Proceedings of the 2011 International SWAT Conference & Workshops - Toledo, Spain.

Effect of Climate Change on Environmental Flow Indicators in the Narew Basin, Poland

Piniewski Mikołaj*
PhD student, Department of Hydraulic Engineering, Warsaw University of Life Sciences, Nowoursynowska Str. 159, 02-787 Warszawa, Poland, mpiniewski@levis.sggw.pl;
*corresponding author
Laizé, Cédric L.R.
Researcher, Centre for Ecology and Hydrology, Wallingford, Maclean Building, Crowmarsh Gifford, OX10 8BB, UK;
Acreman, Michael C.
Professor, Centre for Ecology and Hydrology, Wallingford, Maclean Building, Crowmarsh Gifford, OX10 8BB, UK;
Okruszko, Tomasz
Professor, Department of Hydraulic Engineering, Warsaw University of Life Sciences, Nowoursynowska Str. 159, 02-787 Warszawa, Poland;
Schneider, Christof
PhD student, Center for Environmental Systems Research, University of Kassel, Kurt-Wolters-Strasse 3
34109 Kassel, Germany.

Abstract

This paper discusses the effect of climate change on environmental flows in the semi-natural lowland rivers in north-eastern Poland. The analysed rivers belong to the Narew basin occupying ca. 28.000 km^2. This region is known for its valuable river and wetland ecosystems, many of them in pristine or largely un-impacted conditions. Although many factors have influence on the state of these types of ecosystems, it has recently been widely accepted that flow regime is a key driver. This has led to the development of the environmental flows concept. The objective of this study was to assess changes in environmental flow regime of the Narew river system, caused by climate change, as simulated by hydrological models with different modelling scale: (1) Soil & Water Assessment Tool (SWAT), a river basin scale model; (2) WaterGAP, a global model of water availability and use. The main feature differentiating these models is the level of spatial aggregation of hydrological processes. Both models were run using consistent climate change forcing, in terms of monthly precipitation and temperature changes projected from two General Circulation Models (GCMs) coupled with the A2 emission scenario: (1) IPSL-CM4 from the Institute Pierre Simon Laplace, France; (2) MIROC 3.2 from the Center for Climate System Research, University of Tokyo, Japan. To assess the impact of climate change on environmental flows, we used a method based conceptually on the Range of Variability Approach (RVA) using Indicators of Hydrological Alteration (IHA), a desk-top technique for assessing if environmental flow requirements are met. Preliminary results indicate that environmental flow regime in the Narew basin is subject to climate change risk, whose magnitude varies with climate model and hydrological modelling scale.

Keywords: environmental flows, SWAT, WaterGAP, climate change

Introduction

Among various factors that determine the health of a river ecosystem and its ability to deliver ecosystem services, discharge (flow [m^3s^{-1}]) is one of the most important ones (Norris and Thomas, 1999) and is sometimes called a ‘master variable’ (Power et al., 1995) that shapes many fundamental ecological characteristics of riverine ecosystems. The quantity of water required to maintain a river ecosystem in its desired state is referred to as the environmental flow (http://www.eflownet.org/). The first environmental flows were focused on the concept of a minimum flow level; based on the idea that all river health problems are associated with low flows and that, as long as the flow is kept at or above a critical level, the river ecosystem will be conserved. This perspective is still vital in Poland, where one of the most widely used environmental flow methods sets a single value below which biological life in the river is threatened (‘hydrobiological criterion’) or fish survival is at risk (‘fishing criterion’) (Kostrzewa, 1977; Witowski et al., 2008). However, it is increasingly recognised that all elements of a flow regime, including floods, medium and low flows are important (Richter et al., 1996, Poff et al., 1997).

In the north-east, lowland part of Poland, many of the rivers are in semi-natural state and the surface water abstractions for agriculture, industry and human needs are not as significant as elsewhere (Piniewski et al., 2011a). Hence, the river and floodplain ecosystems requirements should be of high priority to water managers in this region. The Earth’s warming climate, “now evident from observations of increases in global air and ocean temperatures, widespread melting of snow and ice, and rising global sea level” (IPCC, 2007), also observed in Poland (Maksymiuk et al. 2008; Marszelewski and Skowron, 2006), may alter the flow regime significantly and in consequence may pose a serious threat to the river and floodplain ecosystems. Indeed, Poff and Zimmerman (2010) in their comprehensive review of ecological responses to altered flow regimes found out that of the 165 papers analysed, 152 reported decreased values for recorded ecological metrics in response to a variety of types of flow alteration. Acreman et al. (2009) showed that the projections of reduced summer precipitation and increased evaporation will put stress on floodplain wetland plant communities in the UK. The study of Laizé et al. (2010) suggested that climate change can impact European river ecosystems through flow alterations to a large extent.

A well-established quantitative method of estimating impact of climate change on hydrological systems is to use the output from the General or Regional Circulation Models (GCMs/RCMs) as the input to hydrological models (Fowler et al., 2007). The size of the study area often determines the tools applied for this purpose. In the case of regional perspective (the order of magnitude of 10,000 km^2) two types of distributed physically-based models are of particular interest:

1. Catchment-scale models, such as SWAT (Soil and Water Assessment Tool), cf. Arnold et al., 1998, Neitsch et al., 2005.
2. Global or continental hydrological models, such as WaterGAP (Water - Global Assessment and Prognosis), cf. Döll et al., 2003; Alcamo et al., 2003.

Using models from the first group often enables to create more fit-for-purpose model setup, with extensive local datasets and to perform more sophisticated calibration, for the trade-off of time and money necessary to perform the whole study. The models from the second group usually use readily available global datasets and their calibration is not oriented towards individual river basins. Gosling et al. (2011) reported that it is equally feasible to apply the global hydrological model Mac-PDM.09 (Gosling and Arnell, 2011) as it is to apply a catchment model to explore catchment-scale changes in runoff due to global warming from an ensemble of GCMs.

The objective of this study is to analyse the effect of climate change on environmental flow indicators in a semi-natural river basin using distributed models with different degrees of spatial aggregation. This study is a follow-up to the study of Piniewski et al. (2011b) who compared the effect of using SWAT or WaterGAP in the climate change impact assessment on runoff. The conclusion of the latter study was that while the global model was capable to produce results comparable to the catchment model in terms of more generic indicators such as mean annual runoff, direction of change in monthly runoff or shift in peak runoff, differences in magnitudes of projected changes in monthly runoff were clearly present. In the current study the focus is on indicators more relevant for the needs of the water-dependent ecosystems and the approach is more spatial than in the previous one.

Data and Methods

Study area

The River Narew upstream of Zambski Kościelne gauging station is situated in north-east of Poland (Fig.1) and its basin area occupies ca. 28,000 km^2. The rivers of the Narew basin are typical lowland rivers with low slopes and large floodplains. The climate of this part of Poland is moderately warm with annual mean precipitation of ca. 600 mm. Peak runoff usually occurs in rivers after snow thawing in early spring. The dominant soil types are loamy sands, sandy loams and organic soils, whereas the dominant land use is agriculture (46% as arable land and 17% as grassland). The Narew basin is lowly impacted by anthropogenic pressure. The population density is estimated at 59 people per km^2 only (the whole of Poland has a population density of 119 people per km^2). Many of its river valleys are in close to natural state and protected as either national parks or Natura 2000 sites. Further description of the Narew basin was provided by Okruszko and Giełczewski (2004) and more recently, with the emphasis on ecological data on fish and floodplain wetlands, by Piniewski et al. (2011a).

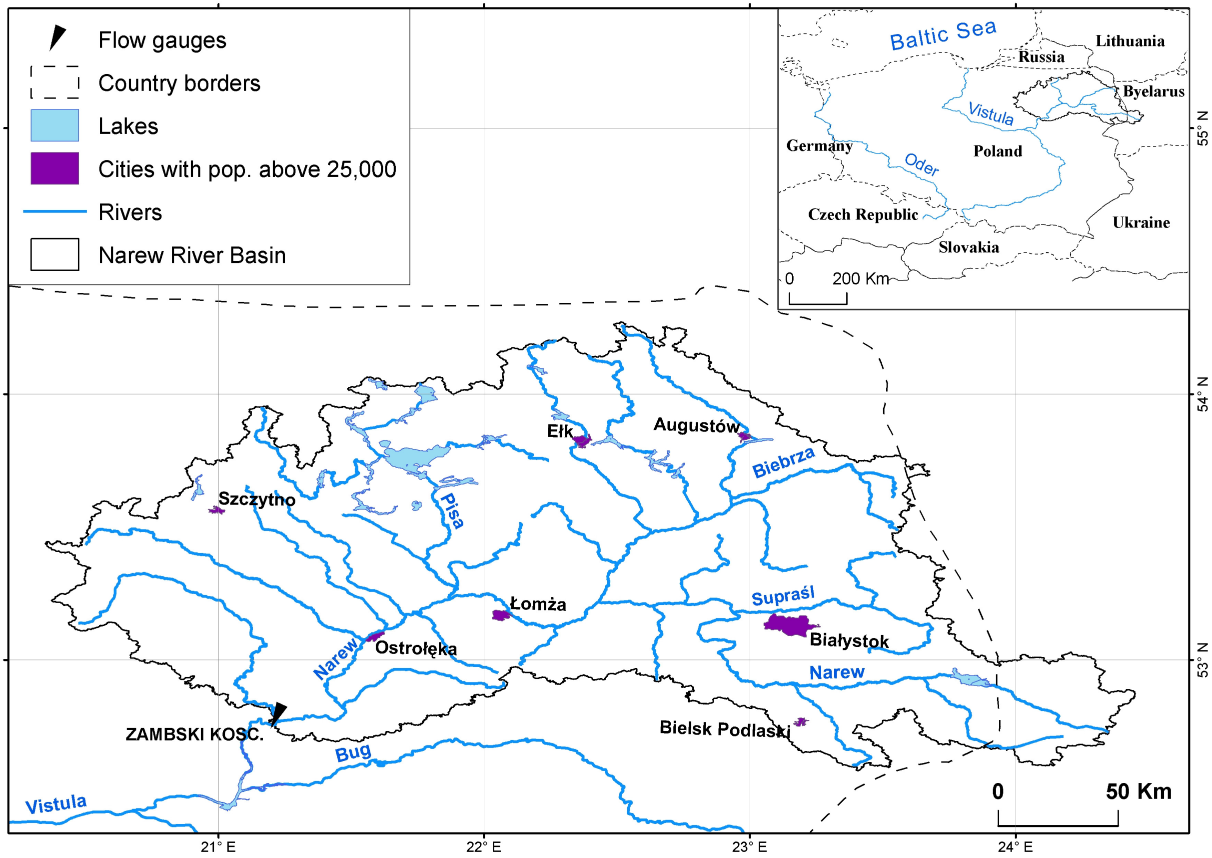


Fig. 1. Map of the study area.

Hydrological models

The catchment-scale model used in this study was the SWAT model (version SWAT2005), developed at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA (Arnold et al., 1998; Neitsch et al., 2005). The global-scale model used was the WaterGAP model, developed at the Center for Environmental Systems Research, University of Kassel, Germany (Döll et al., 2003; Alcamo et al., 2003). It comprises two components: a Global Hydrology Model to simulate the terrestrial water cycle and Global Water Use Model to estimate water consumption and withdrawals of different water use sectors. In this study the latter component was not used, since water use is not an important issue in the Narew basin.

Piniewski et al. (2011b) compared the modelling approaches and main inputs used for the Narew case study in SWAT and WaterGAP. SWAT is a physically-based tool, although it uses many conceptual modelling approaches such as the US SCS curve number method. In SWAT a river basin is subdivided into sub-catchments (each comprising a single river reach) which are further subdivided into hydrological response units (HRUs), obtained through overlay of land use, soil and slope maps in each sub-catchment. In this study the setup of SWAT elaborated by Piniewski and Okruszko (2011) using 151 sub-catchments and 1,131 HRUs was used. In the latter study spatially distributed calibration of SWAT in the Narew basin proved its capability to simulate daily flows in a satisfactory way. The version of WaterGAP applied in this study (i.e. WaterGAP3) works with a spatial resolution of 5 by 5 arc minutes (~6 x 9 km in central Europe) which is an upgrade compared to the previous version used in Alcamo et al. (2003) and Döll et al. (2003) and one of the finest resolutions of global hydrological models (cf. Haddeland et al., 2011). WaterGAP was not calibrated intentionally for the Narew basin, but was applied with its default global settings obtained from the global calibration process. One of the calibration points was the Global Runoff Data Centre station Ostrołęka (GRDC ID 6458810) situated in the lower Narew. In this study SWAT was driven with daily climate input, whereas WaterGAP with monthly input, which needed to be downscaled to daily inputs using statistical methods. We used monthly outputs from both models in the analyses.

River flow as the model output is calculated for individual grids in WaterGAP and for outlets of river reaches in SWAT. Output from all 151 SWAT outlets and from a subset of 85 WaterGAP grid cells representing major rivers in the Narew basin was used for analysis. In order to enhance statistical analysis of environmental flow indicators using output from both models, a one-to-one relationship between the WaterGAP grid cells and the SWAT outlets of river reaches was established. 58 pairs were distinguished based on comparative analysis of drainage topology and upstream catchment areas in WaterGAP and SWAT (Fig. 2). Due to simplified drainage topology of WaterGAP (based on the global drainage direction map DDM5, Döll and Lehner 2002) and irregular size of river reaches in SWAT, the coupling was arbitrary in several cases.

Climate models

The climate change forcing was derived from the output of two GCMs for the time period 2040-2069, hereafter referred to as the 2050s: IPSL-CM4 from the Institute Pierre Simon Laplace, France (Marti et al., 2005) and MIROC 3.2 from the Center for Climate System Research, University of Tokyo, Japan (Hasumi and Emori, 2004), both forced by the SRES-A2 emission scenario (IPCC, 2007). Monthly precipitation and temperature derived from these GCMs was downscaled to a finer resolution using a simple bilinear interpolation approach. To reduce the GCM biases, the delta-change approach was applied. This simple bias correction method builds on the assumption that GCMs more accurately simulate relative changes than absolute values (Fowler et al., 2007). The baseline period for simulations in WaterGAP was 1961-90 and for the simulations in SWAT it was 1976-2000.

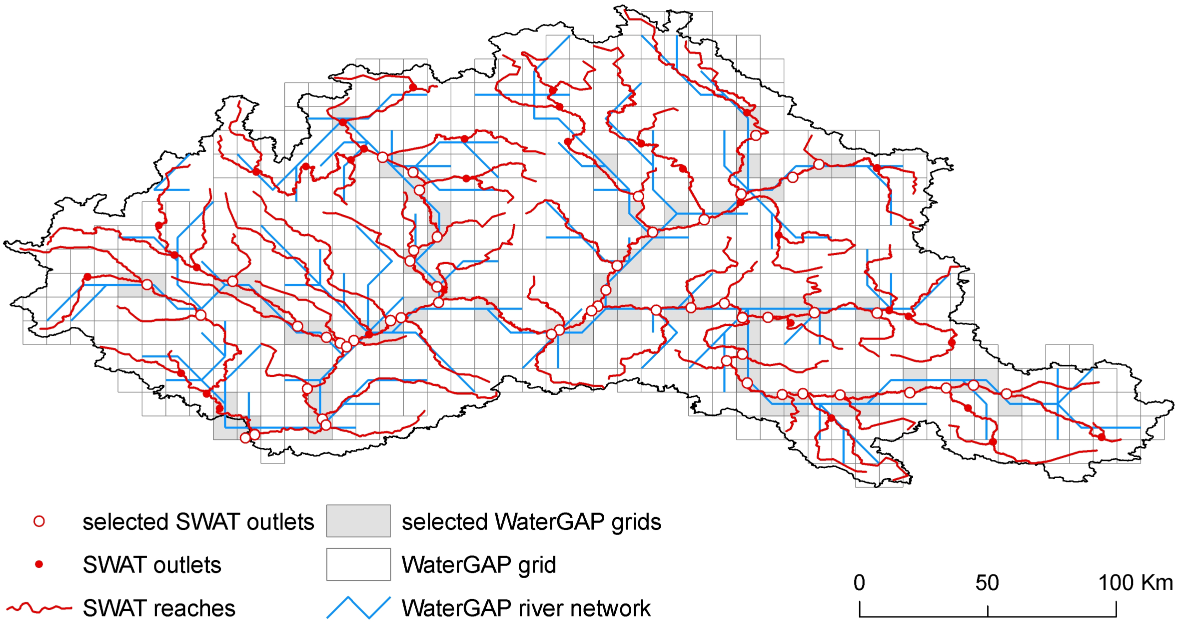


Fig. 2. Selected pairs of SWAT river reach outlets and WaterGAP grids.

Both climate models project similar increase in mean annual basin-averaged temperature, however the seasonal variability of this increase is different (Fig. 3a). Regarding basin-averaged precipitation, the uncertainty of climate model projections is high (Fig. 3b). According to MIROC3.2, there is an 11% increase in annual precipitation whereas according to IPSL-CM4 there is no change. However, the within-year changes vary considerably between the models. For instance, two periods can be found where MIROC3.2 projects a large increase and IPSL-CM4 a little change or a decrease in precipitation: (1) from March to April; (2) from August to October. It is worth to note that despite of differences in magnitude and seasonal variability in precipitation projections, there is a good agreement in spatial gradient of projected changes in mean annual precipitation (Fig. 4 (b) and (d)), with north-west receiving more and south-east less precipitation. The east-west gradient is visible also for projections of future temperature change (Fig. 5 (a) and (c)).

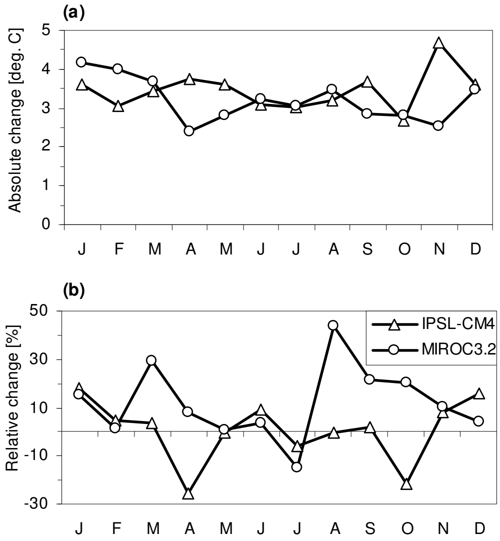


Fig. 3. Basin-averaged changes in temperature (a) and precipitation (b) from IPSL-CM4 and MIROC3.2 (after Piniewski et al. (2011b)).

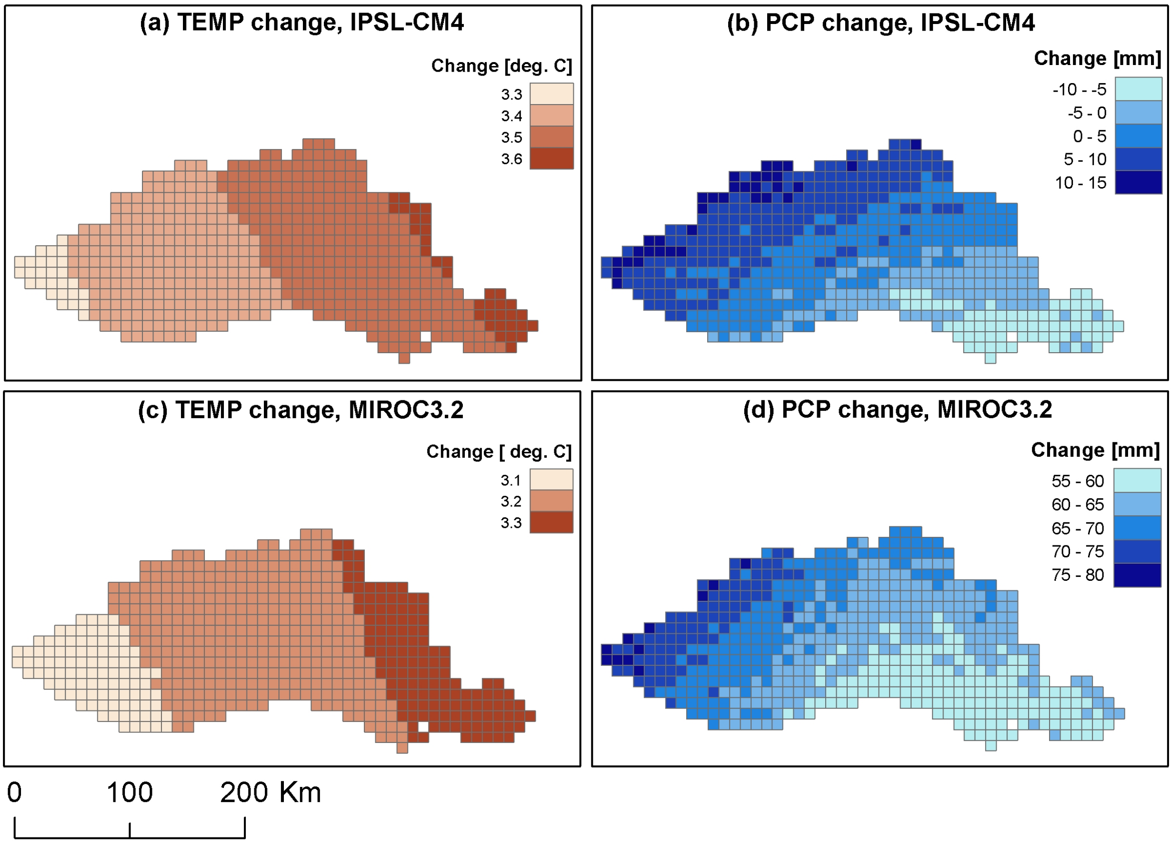


Fig. 4. Spatial variability of GCM-based changes in mean annual temperature and precipitation for IPSL-CM4 and MIROC3.2.

Environmental flow indicators

To assess the impact of climate change on environmental flows, a method was developed (Laizé et al., 2010) based conceptually on the Range of Variability Approach (RVA) using Indicators of Hydrological Alteration (IHA), a desk-top technique for defining environmental flow requirements (Richter et al., 1996, 1997). The IHA/RVA recognises that all characteristics of the flow regime (e.g. low and high flows events) are all ecologically important. The hydrological regime (monthly runoff) is first described by nine parameters (one value per year of record per site) from which indicators (one value per period of record per site) are derived as follows: the median (50th percentile) describes parameter magnitude and the difference between the 75th and 25th percentiles describes variability (with the exception for flood and minimum flow timing parameters, which are months 1 to 12, and are best summarised by their mode). Consequently, there are 16 indicators (7 magnitude indicators + 7 variability indicators + 2 mode indicators); see Table 1 for details. Parameters and indicators are computed for the baseline data and for all scenarios. Indicators P1-P3 are classified as flood indicators,

Based on common expert knowledge, for a given indicator, scenarios are considered not significantly different from the baseline if the indicator difference is within 30% (with the exception of mode indicators for which a threshold of 1 month was used). Differences are aggregated via a colour-coding system: a site was assigned blue, green, amber, or red when its number of indicators differs from the baseline by 0, 1-5, 6-10, or 11-16, respectively.

Due to the fact that SWAT and WaterGAP were run for different baseline periods (SWAT for 1976-2000 and WaterGAP for 1961-90), two cases for comparison were distinguished:

1. Joint baseline period of 1976-1990;
2. Separate baseline periods for each model.

Table 1. Environmental flow indicators.

Regime characteristic	*Parameter monthly (one value per year)*	*Indicator (one value per record)*
Flood Magnitude & Frequency	Number of times that monthly flow exceeds threshold (all-data naturalised Q5 from the baseline period)	Median (**P1**) 25th-75th percentile span (**P2**)
Flood Timing	Month (as number Jan=1, Dec=12) of maximum flow	Mode of month (**P3**)
Seasonal Flow	January flow (mm runoff)	Median (**P4**) 25th-75th percentile span (**P5**)
	April flow (mm runoff)	Median **(P6)** 25th-75th percentile span (**P7**)
	July flow (mm runoff)	Median (**P8**) 25th-75th percentile span (**P9**)
	October flow (mm runoff)	Median (**P10**) 25th-75th percentile span (**P11**)
Low Flow Magnitude & Frequency	Number of months that flow is less than threshold (thresholds = all-data naturalised Q95 from the baseline period)	Median (**P12**) 25th-75th percentile span (**P13**)
Minimum Flow Timing	Month (as number Jan=1, Dec=12) of minimum flow	Mode of month (**P14**)
Low Flow Duration	Number of times that two consecutive months are less than threshold (all-data naturalised Q95 from the baseline period)	Median (**P15**) 25th-75th percentile span (**P16**)

Note: P1-P3 are flood indicators, P4-P11 are seasonal flow indicators and P12-P16 are low flow indicators.

Results

The results presented below show projected impacts of climate change on environmental flows using output generated by WaterGAP and SWAT. The WaterGAP part of the results is a subset of the analysis performed at the pan-European scale (Laizé et al., 2011). Figures 5 and 6 illustrate spatial variability in colour codes derived from aggregation of the environmental flow indicators. It is worth noting that in the case of SWAT there is a relatively good agreement between two climate models, especially for joint baseline period, whilst in the case of WaterGAP, IPSL-CM4 suggests considerably larger impact than MIROC3.2. For each climate model – hydrological model combination it can be observed that for the joint period the impacts are larger than for the separate periods, which might be explained by the fact that in 1979 there was one of the most extreme floods in the 20th century. Using only 15-year period might also result in biased statistics, therefore in the further study only the results for separate periods are presented.

Statistical analysis of SWAT- and WaterGAP-based results was performed for the subset of 58 pairs of SWAT outlets and WaterGAP grid cells (cf. Fig. 2). Percent of pairs with consistent colour codes equalled to 66% for IPSL-CM4 and 69% for MIROC3.2. There was no pair with a green colour code for one model and a red colour code for another model.

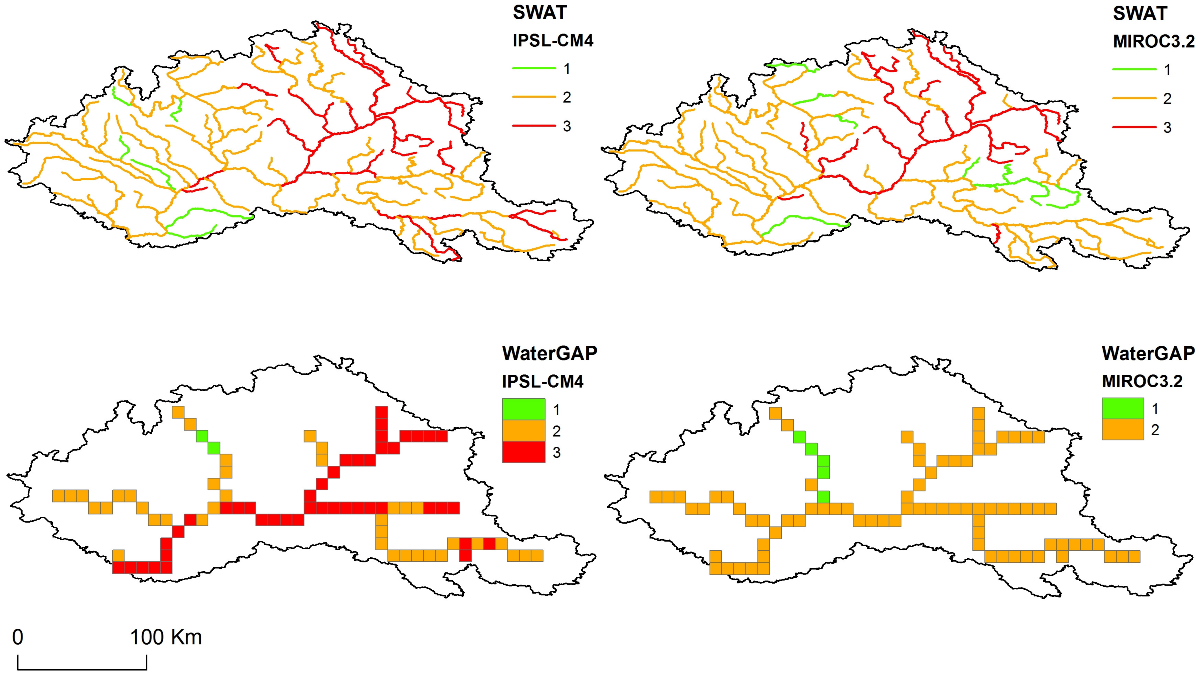


Fig. 5. Colour-coding of the environmental flow indicators for two GCMs and two hydrological models. Case 1: joint baseline period (1 – low impact, 2 – moderate impact, 3 – high impact).

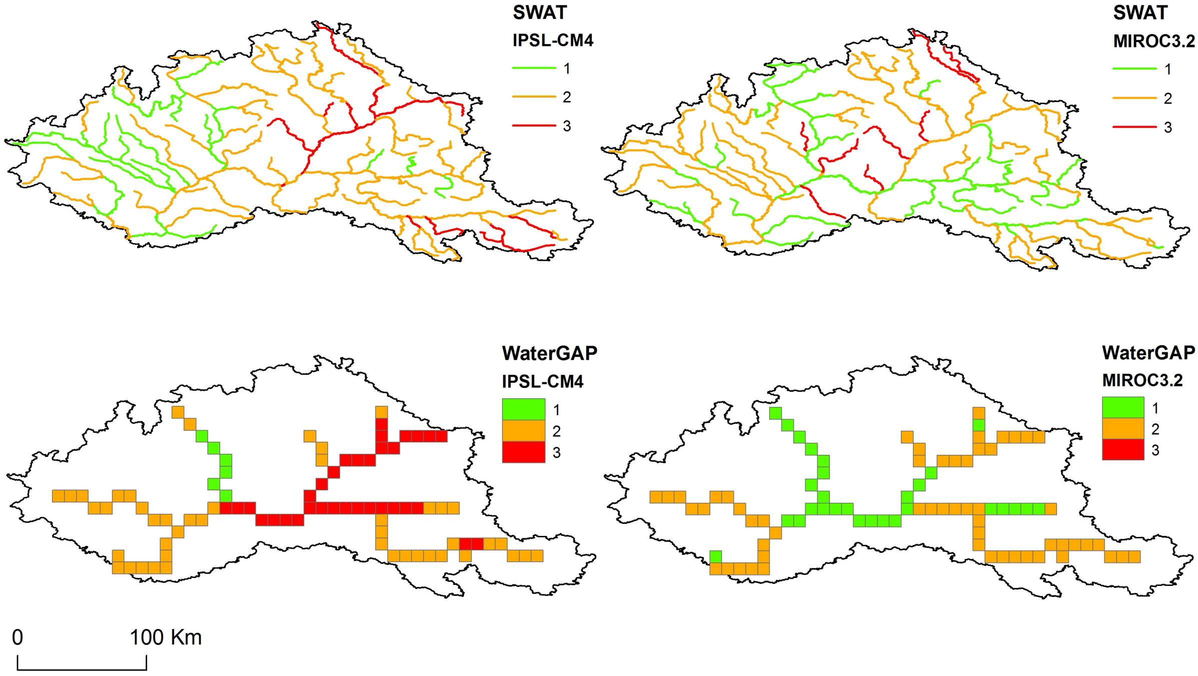


Fig. 6. Colour-coding of the environmental flow indicators for two GCMs and two hydrological models. Case 2: separate baseline periods (1 – low impact, 2 – moderate impact, 3 – high impact).

In an attempt to understand which indicators were responsible for differences between SWAT- and WaterGAP-based estimates, the background data i.e. 16 Richter statistics making up the composite colour-coded index, were analysed (cf. Table 1). Percent of pairs for which the impact of climate models was consistent between SWAT and WaterGAP was variable across the set of Richter statistics (Fig. 7). In average, 61% pairs had consistent impact for IPSL-CM4 and 62% for MIROC3.2. This percentage ranged from 18% for the flood magnitude median (P1) for IPSL-CM4 to 100% for low flow magnitude variability (P13) for IPSL-CM4 as well as low flow magnitude and duration medians (P12 and P15) for MIROC3.2. The highest degree of consistency was reached for low flow statistics (67-77%), while the lowest for flood statistics (39-44%), as illustrated in Fig. 8. The results were also more consistent for the median (64-73%) than for the mode and the mean (48-59%).

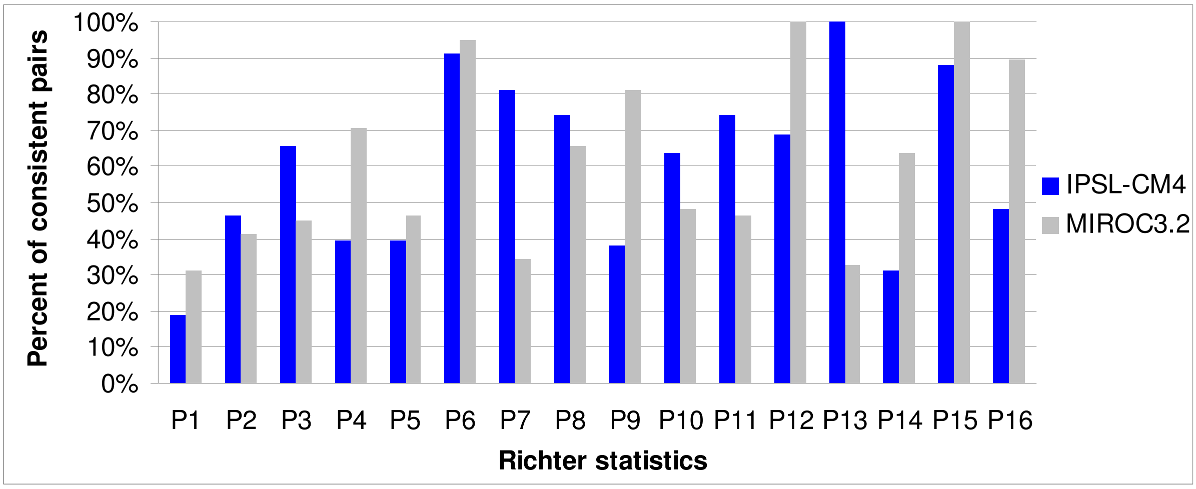


Fig. 7. Percent of pairs for which the impact of two climate models was consistent between SWAT and WaterGAP for each of 16 Richter statistics.

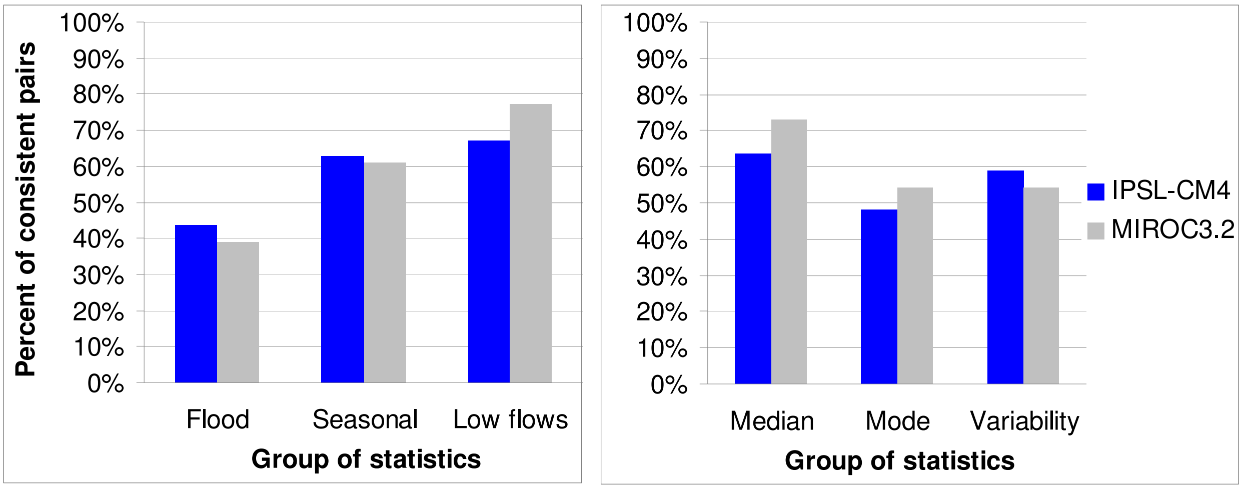
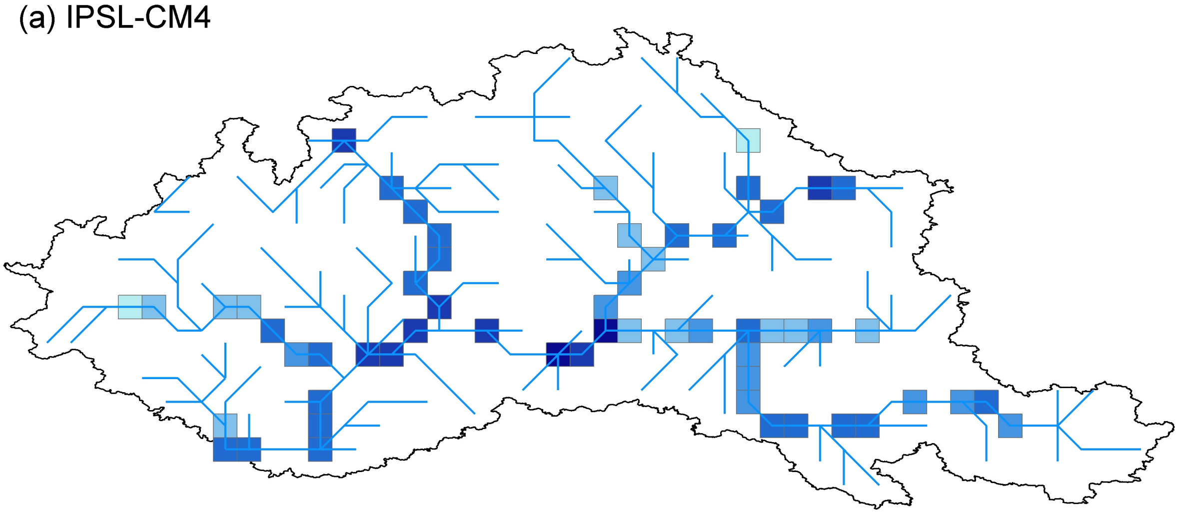


Fig. 8. Percent of pairs for which the impact of two climate models was consistent between SWAT and WaterGAP for different groups of Richter statistics.

Spatial analysis of consistency between SWAT- and WaterGAP-based results shows that there is a strong variability of this phenomenon (Fig. 9). In the case of IPSL-CM4, the lowest consistency can be observed for grid cells with small upstream catchment area. For both climate models there is a good consistency in the River Pisa, which drains the lake district in the northern part of the basin (cf. Fig. 1). This might be explained by lakes acting as a buffer, since both of the models show relatively low impact on studied indicators (cf. Fig. 5 and 6). Another potential reason for inconsistencies between SWAT and WaterGAP is imprecise schematisation of the stream network in the latter model (cf. Fig. 2).

(a) IPSL-CM4



(b) MIROC3.2

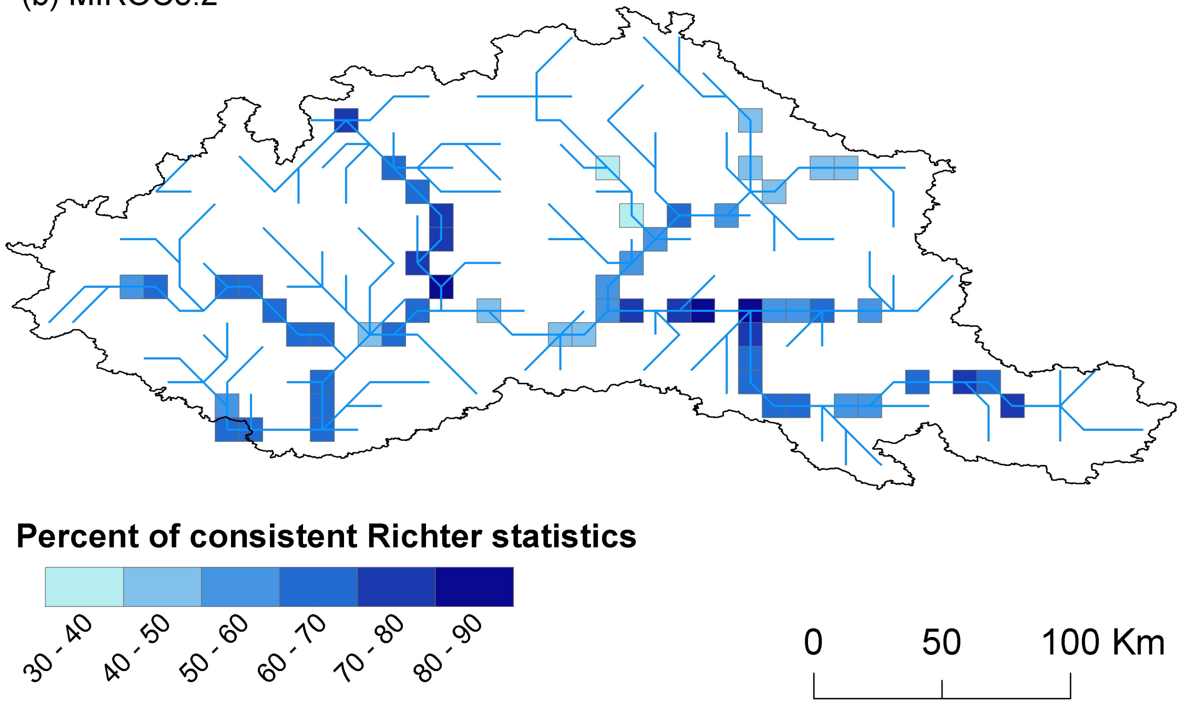


Fig. 9. Map of spatial variability of the percentage of individual indicators (Richter statistics), for which the impact of: (a) IPSL-CM4, (b) MIROC3.2 was consistent between SWAT and WaterGAP.

Conclusions

The impact of climate change on environmental flow indicators in the rivers of the Narew basin is substantial, although spatially variable, climate model dependant and hydrological model dependant. Spatial variability is surprisingly large, taking into consideration that variability in projected temperature and precipitation changes is not very large for this region (cf. Fig. 4). It is not clear whether spatial variability in projected impacts themselves and in the differences between impacts projected by SWAT and WaterGAP can be explained by climatic factors or catchment properties. It is noteworthy that according to the SWAT model, both climate models suggest the most severe impact in the River Biebrza (cf. Fig. 1) which is internationally recognised for its extremely valuable floodplain wetlands (Okruszko, 1990).

The message saying that the most valuable ecosystems would be exposed to the highest climate change risk could concern local water managers and stakeholders, hence this issue requires further studies and deeper understanding.

The presented results suggest that from two climate models showing a comparable change in temperature (cf. Fig. 3 and 4), the one that shows annual precipitation increase by 11% (i.e. MIROC3.2) forces impacts of lower magnitude than the one showing no change in annual precipitation (IPSL-CM4). This could be interpreted that the increase in precipitation acts as a buffer to the increase in temperature.

The degree of consistency in colour-coding indicators between SWAT and WaterGAP (cf. Fig. 5 and 6) is relatively good. For both climate models more than 60% of selected grid cell – reach outlet pairs have consistent colour codes and in none of the cases a difference of two classes is present. This should generally be good information for decision-makers.

Piniewski et al. (2011a) argued that indicators of highest importance for many valuable fish and floodplain wetland plant species in the Narew basin are duration and timing of floodplain inundation. There are no direct counterparts of those in the set of indicators P1-P16 used in the current study, however the closest are P1, P2 and P3 (flood indicators). As illustrated in Fig. 8, for this group of indicators there is the largest disagreement between the hydrological models. Hence, the future work should also focus on studying the impact of climate change on environmental flow indicators relevant for the fish and floodplain wetlands. This, however, would require analysing output with a daily and not monthly time scale.

Acknowledgements

The authors gratefully acknowledge financial support for the projects: *Water Scenarios for Europe and Neighbouring States* (SCENES) from the European Commission (FP6 contract 036822) and for the project *Analysis of the hydrological regime changes of the Central and Eastern European Rivers as a result of anthropogenic and climatic changes in the catchment* (Dec. no. 637/N-Rosja/09/2010) from the Polish Ministry of Science and Higher Education. The first author thankfully acknowledges the financial support for the research visits to the Centre for Ecology and Hydrology, Wallingford, UK from the British Council within the framework of the Polish-British Young Scientists Programme and from the EC within the framework of the SCENES project.

References

Acreman, M. C., Blake, J. R., Booker, D. J., Harding, R. J., Reynard, N., Mountford, J. O., Stratford, C. J. 2009. A simple framework for evaluating regional wetland ecohydrological response to climate change with case studies from Great Britain. *Ecohydrol.* 2: 1-17.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. and Siebert, S. 2003. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrol. Sci. J.* 48(3): 317-337.

Arnold, J. G., Srinavasan R., Muttiah, R. S. and Williams, J. R. 1998. Large area hydrologic modelling and assessment. Part 1. Model development. *J. Am. Water Resour. Assoc.* 34: 73-89.

Döll, P., Kaspar, F. and Lehner, B. 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.* 270: 105-134.

Döll, P. and Lehner, B. 2002. Validation of a new global 30-min drainage direction map. *J. Hydrol.* 258: 214-231.

Giełczewski, M., Stelmaszczyk, M., Piniewski, M. and Okruszko, T. 2011. How can we involve stakeholders in the development of water scenarios? Narew River Basin case study. *Journal of Water and Climate Change* (accepted).

Fowler, H. J., Blenkinsop, S. and Tebaldi, C. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *Int. J. Climatol.* 27: 1547-1578.

Gosling, S. N., Arnell, N. W. 2011. Simulating current global river runoff with a global hydrological model: model revisions, validation and sensitivity analysis, *Hydrol. Processes* 25(7): 1129-1145.

Gosling, S. N., Taylor, R. G., Arnell, N. W. & Todd, M. C. 2011. A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models. *Hydrol. Earth Syst. Sci.* 15: 279-294.

Hasumi, H. and Emori, S. (eds) 2004. K-1 coupled model (MIROC) description. *K-1 Technical Report* 1, Center for Climate System Research, University of Tokyo, Japan.

IPCC (Intergovernmental Panel on Climate Change) 2007. Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

Kostrzewa, H. 1977. Validation of criteria and magnitude of instream flow for Polish rivers. *Mat. Bad., Ser. Gospodarka Wodna i Ochrona Wód.* IMGW Warsaw, Poland [in Polish].

Laizé, C. L. R.; Acreman, M. C.; Dunbar, M.; Houghton-Carr, H.; Flörke, M. and Schneider, C. 2010. Monthly hydrological indicators to assess impact of change on river ecosystems at the pan-European scale: preliminary results. In: *British Hydrological Society Third International Symposium Role of Hydrology in Managing Consequences of a Changing Global Environment,* Newcastle upon Tyne, United Kingdom.

Laizé, C. L. R.; Acreman, M. C.; Dunbar, M.; Houghton-Carr, H.; Flörke, M.; Schneider, C. 2011. Future impacts on pan-European environmental flows. *Hydrol. Sci. J.* (in submission).

Maksymiuk, A., Furmańczyk, K., Ignar, S., Krupa, J. and Okruszko, T. 2008. Analysis of climatic and hydrologic parameters variability in the Biebrza River basin. *Scientific Review Engineering and Environmental Sciences*. 41(7): 59-68 [in Polish].

Marszelewski, W. and Skowron, R. 2006. Ice cover as an indicator of winter air temperature changes: case study of the Polish Lowland lakes. *Hydrol. Sci. J.* 51(2): 336-349.

Marti, O., Braconnot, P., Bellier, J., Benshila, R., Bony, S., Brockmann, P., Cadule, P., Caubel, A., Denvil, S., Dufresne, J-L., Fairhead, L., Filiberti, M-A., Foujols, M-A., T. Fichefet, T., Friedlingstein, P., Gosse, H., Grandpeix, J-Y., Hourdin, F., Krinner, G., Lévy, C., Madec, G., Musat, I., de Noblet, N., Polcher, J. and Talandier, C. 2006. The new IPSL climate system model: IPSL-CM4. *Note du Pôle de Modélisation*, 26, ISSN 1288-1619.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R. and Williams, J. R. 2005. Soil and Water Assessment Tool Theoretical Documentation Version 2005. GSWRL-BRC, Temple.

Norris, R. H., Thomas, M. C. 1999. What is river health? *Freshwat. Biol.*, 41: 197-209.

Okruszko, H. 1990. Wetlands of the Biebrza Valley, their value and future management. PAN, Warszawa: 1-107.

Okruszko T. and Giełczewski M. 2004. Integrated River Basin Management – The Narew River Case Study. *Kasseler Wasserbau-Mitteilungen*, Universität Kassel, 14, 59-68.

Piniewski, M. and Okruszko, T. 2011. Multi-site calibration and validation of the hydrological component of SWAT in a large lowland catchment. In: *Modelling of Hydrological Processes in the Narew Catchment.* D. Świątek and T. Okruszko eds. Geoplanet: Earth and Planetary Sciences, Springer-Verlag Berlin Heidelberg. DOI: 10.1007/978-3-642-19059-9_2 (in press).

Piniewski, M., Acreman, M. C., Stratford, C. S., Okruszko, T., Giełczewski, M., Teodorowicz, M., Rycharski, M. and Oświecimska-Piasko, Z. 2011a. Estimation of environmental flows in semi-natural lowland rivers - the Narew basin case study. *Pol. J. Environ. Stud.* 20(5) (accepted).

Piniewski, M., Voss, F., Bärlund, I., Okruszko, T. and Kundzewicz, Z. W. 2011b. Effect of modelling scale on the assessment of climate change impact on river runoff – a case study for the Narew (Poland). *Hydrol. Sci. J.* (submitted).

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Presteegard, K. L., Richter, B. D., Sparks, R. E. and Stromberg G, J. C. 1997. The natural flow regime. *Bioscience* 47: 769-784.

Poff, N. L., Zimmerman, J. K. H. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwat. Biol.* 55: 194-205.

Power M. E., Sun A., Parker G., Dietrich W. E. and Wootton J. T. 1995. Hydraulic food-chain models. *BioScience*, 45: 159–167.

Richter, B. D., Baumgartner, J. V., Powell, J. and Braun, D. P. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conserv. Biol.* 10(4): 1163-1174.

Richter, B. D., Baumgartner, J. V., Wigington, R. and Braun, D. P. 1997. How much water does a river need? *Freshwat. Biol.* 37(1): 231-249.

Witowski, K., Filipowski, A., Gromiec, M. J. 2008. Calculation of instream flow. Handbook. Instytut Meteorologii i Gospodarki Wodnej, Warsaw, Poland. [in Polish].