for ensemble median). The occurrence of extreme and outlying discharges escalates only for FF horizon (Fig 6). Based on T-student test NF changes of discharge and flow velocity were not statistically significant (p value equaled 0.16 and 0.15, respectively) and the FF changes were statistically significant (p value equaled 0.0001 and 0.001, respectively).

4. Discussion

4.1 Advantages of cascade modelling

Riverine ecosystem managers face increasing need of incorporation of climate change signals in the conservation programs and protection plans. However, successful climate change adaptation requires actions at the appropriate temporal and spatial scales (Pletterbauer et al., 2018). In fact, the issue of scale is nowadays one of the most challenging aspects (Wiens and Bachelet., 2010). It is obvious that Regional Climate Model (RCM) data which is downscaled from General Circulation Models (GCM) operates at coarse scale and cannot be directly used for conservation planning at river reach scale. At large scale, mathematical modelling, with a notable use of spatially-distributed models of intermediate complexity, is the most feasible approach to establish projections of climate change impacts on freshwater resources (Krysanova et al., 2016). However, most commonly in river conservation programs particular river reaches of fine scale are targeted. Therefore, in this study simulations of climate change signal modelled in catchment-scale hydrological SWAT model were incorporated to river reach HEC-RAS model. The undeniable advantage of such approach is evident in the direct comparison of catchment scale and reach scale flow simulations. While the catchment-averaged discharge is predicted to increase for summer and autumn season, reach scale hydrographs routed in HEC-RAS indicate a low decrease in the NF and slight increase for FF horizon. It is due to the fact that topography, soil retention properties and land cover varies across the Upper Narew catchment and affects the river flow differently at different sections along the river. The second reason might be attributed to evapotranspiration increase in the catchment caused by temperature increase and vegetation development in future horizons. It is in line with findings of Junk et al. (2012) who stated that water input from increased precipitation in northern Europe will be offset by the effects of increased evapotranspiration. Given that in the vast majority of studies flow alterations driven by climate change are described by catchment-averaged characteristics (Krysanova et al., 2016), possibly incorrect findings could be drawn concerning the water resources at particular river section.

It is obvious that climate change must be integrated into conservation planning and management. However, it requires the use of proper datasets and tools to avoid misjudged reasoning on potential climate change impact on water resources. Taking the example of the Upper Narew catchment, where precipitation and temperature is projected to increase in future horizons, one could deduce that probably water flow would increase, which in the light of actual results presented in this study is not true. Even the use of hydrological process-based model which solves land phase of the water balance under consideration of daily precipitation, evapotranspiration, runoff components and soil water storage could lead to first conclusion that mean discharge at the basin level will increase. Those findings when taken into account during preparation of conservation plan for the anastomosing section of the river Narew could suggest to not use technical and engineering measurers as water resources are projected to increase. It proves the importance of scale (Wiens and Bachelet., 2010) which is different for RCMs applied at catchment scale and local river conservations plans corresponding to reach-scale hydraulic models.

4.2 Anastomosing river perspectives under climate change

As reported by Marcinkowski et al. (2017a) low flow is the main stressor triggering the loss of anastomoses. In this study it was analyzed in terms of duration and magnitude. Results showed that the number of days with low flows increased for NF and mean daily discharge in summer decreased, which escalates the stressing conditions for this time horizon. HEC-RAS simulations of water flow conditions in the anastomosing sections of the river Narew indicate very low flow velocity (0.09 m/s ensemble median) in the anabranch, which decreases in NF (0.08 m/s ensemble median) and only slightly increases in FF (0.1 m/s ensemble median). Considering the mechanism of anabranches loss presented by Marcinkowski et al. (2017a, 2018b) such hydraulic conditions nowadays and under future projections are preferable for in-stream vegetation development. Typically the abundance of macrophytes are stimulated at low velocities and their growth is restricted at higher velocities. It is due to the fact that water velocity affects photosynthesis through the regulation of the availability of dissolved substances (Madsen et al., 2001). It has been reported that the photosynthetic and nutrient uptake rates of in-stream macrophytes are positively correlated with low water velocities (0–0.1 m/s) (Marshall and Westlake, 1990; Madsen et al., 2001). The prospect of further reduction of river flow velocity in NF horizon suggest further degradation on anastomosing system in coming decades.

One of the major issues in freshwater ecosystems conservation is that the adaptive management must be applied on time to be useful. However, delayed detectability of a climate change signal might cause it comes too late, and hence some degree of anticipation is required. It is well known that the climate models themselves are to some extent uncertain (Maslin and Austin, 2012) albeit reasonable conservation management may consider the use of model projections to guide future interventions. In anastomosing Narew case the simulations at reach scale that were run under consideration of climate projections and process-based catchment modelling, indicate that most possibly by the end of 2050 (NF) water resources will slightly decline. As reported by Marcinkowski et al. (2017a) current flow conditions trigger channel loss through plants overgrowing and river bed aggradation. Simulations which show low flows decrease in NF might only escalate and accelerate the process. From the perspective of anastomosing river conservation, predicted future flow alterations are therefore disadvantageous. It is most likely that findings presented by Marcinkowski et al. (2019) are relevant and the only way to maintain the anastomosing character of the river requires invasive hydro technical solutions.

5. Conclusion

In this study we examined the climate change impact on average flow conditions in the anastomosing section of the River Narew, which is subject to gradual degradation caused by vegetation encroachment and bed aggradation. Cascade modelling has been conducted using catchment scale Soil and Water Assessment Tool (SWAT) model for the Narew catchment coupled with the HEC-RAS one-dimensional unsteady flow model. Using the EURO-CORDEX experiment projections we looked into changes for two future time horizons within 21st century (2021–2050 and 2071–2100) under the Representative Concentration Pathway 4.5. Flow hydrographs derived from SWAT model were routed in the HEC-RAS stream domain. At catchment scale, average daily discharge was predicted to increase for summer and autumn season. However, reach scale simulations indicated a low decrease in the NF and slight increase for FF horizon, which proves the importance of topography, soil retention properties and land cover which vary across the catchment causing different hydrologic response at different sections along the river. Hydraulic modelling indicated extremely low flow velocities in the anastomosing arm (<0.1 m/s) nowadays and under future projections which is preferable for in-stream vegetation development, as typically the abundance of macrophytes are stimulated at low velocities and their growth is restricted at higher velocities. The perspective of further degradation on anastomosing system in coming decades requires actions to be undertaken by freshwater ecosystem managers. Our study, although burdened with limitations and uncertainties might serve as a reference for expected future flow conditions.

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Figure 1

Case study (A- location , B-land use, C-river network, D- vegetation type

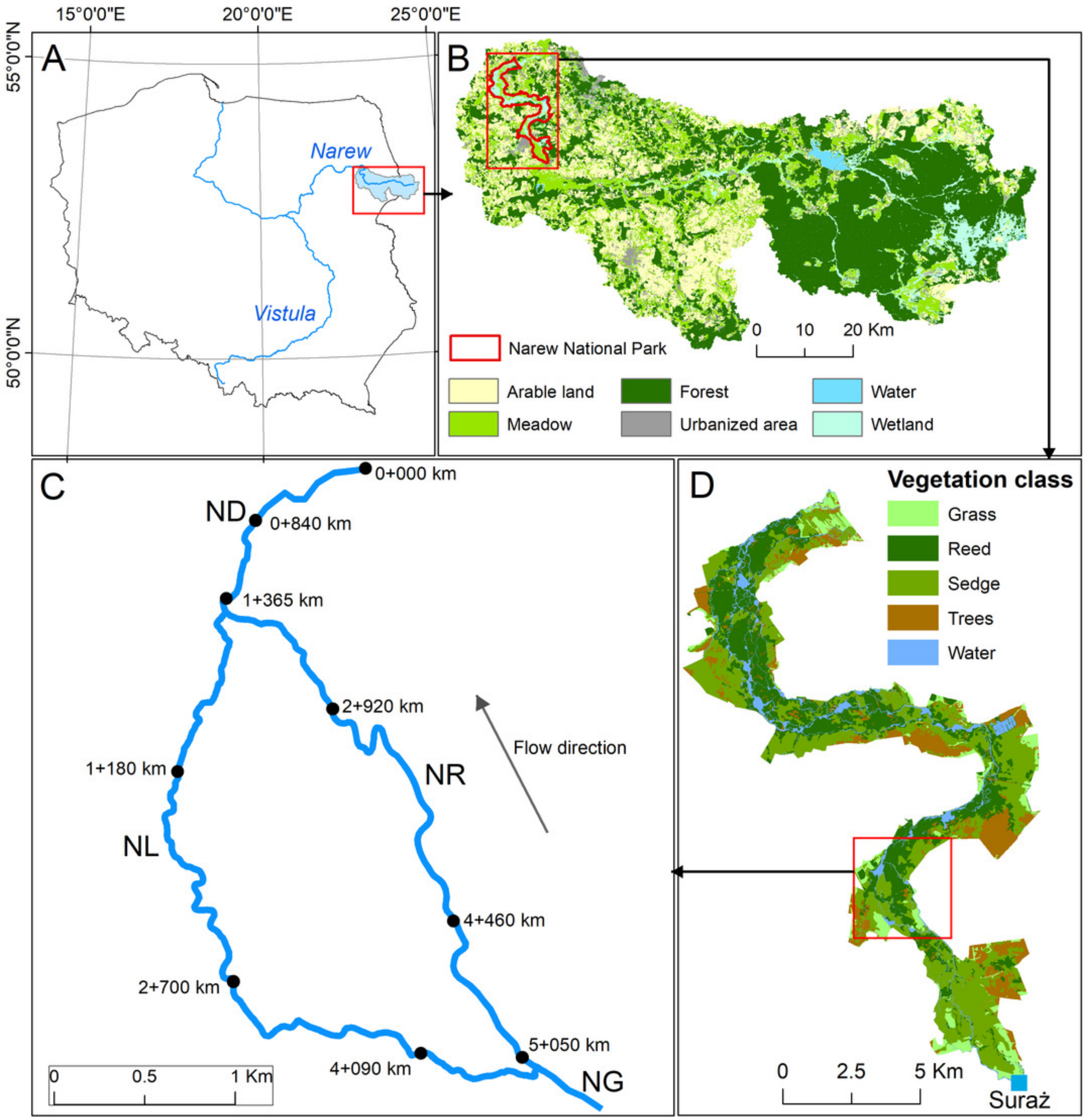


Figure 2

Observed vs simulated discharge in the Suraż gauging station in the calibration and validation period

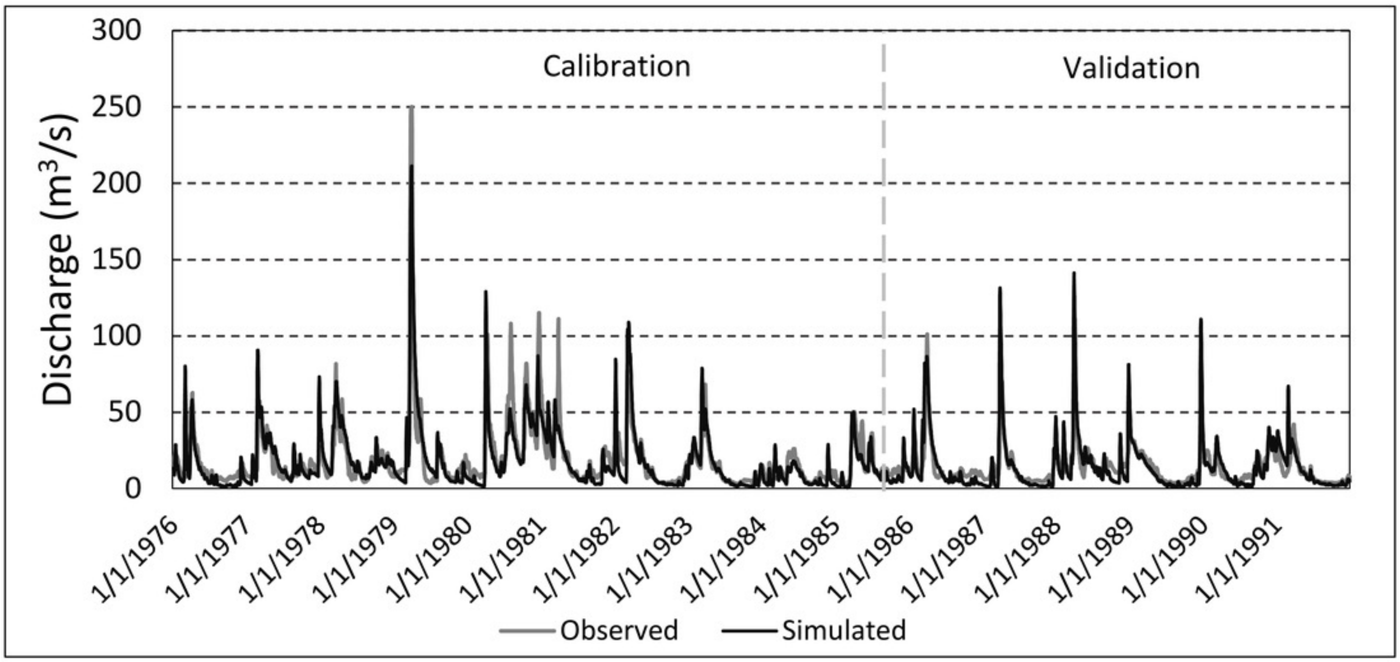
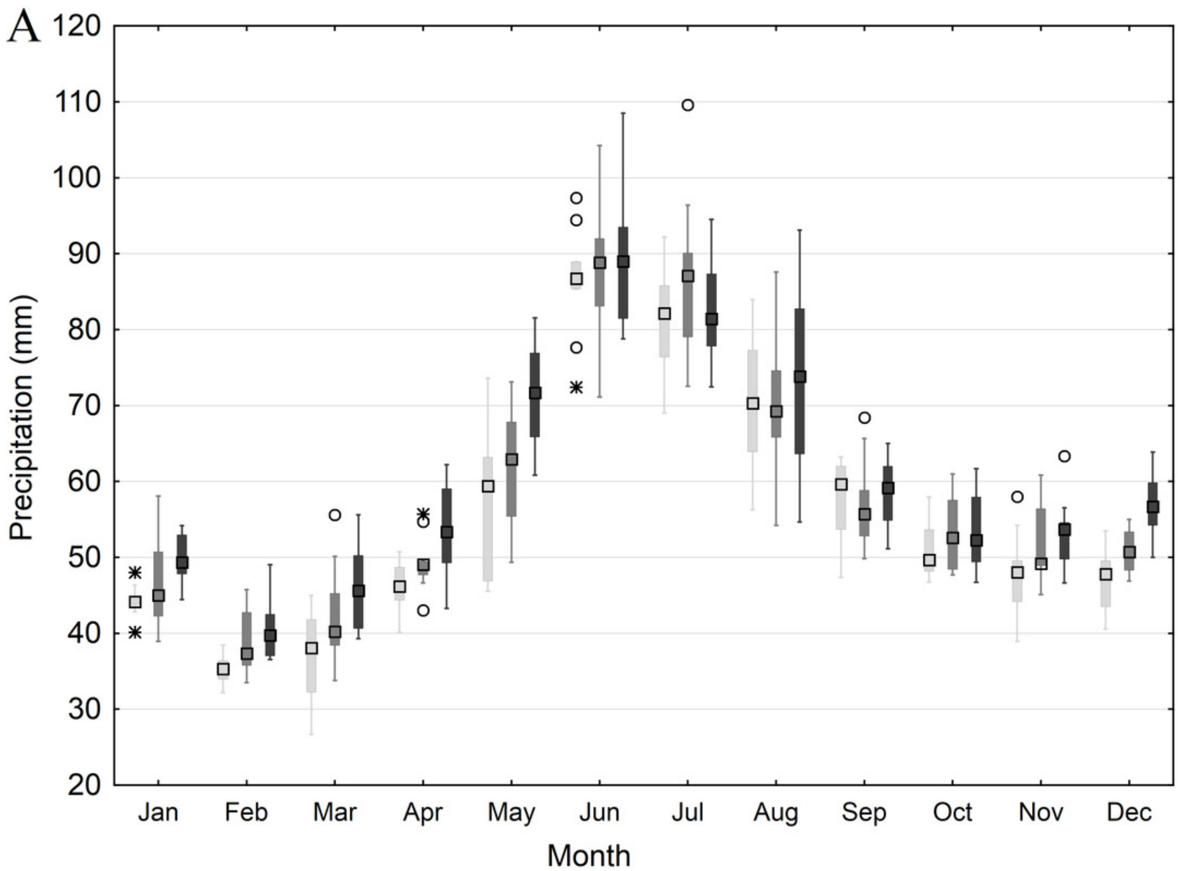


Figure 3

Projected mean monthly (A) sum of precipitation and (B) temperature in the Upper Narew catchment

Light grey color denotes baseline, medium grey – NF and dark grey – FF horizon; squares denote median values, boxes – 1st to 3rd quartile values, whiskers – non outlier range, circles – outliers, asterisk – extremes


A
Precipitation (mm)
120
110
100
90
80
70
60
50
40
30
20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month

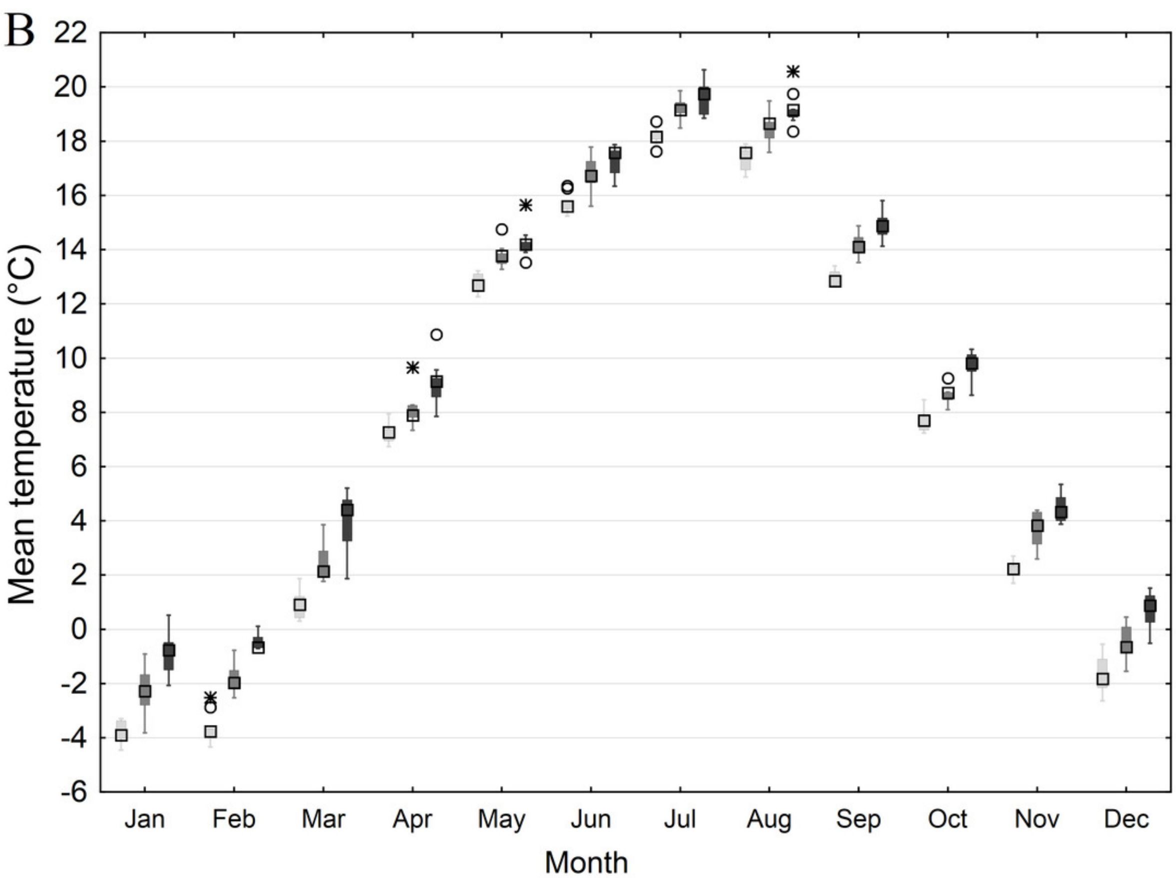

B
Mean temperature (°C)
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month

Figure 4

Simulated mean monthly discharge at the main outlet of the Upper Narew catchment

Light grey color denotes baseline, medium grey – NF and dark grey – FF horizon; squares denote median values, boxes – 1st to 3rd quartile values, whiskers – non outlier range, circles – outliers, asterisk – extremes

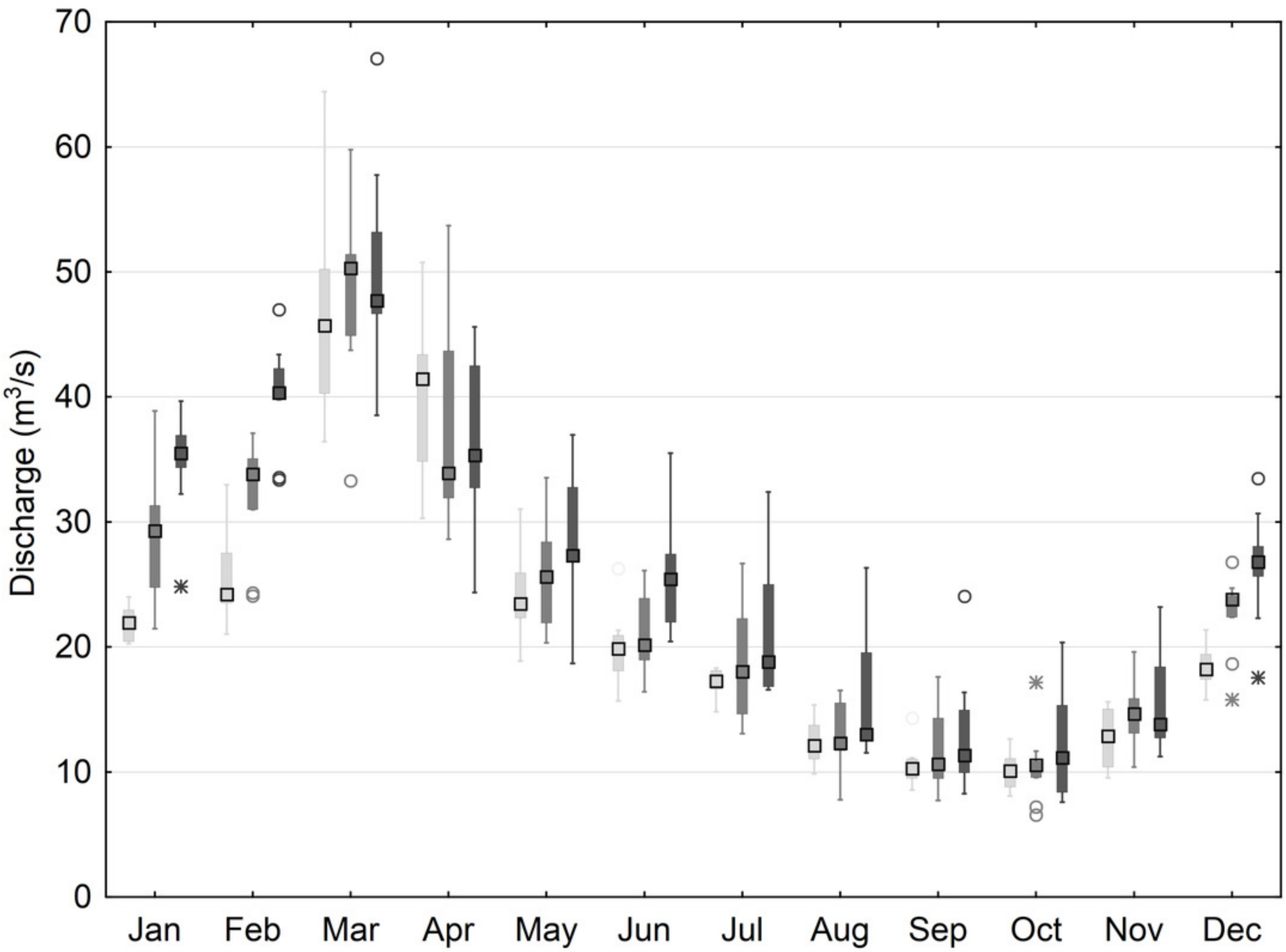


Figure 5

Yearly mean number of days with low discharge ($Q<Q_{80}$) for the anastomosing reach of the River Narew based on SWAT simulations

NOD stands for number of days, light grey color denotes baseline, medium grey – NF and dark grey – FF horizon; squares denote median values, boxes – 1st to 3rd quartile values, whiskers – non outlier range, circles – outliers, asterisks – extremes

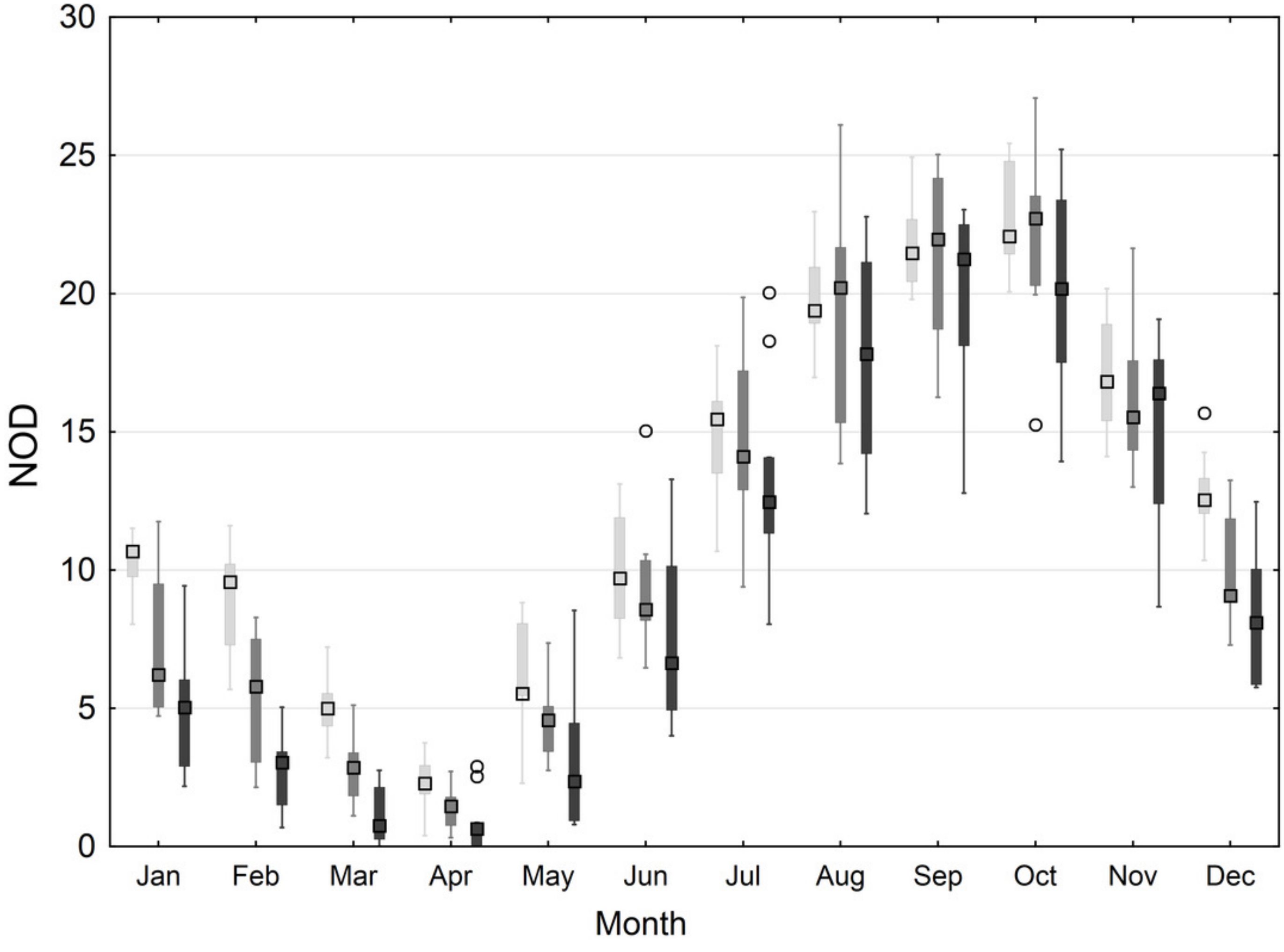


Figure 6

HEC-RAS model simulations of hydraulic condition changes in the main channel (B,D) and the anabranch (A,C)

Squares denote median values, plus marks – mean values, boxes – 1st to 3rd quartile values, whiskers – non outlier range, circles – outliers, asterisks – extremes

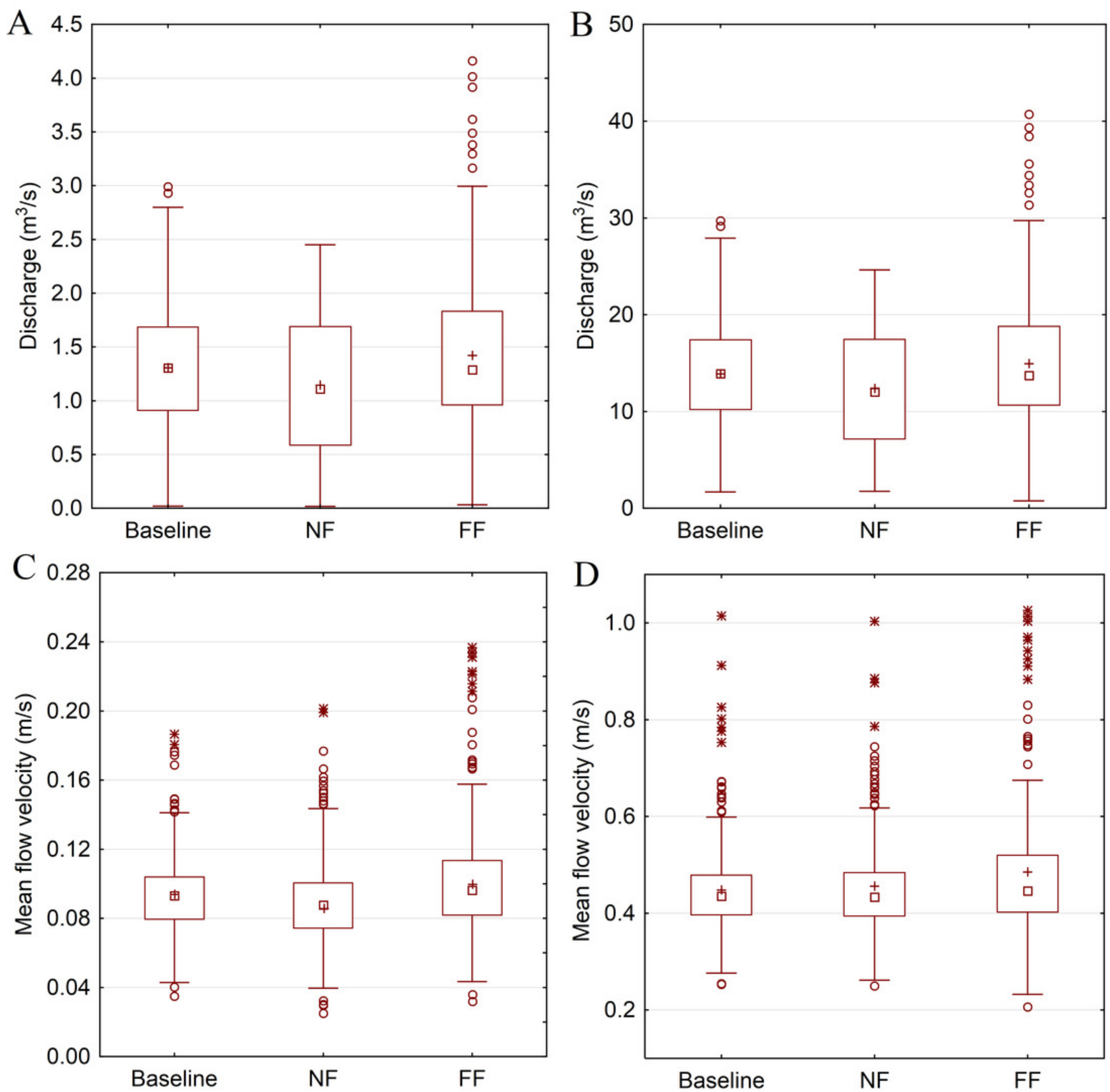

A
B
C
D
Discharge (m³/s)
Mean flow velocity (m/s)
Baseline
NF
FF

Table 1 (on next page)

Model errors (validation run Q=7.4 m^3/s)

Q –discharge, E – mean error in river reach, index m – model result, v – velocity, H – water level

Reach	km	Q [m^3/s]	Q_m [m^3/s]	E_Q [m^3/s]	H [m a.s.l]	H_m [m a.s.l]	E_H [m]	V [m/s]	V_m [m/s]	E_v [m/s]
ND	0+000	7.4	7.40	0.0	115.18	115.16	0.05	0.43	0.46	0.02
	0+840				115.38	115.42		0.41	0.43	
	1+365				115.48	115.57		0.40	0.42	
NR	2+920	6.95	6.85	0.1	115.79	115.83	0.03	0.36	0.38	0.03
	4+460				116.09	116.07		0.37	0.41	
	5+050				116.20	116.16		0.35	0.33	
NL	1+180	0.45	0.55	0.1	115.66	115.71	0.04	0.04	0.05	0.01
	2+700				115.89	115.93		0.07	0.08	
	4+090				116.10	116.06		0.05	0.06	

Table 2(on next page)

Model errors (validation run Q=10.5 m^3/s)

Q –discharge, E – mean error in river reach, index m – model result, v – velocity, H – water level

Reach	km	Q [m³/s]	Q$_m$ [m³/s]	E$_Q$ [m³/s]	H [m a.s.l]	H$_m$ [m a.s.l]	E$_H$ [m]	V [m/s]	V$_m$ [m/s]	E$_v$ [m/s]
	0+000				115.45	115.42		0.47	0.49	
ND	0+840	10.5	10.5	0	115.64	115.68	0.04	0.44	0.47	0.03
	1+365				115.78	115.82		0.41	0.45	
	2+920				116.10	116.07		0.40	0.42	
NR	4+460	9.55	9.64	0.08	116.36	116.30	0.07	0.41	0.41	0.01
	5+050				116.49	116.38		0.39	0.38	
	1+180				115.92	115.95		0.07	0.06	
NL	2+700	0.95	0.87	0.09	116.12	116.14	0.04	0.10	0.09	0.01
	4+090				116.34	116.28		0.09	0.08	