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

Mikołaj Piniewski[a]*, Cédric L.R. Laizé[b], Michael C. Acreman[b], Tomasz Okruszko[a], and Christof Schneider[c]

[a] Department of Hydraulic Engineering, Warsaw University of Life Sciences, Nowoursynowska Str. 159, 02-787 Warszawa, Poland;

[b] Centre for Ecology and Hydrology, Wallingford, Maclean Building, Crowmarsh Gifford, OX10 8BB, UK;

[c] Center for Environmental Systems Research, University of Kassel, Wilhelmshöher Allee 47, 34117 Kassel, Germany.

* Corresponding author (mpiniewski@levis.sggw.pl)

Abstract

Environmental flows, the quantity of water required to maintain a river ecosystem in its desired state, are of particular importance in areas of high natural values. Water-dependant ecosystems are exposed to the risk of climate change through altered precipitation and evaporation. Rivers in the Narew basin in north-eastern Poland are known for their valuable river and wetland ecosystems, many of them in pristine or largely un-impacted conditions. The objective of this study was to assess changes in the environmental flow regime of the Narew river system, caused by climate change, as simulated by hydrological models with different degrees of physical characterisation and spatial aggregation. Two models were assessed: a river basin scale model SWAT, and a continental model of water availability and use WaterGAP. Future climate change scenarios were provided by two GCMs coupled with the A2 emission scenario: IPSL-CM4 and MIROC3.2. To assess the impact of climate change on environmental flows, a method based conceptually on the Range of Variability Approach (RVA) was used. The results indicate that the environmental flow regime in the Narew basin is subject to climate change risk, whose magnitude and spatial variability varies with climate model and hydrological modelling scale. Most of the analysed sites experienced moderate impacts, both for the Generic Environmental Flow Indicator (*GEFI*), the Floodplain Inundation Indicator (*FII*) and the River Habitat Availability Indicator (*RHAI*). The consistency between SWAT and WaterGAP for *GEFI* was medium: in 55 to 66% of analysed sites the models suggested the same level of impact.

Hence, we suggest that state-of-the-art high resolution global or continental-scale models, such as WaterGAP, could be useful tools for water management decision-makers and wetland conservation practitioners, whereas models such as SWAT should serve as a complimentary tool for more specific smaller-scale, local assessments.

Abbreviations: SWAT, Soil & Water Assessment Tool; WaterGAP, Water – Global Assessment and Prognosis; GCM, General Circulation Model; GEFI – Generic Environmental Flow Indicator; FII – Floodplain Inundation Indicator; RHAI – River Habitat Availability Indicator.

Introduction

Amongst the 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 (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 (Acreman and Dunbar, 2004; http://www.eflownet.org/). The first environmental flows were focused on the concept of a minimum flow – 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 minimum level, the river ecosystem will be conserved. This perspective is still common 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; Poff et al., 2010).

Many of the world's freshwater ecosystems are under severe threat from human pressure (Vőrősmarty et al., 2010), particularly anthropogenic climate change (Kernan et al., 2010). In the north-east, lowland part of Poland, many of the rivers are in a semi-natural state and surface water abstractions for agriculture, industry and human needs are not as significant as elsewhere (Piniewski et al., 2011). Maintaining their good ecological status (as indicated in the EU Water Framework Directive) requires detailed analyses of the river-floodplain connectivity and its vulnerability to human induced changes. Assuming that there will be no direct threats to the river-floodplain morphology (building embankments or channelising the river), flow regime alteration poses the main threat to the floodplain ecosystem. Analysis of the flow regime changes followed by the ecohydrological consideration of its possible impact on the in-stream and floodplain ecosystems should be of high priority to water managers in this region. There is growing evidence that the Earth's climate is warming from observations of increases in global air and ocean temperatures, widespread melting of snow and ice and rising global sea level (IPCC, 2007); this is also observed in Poland (Maksymiuk et al., 2008; Marszelewski and Skowron, 2006). Climate change is likely to alter river flow regimes significantly, and as a consequence may pose a serious threat to river and floodplain ecosystems. Indeed, Poff and Zimmerman (2010) in their comprehensive review of ecological responses to altered flow regimes found that of the 165 papers analysed, 152 reported decreased values for recorded ecological metrics in response to a variety of types of flow alteration. Döll and Zhang (2010) concluded that ecologically relevant river flow characteristics may be globally impacted more strongly by climate change than by dams and water withdrawals in recent years. 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. Climate change is also projected to impact European river (Laizé et al., 2010) and wetland (Okruszko et al., 2011) ecosystems significantly through flow alterations.

A well-established quantitative method of estimating impacts of climate change on hydrological systems is to use the output from 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 models are of particular interest:

1. Catchment-scale physically-based models, such as SWAT (Soil and Water Assessment Tool), cf. Arnold et al. (1998), Neitsch et al. (2005).

2. Global or continental conceptual 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 facilitates the creation of a more fit-for-purpose model setup, with extensive local datasets allowing more detailed calibration, for the trade-off of time and money necessary to perform the whole study. These models tend to be used for catchment specific assessment and decisions. The models from the second group are used for continent and global scale analysis. For example, Vőrősmarty et al. (2010) analysed incident human water security and biodiversity threats in a global geospatial approach. These models usually employ readily available global datasets, and their calibration is not oriented towards individual river basins. They provide consistency between river basins which allows broad scale comparisons and policy formulation. Gosling et al. (2011) reported that it is equally feasible to apply the global hydrological model Mac-PDM.09 (Gosling and Arnell, 2010) 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 EC FP6 research project "Water Scenarios for Europe and for Neighbouring States" (SCENES) developed a set of comprehensive water scenarios of Europe's freshwater's futures up to 2050s (Kämäri et al., 2008) and employed WaterGap to produce river flow outputs. The project results provide an excellent opportunity to compare continental-scale model outputs with basin-specific model outputs. In particular, the SCENES Webservice[1] (Schneider, 2011) contains interactive maps, for future climate and socio-economic scenarios, of various ecohydrological indicators related to the following topics: environmental flows (equivalent to *GEFI* from this paper; Houghton-Carr (ed., 2011), floodplain flooding (Schneider et al., 2011a), ecosystem services of wetlands (Okruszko et al., 2011), macrophyte diversity and habitat suitability for fish. These allow assessment of impacts on river ecosystems.

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 physical characterisation and spatial aggregation. To this end, we first evaluate the performance of two example models (SWAT and WaterGAP) in the baseline period and analyse the impacts of two climate change scenarios on flow parameters at the catchment outlet. These initial steps are followed by the spatially explicit analysis of climate change impacts on three developed environmental flow

[1] http://www.cesr.de/SCENES_WebService/ [last accessed 30/1/2012]

indicators, conceptually built upon the Indicators of Hydrologic Alteration (IHAs; Richter et al., 1996). Furthermore, the comparison between the impacts obtained using SWAT and WaterGAP provides an initial estimate of the uncertainty related to using a continental-scale or a catchment-scale model. In discussion, we assess the issue of trade-offs related to using either model and suggest possible approaches to be applied at decision-making level. We also discuss environmental ramifications of this study, as well as the uncertainties related to climate modelling and downscaling approaches.

Data and Methods

Study area

The River Narew is situated in north-east Poland (Fig.1); the basin area upstream of the Zambski Kościelne gauging station is 28,000 km^2. The rivers of the Narew basin are typical lowland rivers with low slopes and large floodplains. Mean January and July temperatures are -3ºC and 17 ºC respectively, and annual mean precipitation of ca. 600 mm. Figure 2 shows discharge hydrographs at the basin outlet for two example hydrological years: a wet year 1994 and a dry year 2003. Both in dry and wet years, flood peaks are associated with snow-melt that usually occurs in early spring or during warmer spells of winter. As shown in Figure 2, flood magnitude can vary considerably between dry and wet years. Since evapotranspiration is the dominant process in summer, floods occur very rarely in this season, even after heavy rainfall. Hence, the period between July and September is typically the low flow period. The hydrographs shown in Fig. 2 represent the whole basin and even though the flow regime of this area is rather uniform, some local variations certainly exist. For example, the River Pisa (cf. Fig. 1) draining the lake district in the north reflects far less intra-annual variation than the River Narew at its main outlet. In contrast, some of the small tributaries of the Narew represent much more flashy flow regime.

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 not significantly impacted by regulating impoundments (weirs and dams) or water abstractions and discharges (cf. Piniewski et al., 2011). Compared to the whole area of Poland, the Narew basin can be characterised by: ca. two times lower population density, ca. 8% lower urbanisation rate, the absence of heavy industry (food and wood production being the main industry branches) and less intensive agriculture, whose pressure is exerted rather in terms of water quality than quantity (Giełczewski et al. 2011). Many of its river valley bottoms are in a virtually natural state, and protected as either national parks or Natura 2000 sites (Fig. 1). A further description of the Narew basin is provided by Okruszko and Giełczewski (2004) and Okruszko et al. (2012), with respect to integrated water management, and by Piniewski et al. (2011) with respect to ecological data on fish and floodplain wetlands.

Hydrological models

The catchment-scale model used in this study was SWAT (version SWAT2005), developed at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA (Arnold et al., 1998; Neitsch et al., 2005). This was selected because of its suitability to model large river basins and wide-spread application (Gassman et al., 2007). The continental-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). This was selected because of its availability through the SCENES project. WaterGAP comprises two components: a Global Hydrology Model to simulate the terrestrial water cycle, and a 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, from the modelling point of view, water use is not an important issue in the Narew basin (Okruszko and Giełczewski, 2004; Piniewski et al., 2011).

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 using 151 sub-catchments and 1,131 HRUs (Piniewski and Okruszko, 2011) 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; Schneider et al., 2011a; Flörke et al., 2011; Beek et al., 2011, Okruszko et al., 2011) works with a spatial resolution of 5 by 5 arc minutes (~6 × 9 km in central Europe), which is an upgrade compared to the previous version used by Alcamo et al. (2003) and Döll et al. (2003), and one of the finest resolutions of large-scale hydrological models (cf. Haddeland et al., 2011). WaterGAP was not set up intentionally for the Narew basin, but was applied with its parameters set at continental scale calibrated using river flow data from across Europe from the Global Runoff Data Centre stations. This included two stations on the Narew River, Ostrołęka and Suraż (GRDC IDs 6458810 and 6458805, respectively; cf. Fig. 1 for locations) with discharge data of the time period 1951-80. The performance of both models in the baseline period was tested at the Ostrołęka station (more representative for the whole basin than Suraż), which is a necessary step before any model application in the climate change impact study. In our case, this step is particularly essential for WaterGAP, which have not yet been tested for the NRB in a published source, in contrast to SWAT, which was tested at multiple gauges in the NRB (cf. Piniewski and Okruszko, 2011).

In this study SWAT was driven with daily climate inputs interpolated from meteorological stations, and WaterGAP with monthly inputs, which were disaggregated to daily inputs using statistical methods. Temperature and cloud cover were disaggregated using a cubic-spline-function between the monthly means, which were assigned to the middle of each month. Precipitation was distributed evenly over the number of wet days per month, which were distributed within the month applying a two-state, first-order Markov Chain with parameterisation proposed by Geng et al. (1986).

The time period of reference simulation in both models, hereafter referred to as the baseline, was 1976-2000. Both models were run with a daily time step, whereas results were analysed using both daily and aggregated monthly outputs. River flow as 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. 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. To achieve this, 58 pairs were distinguished, based on comparative analysis of drainage topology and upstream catchment areas in WaterGAP and SWAT (Fig. 2). Due to the simplified drainage topology of WaterGAP (based on the global drainage direction map DDM5; Döll and Lehner

2002) and irregular size of the river reaches in SWAT, the coupling was approximate in several cases (see Fig. 3).

Climate models

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). The A2 scenario was chosen in the SCENES project at pan-European level by stakeholders (Pan-European Panel members; cf. Kämäri et al., 2008). It was argued that it fits best the narrative storylines produced by the PEP members. In addition, results for GCMs available for this scenario were compared concluding that the two above-mentioned GCMs are well representing the variability between the existing climate models, especially in terms of precipitation projections.

The future climate input was then derived by the delta-change approach in order to reduce the GCM biases. Therefore, the future climate input was scaled in consideration of the difference between observed and simulated climate of the reference period (Henrichs and Kaspar 2001; Lehner et al., 2006). For temperature, the difference between future and present-day temperature values from the GCMs were added to the baseline time series. For precipitation, observed precipitation time series were multiplied with the respective ratio between future and present-day precipitation. An exception to this rule was applied when present-day precipitation is close to zero (< 1mm); in this case the respective value was added.

In WaterGAP, for the baseline time series, climate data from Climate Research Unit (CRU) of the University of East Anglia, Norwich, U.K. (version TS 2.1, Mitchell and Jones, 2005) were applied. All climate data have been rescaled to the 5 arc minute grid of WaterGAP using a simple bilinear interpolation approach. In SWAT, the main climate data source for the baseline time series were daily station data from the Polish Institute of Meteorology and Water Management network and additional data source was MARS-STAT database (van der Goot and Orlandi, 2003).

The delta-change approach is a simple bias correction method that builds on the assumption that GCMs more accurately simulate relative changes than absolute values (Fowler et al., 2007). In addition the spatial information density of the coarse resolution GCM output is improved with the higher resoluted baseline (CRU for WaterGAP and climate stations for SWAT) dataset. However, by applying this approach, future trends in climate possess current climate variability.

Both climate models project similar increases in mean annual basin-averaged temperature, however the seasonal variability of this increase is different (Fig. 4a). The mean annual temperature increase equals 3.5ºC for IPSL-CM4 and is by 0.3ºC higher than the increase projected by MIROC3.2. Regarding basin-averaged precipitation, the uncertainty of climate model projections is high (Fig. 4b). 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 small change or a decrease in precipitation: (1) from March to April; (2) from August to October.

Environmental flow indicators

To assess the impact of climate change on environmental flows, a method was developed (Laizé et al., 2010; Houghton-Carr (ed.), 2011) based conceptually on the Range of Variability Approach (RVA) using Indicators of Hydrological Alteration (IHAs), a desk-top technique for assessing the implications of flow change for river ecosystems (Richter et al., 1996, 1997). This approach recognises that all characteristics of the flow regime (e.g. low and high flows events) are ecologically relevant. For example, floods are important for connectivity between rivers and their floodplains, for floodplain vegetation, and producing back-water fish spawning habitat, whilst low flows are important for the growth of juvenile fish. Further in this section, we will explain the specific ecological relevance of the selected hydrological indicators. In the method developed by Laizé et al. (2010) and Houghton-Carr (ed., 2011), the hydrological regime (monthly or daily runoff) is first described by eight parameters (one value per year of record per site) from which the indicators (one value per period of record per site) are derived as follows: the median (50^{th} percentile) describes parameter magnitude and the difference between the 75th, and 25th percentiles, i.e. inter-quartile range (IQR), describes variability (with the exception of the timing of flood and minimum flow monthly parameters, which are months 1 to 12, and are best summarised by their mode). Consequently, there are 14 indicators (6 magnitude indicators + 6 variability indicators + 2 mode indicators); see Table 1 for details. These were considered to appropriately characterise the flow regime as exhibited in Figure 2 and its ecological relevance as described below. Parameters and indicators are computed for the baseline data and for all scenarios.

Table 1. Description of selected indicators composing the Generic Environmental Flow Indicator (*GEFI*).

Parameter daily (one value per year)	*Parameter monthly (one value per year)*	*Indicator (one value per record)*¶	*Flow type*	*Regime characteristic*
Number of high pulses†	Number of months above threshold‡	Median (**P1**); IQR (**P2**)	High flows	Magnitude; Frequency
Julian date of maximum flow	Month of maximum flow	Median/Mode# (**P3**)	High flows	Timing
January mean flow	January mean flow	Median (**P4**); IQR (**P5**)	Seasonal flows	Magnitude; Timing
April mean flow	April mean flow	Median (**P6**); IQR (**P7**)	Seasonal flows	Magnitude; Timing
July mean flow	July mean flow	Median (**P8**); IQR (**P9**)	Seasonal flows	Magnitude; Timing
October mean flow	October mean flow	Median (**P10**); IQR (**P11**)	Seasonal flows	Magnitude; Timing
Number of low pulses†	Number of months below threshold§	Median (**P12**); IQR (**P13**)	Low flows	Magnitude; Frequency
Julian date of minimum flow	Month of minimum flow	Median/Mode# (**P14**)	Low flows	Timing

[†]High/low pulses – number of annual occurences during which flow magnitude exceeds an upper threshold (all-data naturalised Q25 from 1976-2000) or is below a lower threshold (all-data naturalised Q75 from 1976-2000), cf. Richter et al. (1996);
[‡]Threshold = all-data naturalised Q5 from 1976-2000;
[§]Threshold = all-data naturalised Q95 from 1976-2000;
[¶]Indicator identification code in parentheses;
[#]Median for daily parameter, mode for monthly parameter.

Threshold values of the indicators were defined to assess whether any scenario is significantly different from the baseline. The threshold chosen was as indicator difference of 30% (with the exception of mode indicators for which a threshold of 1 month was used) based on expert judgement, and an assessment of global literature (e.g. Jones, 2002; Acreman et al., 2008; Okruszko et al., 2011, and references therein). An indicator was assigned the value of 1 if the threshold criterion was exceeded (impact) or 0 if this threshold was not surpassed (no impact). Scores were aggregated via a colour-coding system: a site was assigned blue (no impact), green (low impact), amber (medium impact), or red (large impact) when the total of indicators was equal to 0, 1-4, 5-9, or 10-14, respectively (Table 2). This aggregated index will be further referred to as the Generic Environmental Flow Indicator (*GEFI*).

Table 2. Colour-coding system of environmental flow indicators

Impact	*Colour code*	*Number of indicators (P1-P14) exceeding threshold*		
		Generic Environmental Flow Indicator (GEFI)	*Floodplain Inundation Indicator (FII)*	*River Habitat Availabilty Indicator (RHAI)*
No	Blue	0	0	0
Small	Green	1-4	1	1
Moderate	Amber	5-9	2-3	2-3
Large	Red	10-14	4-5	4-5

The colour-coding system was also used to calculate indicators having a more direct ecological relevance than the composite index based on the total of 14 individual indicators listed in Table 1. The Narew basin is known for its floodplain wetlands that provide various ecosystem services for:

-wetland vegetation communities that require floodplain inundation of variable duration (e.g. rush and sedge communities, Molinia and mesic meadows) cf. Piniewski et al. (2011), Chormański et al. (2011), Okruszko and Kiczko (2008), Dembek et al. (2004);

-phytophilous fish communities (e.g. northern pike and wels catfish) for which floodplain wetlands are preferred spawning habitats in spring, cf. Piniewski et al. (2011), Casselman and Lewis (1996), Górski et al. (2010), Hanrahan (2007), Anon. (2008);

-waterfowl (e.g. marsh- and reed-warblers) cf. Dyrcz et al. (2010), Zduniak (2008).

Hence, an indicator, called Floodplain Inundation Indicator (*FII*) was developed to quantify the importance of those flood-related features. *FII* is calculated as the total of indicators P1, P2, P3, P6 and P7 from the Table 1. Those indicators cover all main ecological consequences of changes in flooding phenomena – timing, duration or magnitude. Flows in successive months are often correlated (e.g. as shown in Fig. 2 the hydrographs for wet and dry years, even though different, preserve the same features) and redundancy analysis (Olden and Poff, 2003) has shown that selecting a single month can represent flows in a season. Furthermore, April flows are key to driving floodplain vegetation communities and fish spawning (Piniewski et al., 2011). The corresponding colour-coding system is presented in Table 2.

The last indicator considered accounts for importance of physical habitat availability for fish and macroinvertebrates during natural low flow periods, particularly in summer. It is calculated from those indicators in Table 1 that are related to low flows: P8, P9, P12, P13 and P14, and is referred to as the *RHAI* – River Habitat Availability Indicator. June flow magnitude and frequency have been incorporated into this indicator, as they well represent low flow events in the Narew basin (Fig. 2). Low flows maintain appropriate water temperatures, dissolved oxygen, and water chemistry. For example, Copp et al. (1994) reported that water velocity was the most influential environmental variable for habitat preference of 0+ juvenile fish in Hungarian/Slovak floodplain of the Danube River. At this life history stage of fishes, flows higher than natural can be as detrimental to the river ecosystems as flows lower than natural because, for example, velocities may exceed the swimming speed of the juvenile fish. *RHAI* is classified into the colour coding system in the same manner as *FII* (Table 2).

Results

The main objective of our study is to analyse the impact of climate change on environmental flow indicators using two models with different modelling scale. An essential preceding step is however to analyse the model performance in the baseline period as well as the pure effect of climate change on selected flow parameters, which can bring an insight into the further process of explaining differences between the future impacts on environmental flow indicators.

Model performance in the baseline period

Figure 5 shows modelled and measured daily flows at the Ostrołęka station (GRDC no. 6458810; cf. Fig. 1), whereas Table 3 presents selected goodness-of-fit measures and flow statistics, which correspond to the IHAs from Table 1. Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2), two widely used model efficiency criteria used in hydrological modelling (Moriasi et al., 2007) are higher for SWAT than for WaterGAP, both in case of daily and monthly time scale. Furthermore, both measures are higher for monthly data than for daily data. This was expected for both models, but especially for WaterGAP, in which the original climate data had monthly time scale that was disaggregated into daily scale, as previously mentioned.

Table 3. Selected goodness-of-fit measures and simulated and modelled flow parameters for daily and monthly simulations for the baseline period 1976-2000.

Goodness-of-fit measures	*SWAT*	*WaterGAP*	*Measured*
NSE daily	0.66	0.15	
NSE monthly	0.74	0.40	
R^2 daily	0.67	0.39	
R^2 monthly	0.75	0.53	
Percent bias [%]	-3	-19	
Selected flow parameters [cms]			
Magnitude† of Jan. mean flow	119	50.8	122
Variability† of Jan. mean flow	94.8	23.2	77.7
Magnitude of Apr. mean flow	185	178	211
Variability of Apr. mean flow	60.8	84.9	71.7
Magnitude of Jul. mean flow	85.5	80.9	77.9
Variability of Jul. mean flow	43.6	32.8	34.1
Magnitude of Oct. mean flow	53.9	52.1	72.7
Variability of Oct. mean flow	52.6	22.6	43.7
Monthly Q95	33.4	37.4	46.4
Monthly Q5	227	203	229

[†]Magnitude expressed as 50th percentile and variability as the IQR, cf. Table 1.

The weakest point of WaterGAP simulation can be attributed to the winter season, when for example the model underestimated the median of mean January flows by 58%, which largely contributes to the mean annual model bias of 19% (Table 3). SWAT, in contrast, shows very little mean annual bias (3%), however it tends to under-predict flows in spring and autumn, and over-predict in summer. The magnitude of these seasonal biases in SWAT does not exceed 25%. As regards the inter-annual variability at monthly scale, this feature is strongly underestimated by WaterGAP in October and January. The high and low flows are modelled relatively well by both models. Both SWAT and WaterGAP underestimate monthly Q95 and Q5 indices, in the worst case by 28% (Table 3).

Overall, the model performance well reflects the differences between the modelling scale of the analysed models and of the quality of input data used by them. The conclusion is that the model behaviour in the baseline period is satisfactory and further analysis focused on the impacts of climate change can be made.

Impacts on flow parameters

Figure 6 illustrates the magnitude of projected changes in selected flow parameters at the basin outlet, under climate change scenarios from two GCMs. The results show that under IPSL-CM4 both models indicate a nearly 20% decrease in mean flow, whereas under MIROC3.2 both indicate a 12% increase. This behaviour is clearly consistent with projected temperature and precipitation changes of both climate models (Fig. 4). When it comes to other parameters than mean flow, SWAT and WaterGAP are less consistent as far as the magnitude of change is concerned, however they usually agree about the direction of change. The only example of apparent disagreement in direction of change is Q5 under MIROC3.2, for which SWAT shows an increase by 17% and WaterGAP a decrease by 11%.

The largest magnitude of change can be observed for the median of January mean flows (Fig. 6). This parameter is supposed to largely increase according to both models, and under both GCM scenarios. The relative change is a bit misleading in the case of this parameter, since it was largely underestimated by WaterGAP in the baseline period (cf. Table 3). When the absolute differences are taken instead, the models are fairly more consistent. This large increase in January flow can be explained by the increase in precipitation during three months in a row (from November to January, cf. Fig. 4) accompanied by an increase in temperature, which triggers a more rapid snow melt (if any, because most of January precipitation will come as rain in these scenarios). The other interesting feature shown in Figure 6 is a reduction of April flow by each model for each climate scenario, ranging from -14% to -39%. This is not so surprising for IPSL-CM4 which projects a 25% decrease in precipitation in this month, but is a bit surprising for MIROC3.2 which shows an increase in precipitation both in March and April.

Impacts on environmental flow indicators

Figures 7 and 8 illustrate spatial variability in environmental flow indicators: Figure 7 in *GEFI*, and Figure 8 in *FII* and *RHAI* (cf. Table 1 and 2). Table 4 summarises the statistics of sites under different levels of impact for three studied indicators.

Table 4. Per cent of outlets (SWAT) and grid cells (WateGAP) with different degrees of impact for three studied indicators, *GEFI*, *FII* and *RHAI* and different combinations of GCM, time scale and hydrological model.

Indicator	*GCM*	*Time scale*	*Model*	*No impact*	*Low impact*	*Moderate impact*	*High impact*
GEFI	IPSL-CM4	daily	SWAT	0	23	67	11
			WaterGAP	0	15	81	4
		monthly	SWAT	0	23	62	15
			WaterGAP	0	2	92	6
	MIROC3.2	daily	SWAT	0	21	75	4
			WaterGAP	0	10	88	2
		monthly	SWAT	0	22	71	7
			WaterGAP	0	21	79	0
		Mean		**0**	**17**	**77**	**6**
FII	IPSL-CM4	monthly	SWAT	4	17	66	13
	MIROC3.2	monthly	SWAT	4	18	62	17
		Mean		**4**	**18**	**64**	**15**
RHAI	IPSL-CM4	monthly	SWAT	11	23	62	4
	MIROC3.2	monthly	SWAT	7	26	56	12
		Mean		**9**	**25**	**59**	**8**

It is noteworthy that in each of eight combinations of variables (hydrological model, GCM and time scale), the most dominating class, including in average 77% of sites, is the “moderate impact”. This suggests that climate change will have a measurable impact on the aquatic ecosystems of most parts of the Narew basin. The visual assessment of spatial patterns (more rigorous statistical analysis will be shown further) indicates, that there is only a moderate agreement between results of the two hydrological models in terms of climate change-induced impact on environmental flow indicators. However, the proportion of “large impact” sites as well as “low impact” sites is always higher in

SWAT (Table 4), which could be interpreted in a way that WaterGAP is less sensitive to the climate change signal, or that SWAT is more sensitive to small scale processes, in general. This is also consistent with Figure 6, which shows that in majority of cases SWAT indicates higher magnitude of change in parameters.

In general, impacts on environmental flow indicators are higher for IPSL-CM4 than for MIROC3.2. As shown in Figure 4, the climate change signal for temperature was slightly stronger for IPSL-CM4, whereas for precipitation there were large within-year variations, however MIROC3.2 signal could be considered stronger. The spatial patterns are similar between the GCMs only in the case of WaterGAP and daily time scale. For SWAT, the patterns differ considerably between GCMs regardless of the time step. For instance, in the case of IPSL-CM4 a large portion of the River Biebrza (cf. Fig.1) exhibits a high impact, whereas for the MIROC3.2 the Biebrza is largely un-impacted, though many small headwater rivers are impacted.

Since all seasonal indicators (P4-P11) yield the same scores regardless of the time step used in calculations, there is a limited potential of observing a difference between monthly and daily maps from Figure 7. Hence, the comparison between the results obtained using monthly and daily time steps will be examined further, only for the flood and low flow indicators (P1-P3 and P12-P14, cf. Table 1).

Results from SWAT based on daily output suggest that the majority of river reaches will be under moderate impact in terms of most ecologically-relevant indicators *FII* and *RHAI* (Fig. 8). This implies that connectivity between the river and its floodplains may be reduced, and habitat for vegetation, invertebrates, water birds and fish may be degraded or lost. Similarly as in Figure 7, more severe impacts can be observed for a drier climate change scenario from IPSL-CM4 than for a wetter scenario from MIROC3.2. In contrast to *GEFI*, for each case in Figure 8 there is at least several reaches for which no impact can be observed. Most of the reaches under high impact are distributed around the basin, with small upstream catchment areas. The proportion of the sites with no or little impact is higher in the western part of the basin than in the eastern part.

Consistency of impacts

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. 3). Per cent of pairs with consistent colour codes equalled to 60% for IPSL-CM4 and 66% for MIROC3.2 in the case of monthly time step and 55 and 62% respectively for the daily time step.

To understand which indicators were responsible for differences between SWAT- and WaterGAP-based estimates, the background data (i.e. 14 hydro-ecological parameters making up the *GEFI*) were analysed (cf. Table 1). All indicators are binary: they can either show or not show an impact, depending on the 30% exceedance threshold. Hence, when comparing SWAT- and WaterGAP-based indicator values, there are four possible cases: (1) neither of models shows an impact; (2) both models show an impact; (3) only SWAT shows an impact, and (4) only WaterGAP shows an impact. Figure 9 illustrates the distribution of the above features over the 58 analysed pairs of SWAT outlets and WaterGAP grid cells.

The percentage of pairs for which the impact of climate models was consistent (ie. sum of cases (1) and (2)) between SWAT and WaterGAP was variable across the set of hydro-ecological parameters. On average, 55% pairs had consistent impact for IPSL-CM4 and 59% for MIROC3.2. This percentage ranged from 19% for the IQR of mean January flow (P5) for IPSL-CM4 to 100% for low flow magnitude median (P12) for MIROC3.2. Figure 6 can partly help to explain the behaviour in Figure 9. For example, Figure 6 shown that April flow is likely to be significantly lower under IPSL-CM4 scenario as simulated by SWAT and WaterGAP, hence Figure 9 shows that for P6 and P7 a large part of sites shows consistency between the models in showing an impact. A similar case is with January flow under MIROC3.2 in Figure 6 and parameter P4 in Figure 9. The comparison of Figures 6 and 9 brings also the conclusion about the role of the 30% exceedance threshold that was used to classify sites as either impacted or unimpacted, ie. Figure 6 illustrated that under IPSL-CM4 WaterGAP simulated a 51% increase in January flow, whereas SWAT simulated only 12% increase. In consequence, Figure 9 shows that for P5 under IPSL-CM4, for majority of sites only WaterGAP shows an impact.

Spatial analysis of consistency between SWAT- and WaterGAP-based results shows that there is a strong geographical variability (Fig. 10). In the case of IPSL-CM4, the larger upstream catchment area, the higher consistency: for three groups of grid cells divided with respect to their upstream catchment area: (1) smaller than 2,000; (2) between 2,000 and 10,000 and (3) larger than 10,000 km^2, mean consistency equals 53%, 60% and 72%, respectively. For both climate models there is good consistency in the River Pisa, which drains the lake district in the northern part of the basin (cf. Fig. 1), and therefore has a more stable flow regime than other rivers in the catchment. This might be explained by the lakes acting as a hydrological buffer, since both of the models show relatively low impact on studied indicators (cf. Fig. 7). Another potential reason for inconsistencies between SWAT, and WaterGAP is imprecise schematisation of the stream network in the latter model (cf. Fig. 3). As previously mentioned, the choice of corresponding pairs of WaterGAP grid cells and SWAT outlets was approximate in several cases, which may be the cause of at least some of the observed inconsistencies.

As previously mentioned, the comparison between the impacts estimated using different time scale of modelled output data, should be studied only for flood and low flow IHAs: P1-P3 and P12-P14. For each of these IHAs and each combination of hydrological model and GCM we calculated the percentage of sites for which the impacts were the same regardless of the time scale. On average, 54% of all cases showed consistent impacts, ranging from 47% for P2 to 67% for P14.

Discussion

Our results suggest that WaterGAP and SWAT produce broadly similar, though locally different projections of the impacts of climate change on river ecosystems. Under certain conditions the use of WaterGAP might lead to different adaptation and mitigation measures than employing those resulting from using SWAT. However, it largely depends on which level of detail the decision-making process would be based. If decisions were to be based on the broadest level, such as pie charts in Figures 7 and 8, which summarise impacts over a whole catchment, they would likely be the same. However, if decisions were to be based on the most detailed level, e.g. for a small tributary river or for a single indicator, then, according to Figures 9 and 10, the chance that they would be different is relatively high.

Hence, a challenging question is: what is the added value of using a catchment model in climate change assessment studies focused on environmental flows at country-, region-, river basin-level, or river reach-level compared to using a global hydrological model? Global models are typically set up, and run by certain institutions, and thus not available for a wide public. Their obvious advantage is their global or continental coverage, which is particularly attractive to regional policy-makers, such as in the European Commission, because they provide consistency of approach between river basins across the whole area of interest (e.g. continent) and permit fair policy making. The trade-off is that there are important uncertainties, e.g. related to the accuracy of continental models at small spatial scales, which is usually of interest of local stakeholders. It is obvious that tailor-made catchment models can answer the questions of their interest, but the trade-off related to time and resources that need to be invested, should be considered. For example, SWAT is a public domain model, which is popular worldwide (Gassman et al., 2007) and very flexible. However, to set-up and calibrate the model for a region of interest may require a considerable amount of time and human resources, as proved the study of Piniewski and Okruszko (2011). They reported that it took nearly three months of pure computational time to comprehensively calibrate SWAT for the NRB using automatic calibration tools, not to mention time required for assembling input data and setting the model up. The detailed results from global models are usually published only in scientific publications, e.g. Gosling et al. (2011), Döll and Zhang (2010), Laizé et al. (2010) or Schneider et al. (2011a) although summary results, such as continental maps, are sometimes included in more widely accessible reports e.g. those of the IPCC or regional scale water resources or ecological assessment. One of the few, if not the only, exceptions to this is the SCENES Webservice (Schneider, 2011), which is a WebGIS platform containing 730 pan-European maps of drivers, pressures, state variables and impact indicators that are all readily available for use by a wide public. The only similar WebGIS service with global hydrological maps, of which the authors are aware, is the Digital Water Atlas[2] of the Global Water Systems Project. The Atlas contains 70 global maps, of which several are focused on ecohydrology, e.g. maps of the estimated volume of water required for the maintenance of freshwater-dependent ecosystems at the global scale (GWSP Digital Water Atlas, 2008). However, this WebGIS provides

[2] http://atlas.gwsp.org/ [last accessed 30/1/2012]

data for the current conditions only, which is a substantial difference compared to the SCENES Webservice.

One possible way of making good use of the results derived from both types of models would be to apply a tiered risk-based approach in which the results from an easily accessible platform, such as the SCENES WebService, would serve for screening of broad-scale patterns appropriate for strategic assessment, whereas the catchment model would be used only in a limited number of places, of special interest to water managers and conservation practitioners with responsibilities for floodplain / wetland protected areas, for local planning issues such as dam construction, irrigation investment etc. The trade-off in time and resources reflects the finer resolution results required at local level to address local issues. A risk-based tier approach of this type was developed for impact assessment of wetlands by Acreman and Miller (2007). The basic principle is to start with simple analysis tools and adopt more complex techniques if necessary; i.e. use the simplest approach that gives an acceptable level of confidence, moving to a higher level if there is a high degree of uncertainty in the results.

In the more general context of water resources planning, the trade-off between using models of different accuracy in climate change impact studies, the three-tier hierarchy of the nested planning levels is noteworthy, e.g. as used by the U.S. Water Resources Council (WRC; Stakhiv and Major, 1997). In this approach level A encompassed framework studies for multiple river basin or large systems, level B strategic plans and project priorities at the 2-digit U.S. Geological Survey (USGS) level, whereas level C project feasibility studies at the watershed level (6- or 8-digit USGS level). Hamilton et al. (2010) emphasised that the global nature of climate change differentiates it from other environmental stressors, such as land use change or water abstractions. It will require refocusing water policy implementation from the local scale, corresponding to the level C studies, to a watershed scale or larger scale, which would correspond to levels A and B from the WRC policy.

A good example of global analysis of water and ecosystems is that of Vőrősmarty et al. (2010) who analysed incident human water security and biodiversity threats in a global geospatial approach. They found that 65% of the aquatic habitat supported by global river discharge is under moderate to high threat, which well explains the observed global biodiversity loss. They conclude that assessing competition between ensuring water security, and protecting freshwater habitats requires high-resolution spatial approaches that engage policymakers and water managers at scales relevant to their decisions, including subnational administrative units, river basins and individual stream reaches. The results of our analysis support this statement. Even in a catchment like the Narew, without direct threat of human intervention on river–floodplain system, we can expect changes which endanger the ecosystem functioning. In particular flood pulse (assessed by *FII*) and thus functioning of riparian ecosystems should be considered as more endangered than the status and functioning of the in-stream ecosystems (assessed by *RHAI*).

One of the issues hampering the development of policies to protect aquatic ecosystems from the hydrological effects of climate change is large uncertainty in the GCMs (Kundzewicz and Stakhiv, 2010). Poland lies within the zone of highly uncertain projections of precipitation (Nohara et al., 2006) and, hence, of runoff (Milly et al., 2005). Two climate models that were used in this study also exhibited large inconsistency in future projections of precipitation (cf. Fig. 4) and runoff (cf. Fig. 6). In response to questions of model uncertainty, the UK Climate Change Impacts programme (www.ukcip.org.uk) has produced a set of 10,000 possible realisations of each climate scenario. However, using these presents a challenge for complex models with long run-times. The need to reduce this uncertainty is well-documented (Kundzewicz et al., 2008), and hence, its incorporation into decision-making process is unavoidable. It is unlikely that the climate models will begin to provide useful information for vulnerability assessments earlier than a decade from now (Kundzewicz and Stakhiv 2010). Other climate-related sources of uncertainty in our assessment lie in:

- using the delta change approach for correcting the GCM biases;
- interpolation of monthly baseline climate inputs to daily values (only in WaterGAP, as in SWAT daily station data for the baseline period were applied).

As shown e.g. by Beldring et al. (2008) or te Linde et al. (2010), the delta change approach is not able to address changes in future climate variability. However, only recently bias corrected, daily climate forcing datasets have become available for global or continental analysis (e.g. WATCH forcing data, Weedon et al., 2011) and hence, could not be used within the SCENES project. Consequently, climate input data needed to be artificially downscaled for WaterGAP to the daily time step. The downscaling followed the method proposed by Geng et al., 1986, which is similar to the approach taken by Gosling and Arnell (2010) for global runoff simulations, apart from the fact that the former approach provided more variability in precipitation and temperature. Regarding annual runoff, they concluded that downscaling of monthly climate input to the daily time step worked well, except in regions where the day-to-day variability in relative humidity is high. However, in modelling environmental flow indicators, the uncertainties related to using interpolation of climate data are likely to be higher. Indeed, as shown by Schneider et al. (2011b) flood peaks were underestimated by WaterGAP when monthly climate data were used in comparison to daily climate data. This could explain why ”large impact” sites as well as “low impact” sites are more frequent in SWAT, and why the percentage of consistent pairs is slightly higher for the monthly than for the daily values. In summary, taking advantage of readily available global bias-corrected daily climate datasets, the methodology used here could be improved in future studies.

Conclusions

This study shows that there is a considerable variability in projected impacts of climate change on environmental flow indicators. This variability is expressed both in terms of spatial distribution of impacts as well as in terms of climate model, hydrological model and type of indicator in consideration. However, it is noteworthy that the moderate impacts dominated throughout the Narew catchment. This means that in particular some of the important ecosystem services of the Narew river system, such as providing habitat for fish spawning and waterfowl feeding and roosting on the flooded floodplains or providing appropriate in-stream habitat for fish and macroinvertebrates, might be at risk in the future scenarios. This information should be taken into account when addressing the issue of impact of climate change on ecological status of the analysed rivers in the second cycle River Basin Management Plans.

One of the implications of this study is that broad-scale models, such as WaterGAP, can provide useful results on the effects of hydrological change on river ecosystems that can be used directly by decision-makers for broad-scale planning and also for feasibility studies of specific river reaches. To this end, open WebGIS services, such as the SCENES Webservice, are very useful tools. However, where development of specific infrastructure or regulation of abstraction is focused on small river basins with many minor tributaries a local model, such as SWAT, would be more appropriate. Hence, using a tiered approach in which the large-scale model would be used at the first-step level, and the more detailed catchment model would be used for rivers or regions of special interest, is one of the ways of efficient decision-making in climate change impact studies focused on environmental flows. Future research should concentrate on how to make GCM projections more useful for practical water management problems, and how to incorporate climate modelling uncertainty into decision-making process.

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Fig. 1. Map of the study area.

Fig. 2. Observed daily discharge hydrographs at the basin outlet (Zambski Kościelne station on the Narew) during a wet year 1994 and a dry year 2003. Hydrological year in Poland lasts from 1 November to 31 October. Q denotes discharge [cms, or m^3s^{-1}] and P denotes precipitation [mm].

Fig. 3. Selected pairs of SWAT river reach outlets and WaterGAP grid cells.

Fig. 4. Basin-averaged changes in temperature (A), and precipitation (B) from IPSL-CM4 and MIROC3.2.

Fig. 5. Modelled and measured daily flows of the River Narew at Ostrołęka GRDC station no. 6458810 during the simulation period 1976-2000.

Fig. 6. Projected changes in monthly flow parameters relative to baseline under two GCMs as simulated by SWAT and WaterGAP at the basin outlet. The parameters are, respectively: mean flow, median of January/April/July/October mean flow, low flow index Q5 and high flow index Q95.

Fig. 7. Colour-coding of the environmental flow indicators for all combinations of two GCMs, two hydrological models and two time steps: (A) IPSL-CM4 – SWAT – daily, (B) IPSL-CM4 – WaterGAP – daily, (C) IPSL-CM4 – SWAT – monthly, (D) IPSL-CM4 – WaterGAP – monthly, (E) MIROC3.2 – SWAT – daily, (F) MIROC3.2 – WaterGAP – daily, (G) MIROC3.2 – SWAT – monthly, (H) MIROC3.2 – WaterGAP – monthly. Pie charts show proportions of different categories in corresponding maps.

Fig. 8. Floodplain Inundation Indicator (*FII*) and River Habitat Availability Indicator (*RHAI*) for IPSL-CM4 (A-B) and MIROC3.2 (C-D). Pie charts show proportions of different categories in corresponding maps.

Fig. 9. Consistency of monthly hydro-ecological parameters between SWAT and WaterGAP for two climate models: (A) IPSL-CM4, and (B) MIROC3.2. Key: 1 – neither of models showing an impact; 2 – both models showing an impact; 3 – only SWAT showing an impact; 4 – only WaterGAP

showing an impact. P1 – P3 are flood indicators; P4 – P11 are seasonal flow indicators and P12-P14 are low flow indicators (cf. Table 1).

Fig. 10. Map of spatial variability of the percentage of the IHAs, for which the impact of: (A) IPSL-CM4, (B) MIROC3.2 was consistent between SWAT and WaterGAP.

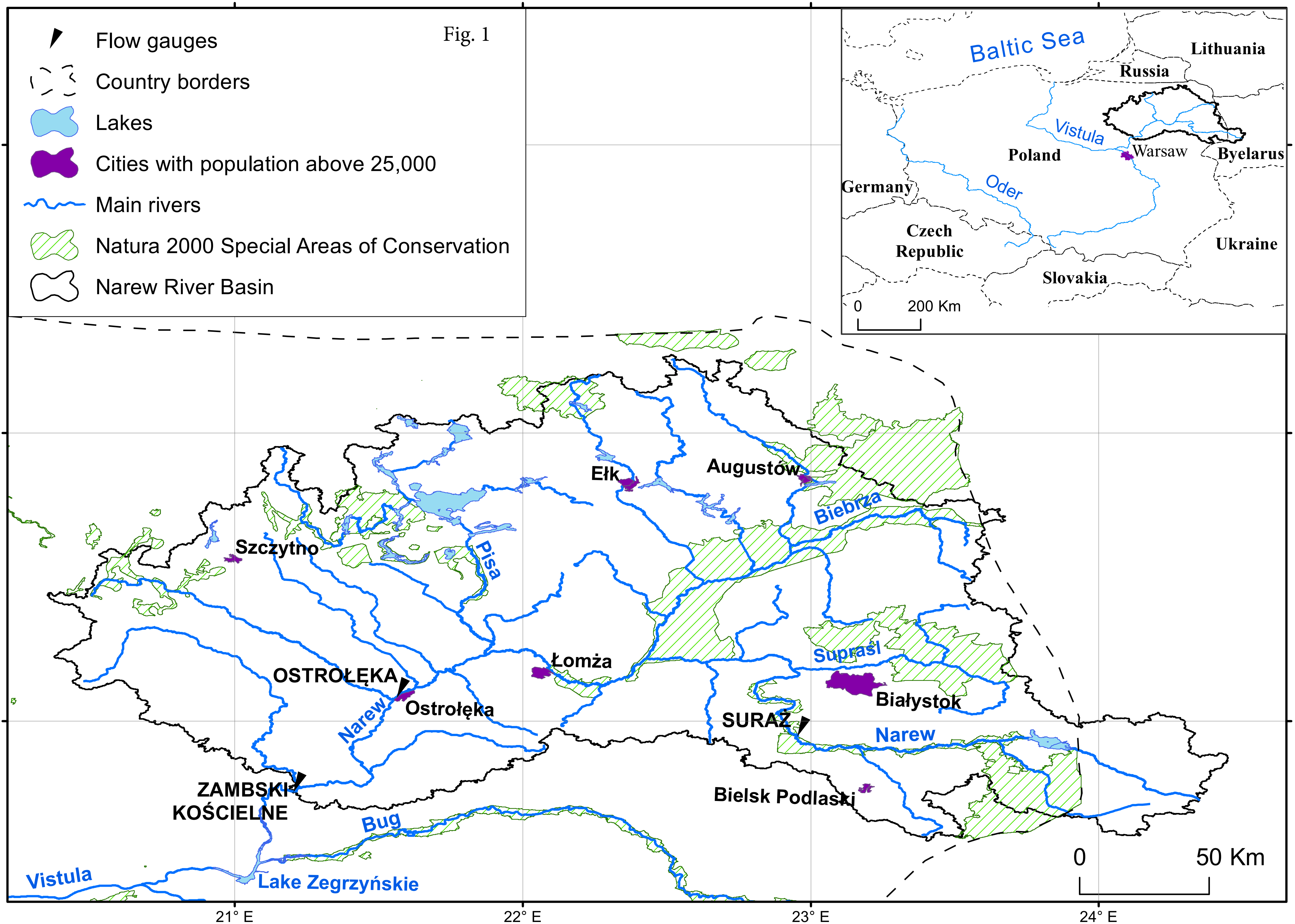
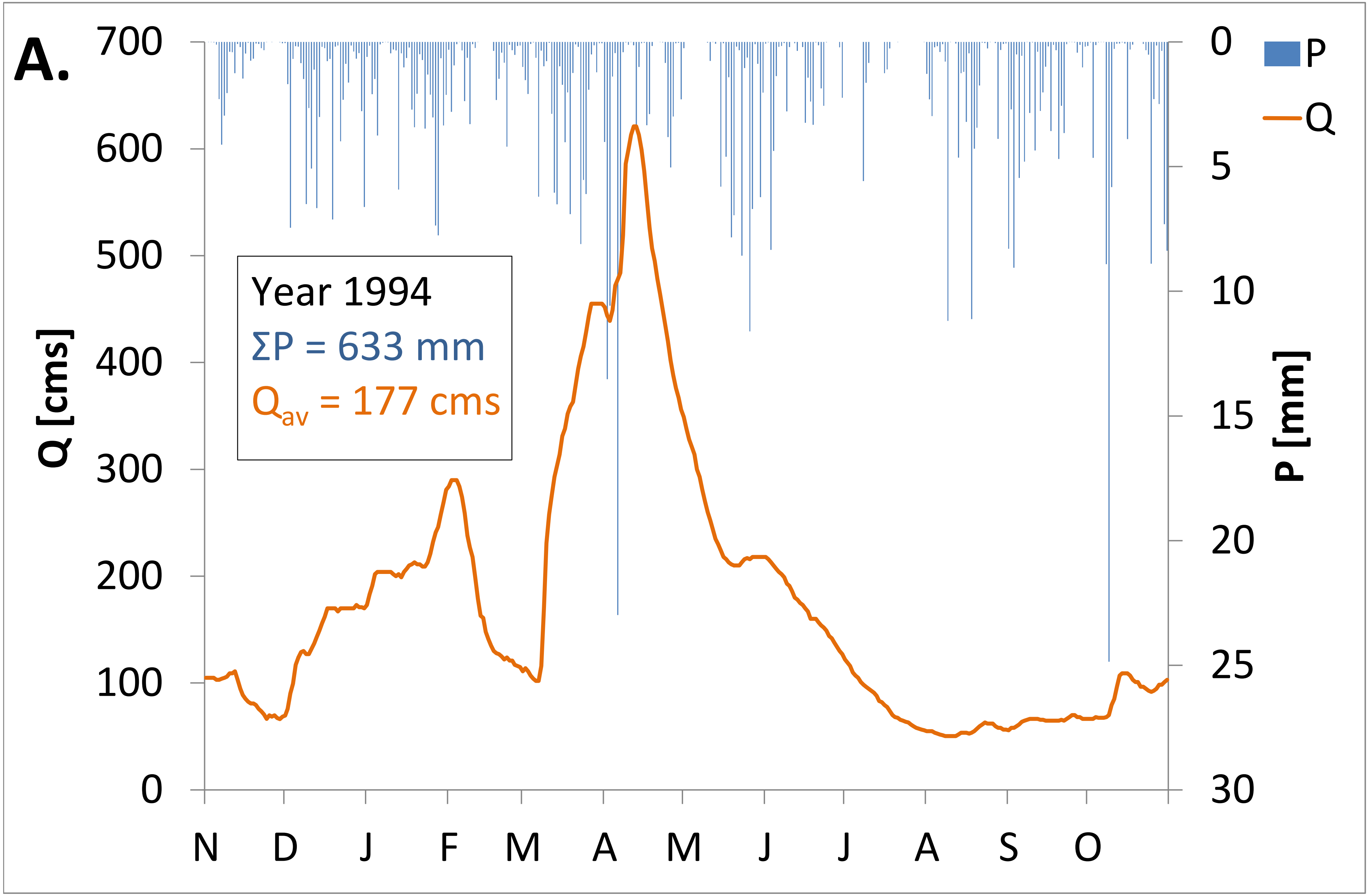


Fig. 1
Flow gauges
Country borders
Lakes
Cities with population above 25,000
Main rivers
Natura 2000 Special Areas of Conservation
Narew River Basin
Baltic Sea
Lithuania
Russia
Vistula
Poland
Warsaw
Byelarus
Germany
Oder
Czech Republic
Ukraine
Slovakia
0
200 Km
55° N
54° N
53° N
Ełk
Augustów
Biebrza
Szczytno
Pisa
Łomża
OSTROŁĘKA
Ostrołęka
Narew
Supraśl
Białystok
SURAŻ
Narew
ZAMBSKI KOŚCIELNE
Bielsk Podlaski
Bug
Vistula
Lake Zegrzyńskie
0
50 Km
21° E
22° E
23° E
24° E

Fig. 2


A.
Q [cms]
700
600
500
400
300
200
100
0
Year 1994
ΣP = 633 mm
Qav = 177 cms
N
D
J
F
M
A
M
J
J
A
S
O
0
5
10
15
20
25
30
P [mm]
P
Q

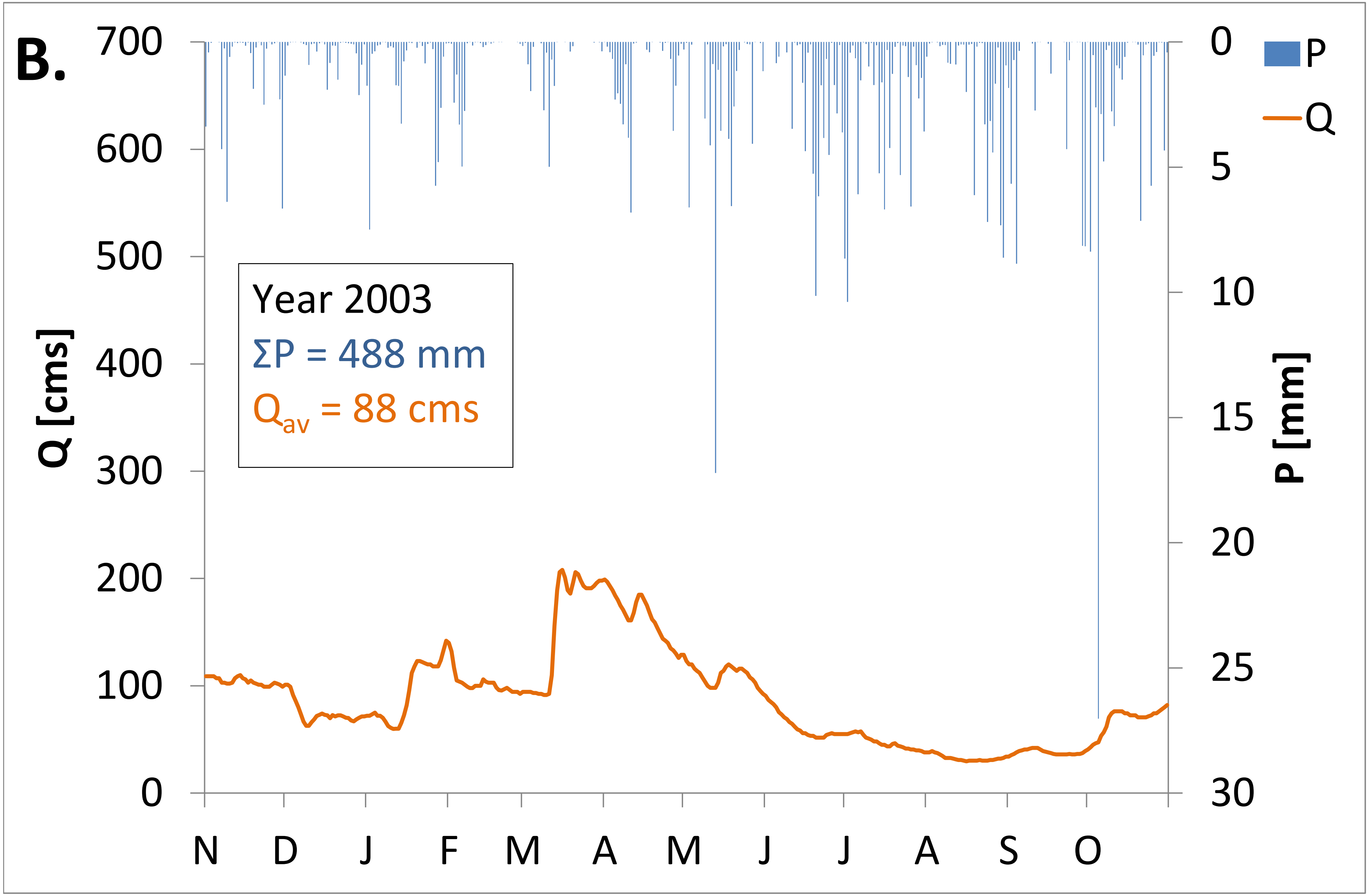

B.
Q [cms]
700
600
500
400
300
200
100
0
Year 2003
ΣP = 488 mm
Q_av = 88 cms
N
D
J
F
M
A
M
J
J
A
S
O
0
5
10
15
20
25
30
P [mm]
P
Q

Fig. 3

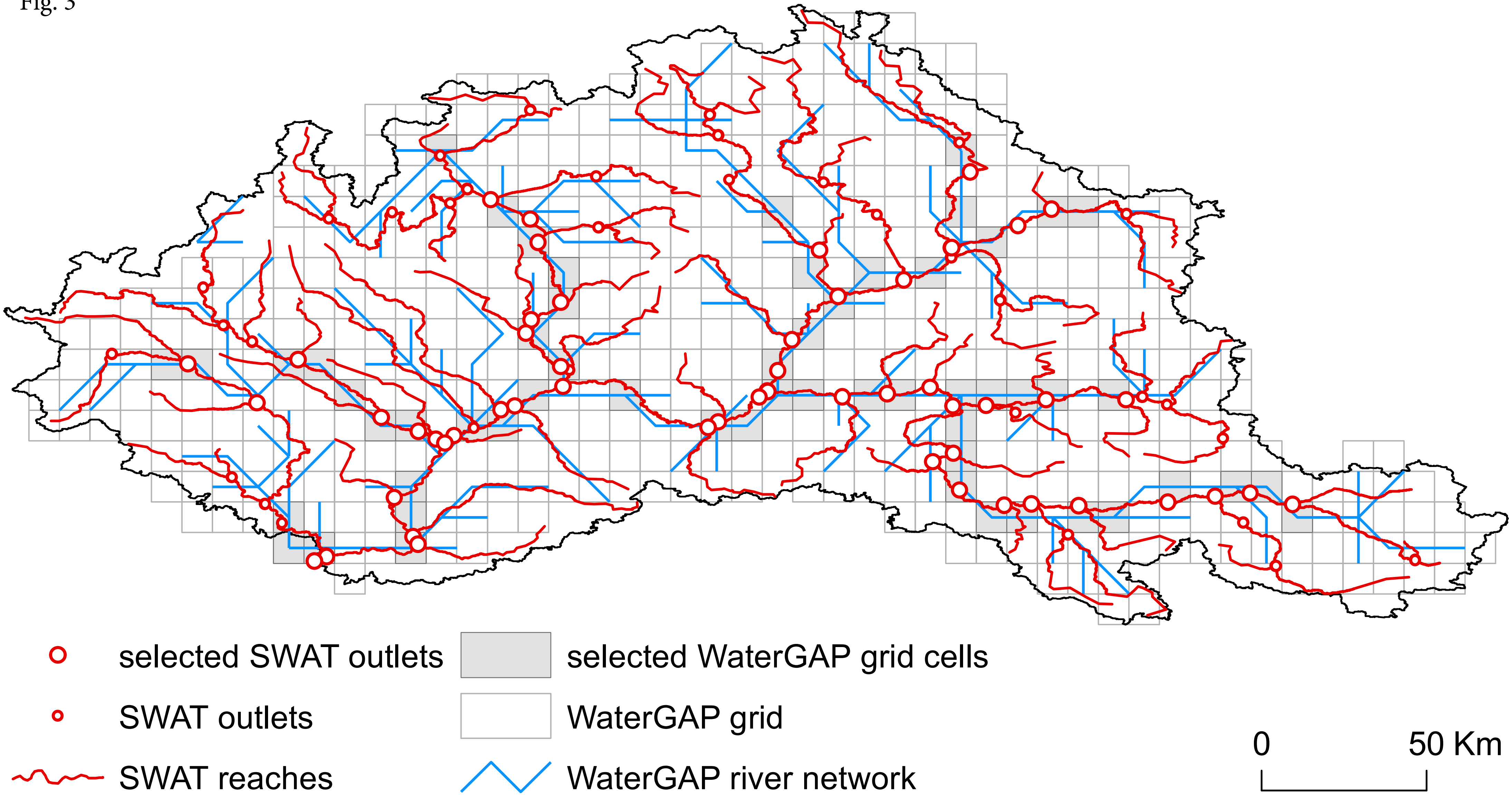
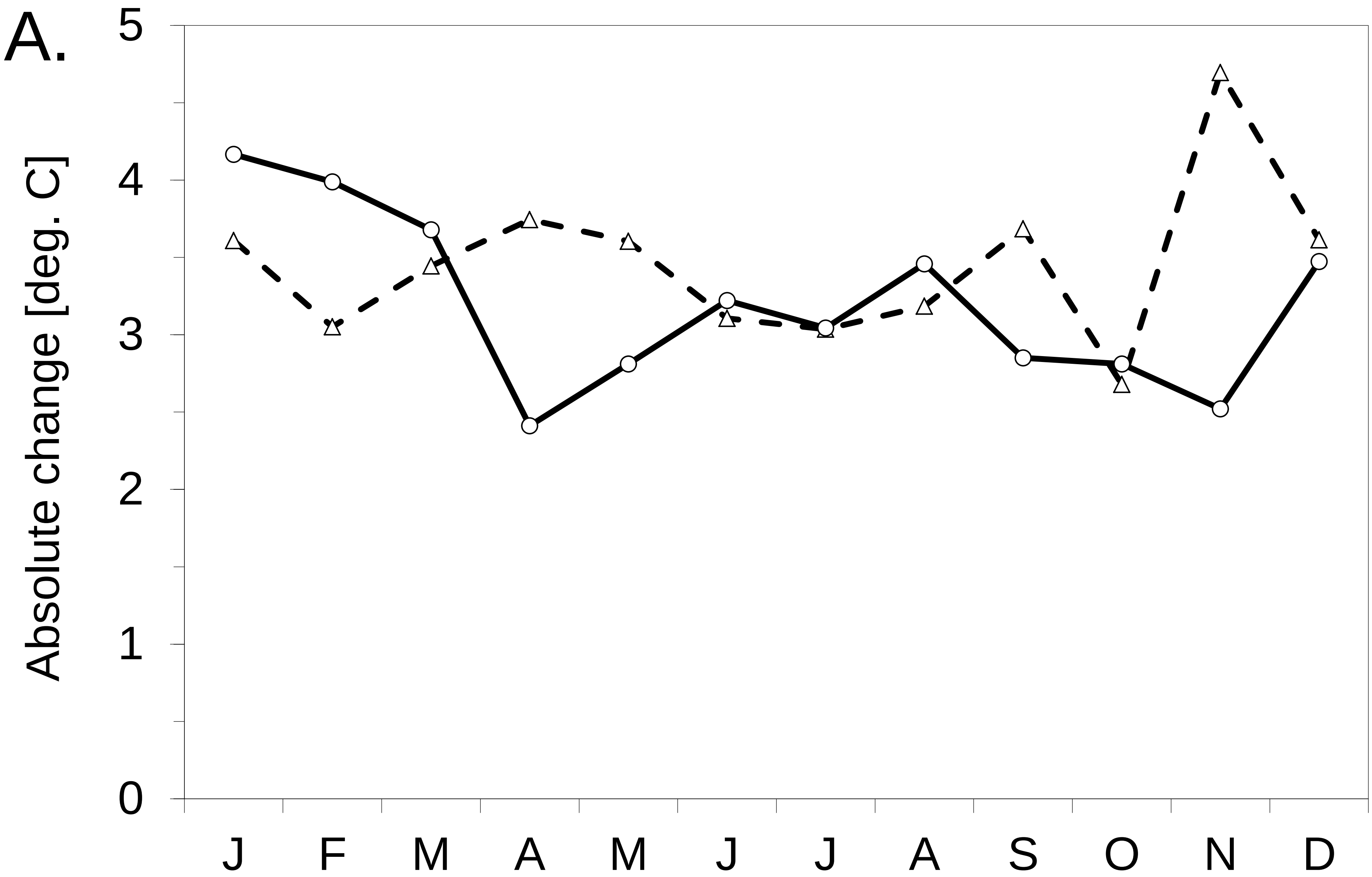
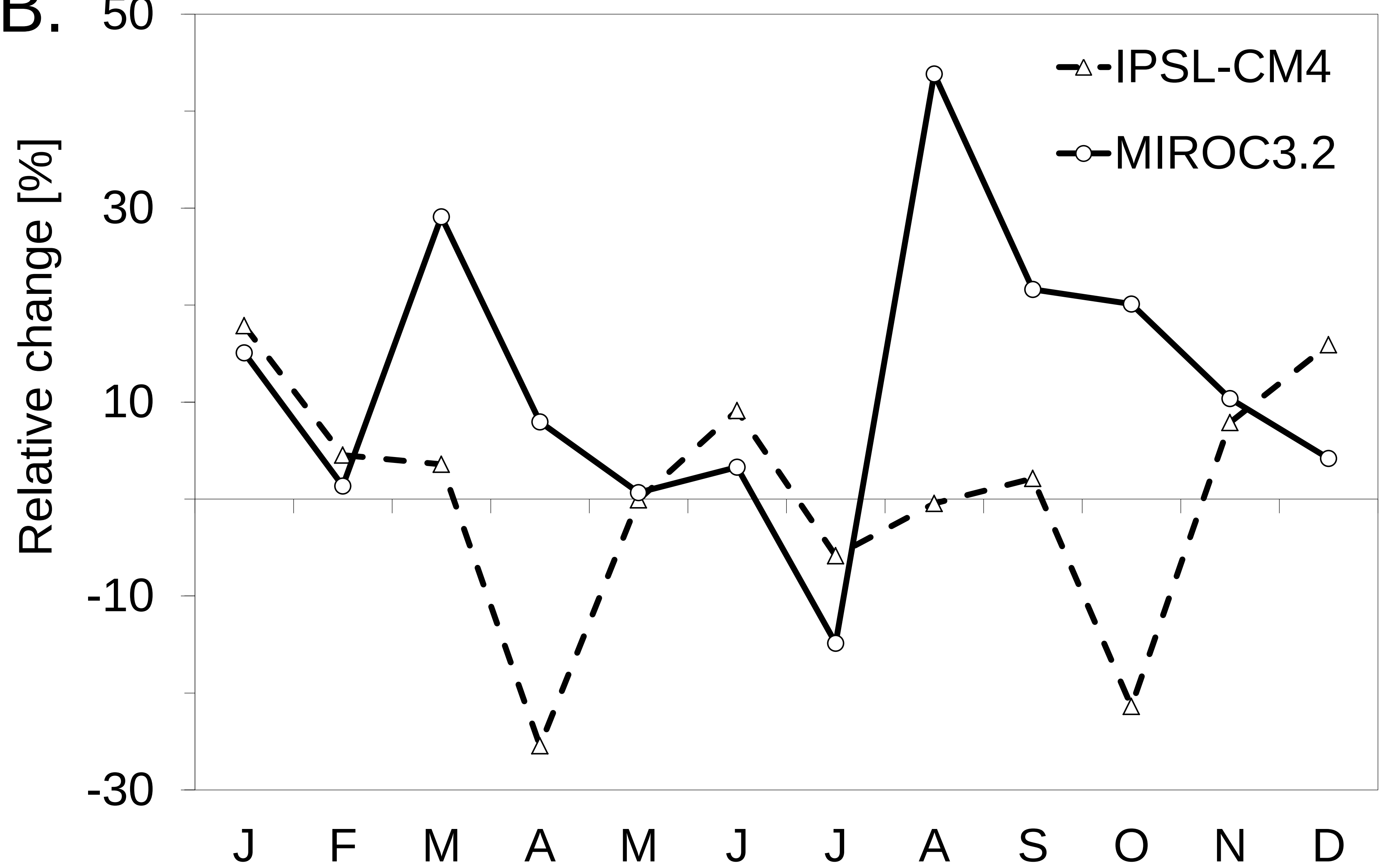

selected SWAT outlets
SWAT outlets
SWAT reaches
selected WaterGAP grid cells
WaterGAP grid
WaterGAP river network
0
50 Km

Fig. 4

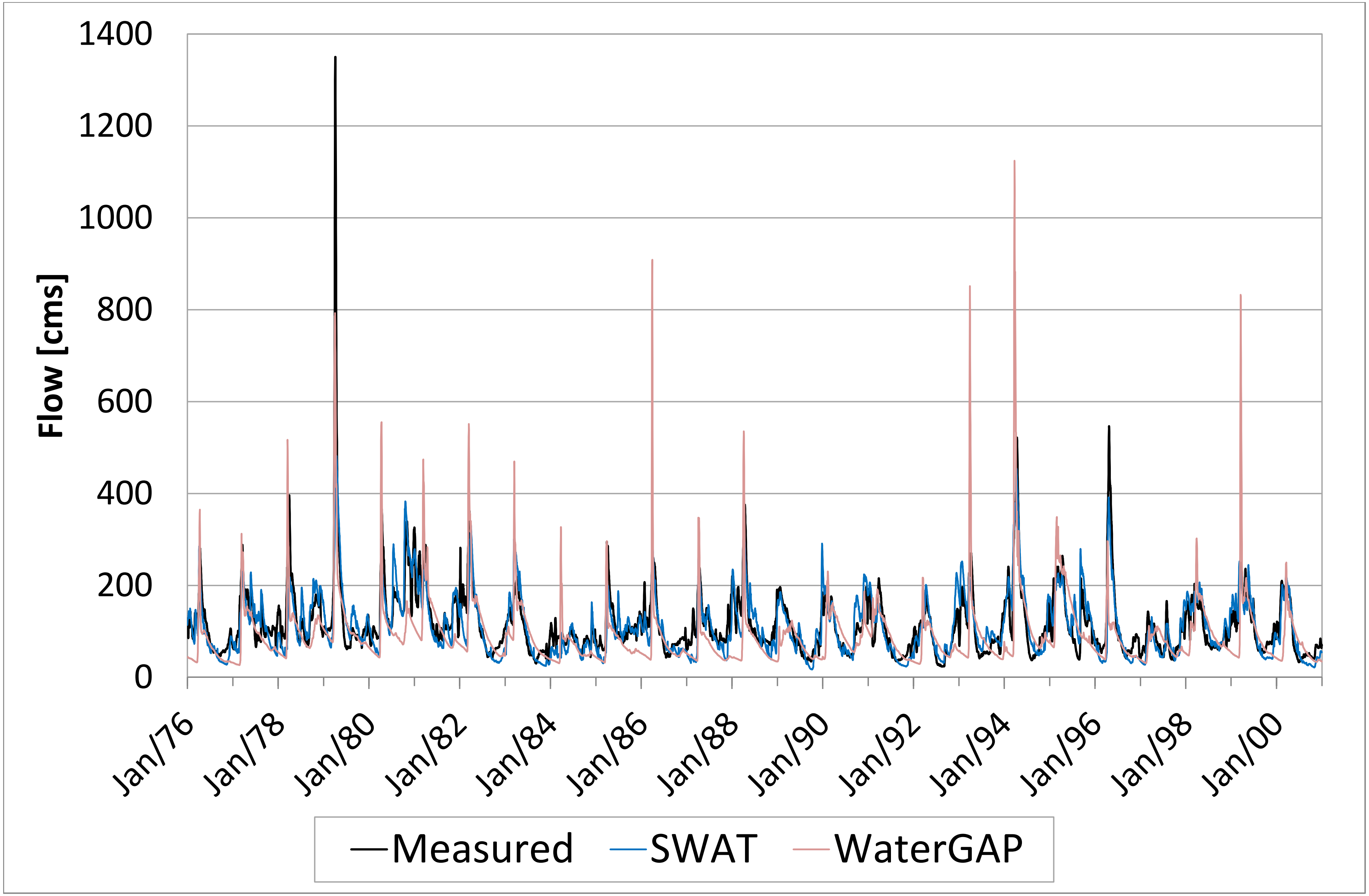


B.



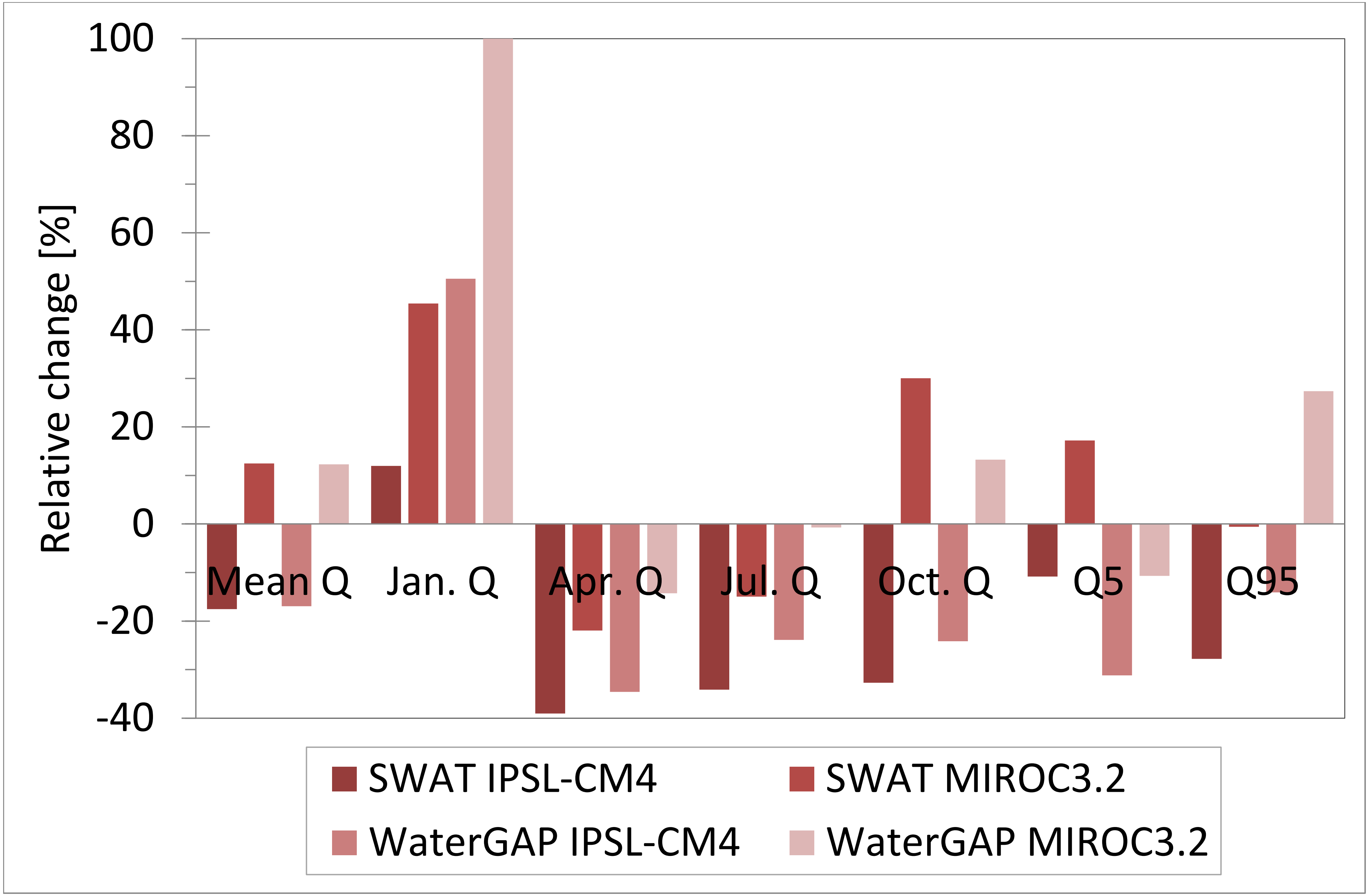
50
30
10
-10
-30
Relative change [%]
IPSL-CM4
MIROC3.2
J
F
M
A
M
J
J
A
S
O
N
D

Fig. 5



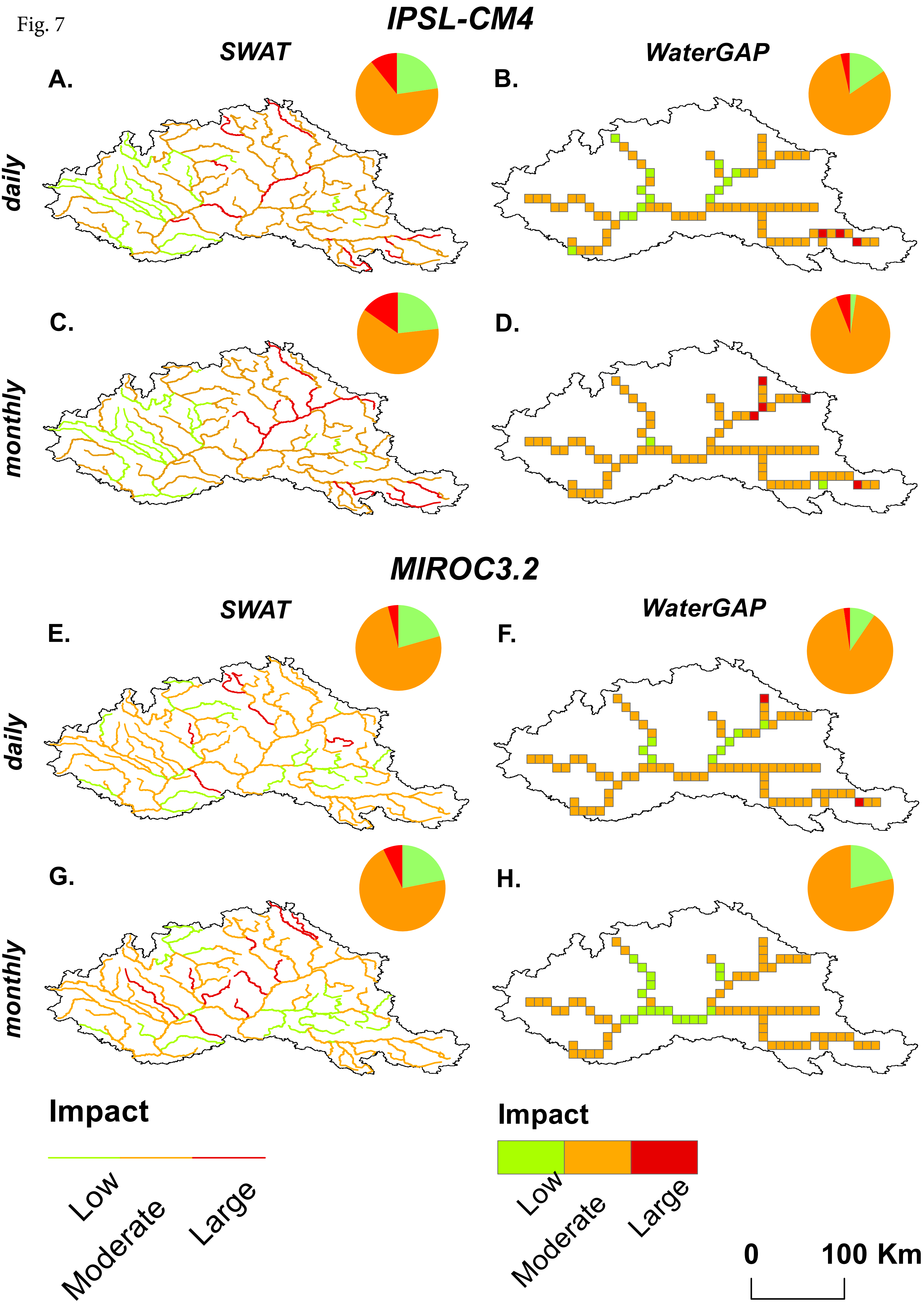
1400
1200
1000
800
600
400
200
0
Flow [cms]
Jan/76
Jan/78
Jan/80
Jan/82
Jan/84
Jan/86
Jan/88
Jan/90
Jan/92
Jan/94
Jan/96
Jan/98
Jan/00
Measured
SWAT
WaterGAP

Fig. 6



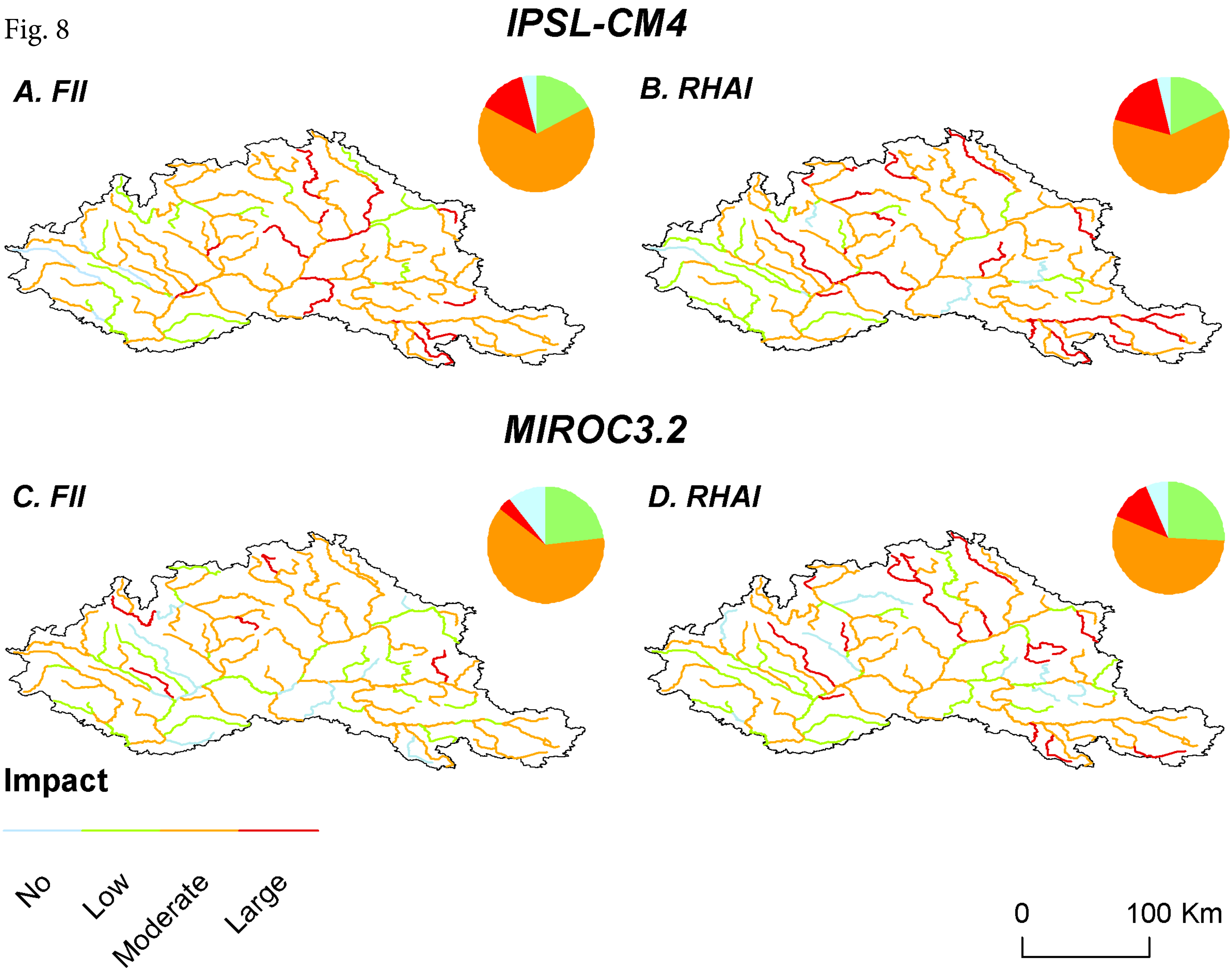
Relative change [%]
100
80
60
40
20
0
-20
-40
Mean Q
Jan. Q
Apr. Q
Jul. Q
Oct. Q
Q5
Q95
SWAT IPSL-CM4
SWAT MIROC3.2
WaterGAP IPSL-CM4
WaterGAP MIROC3.2

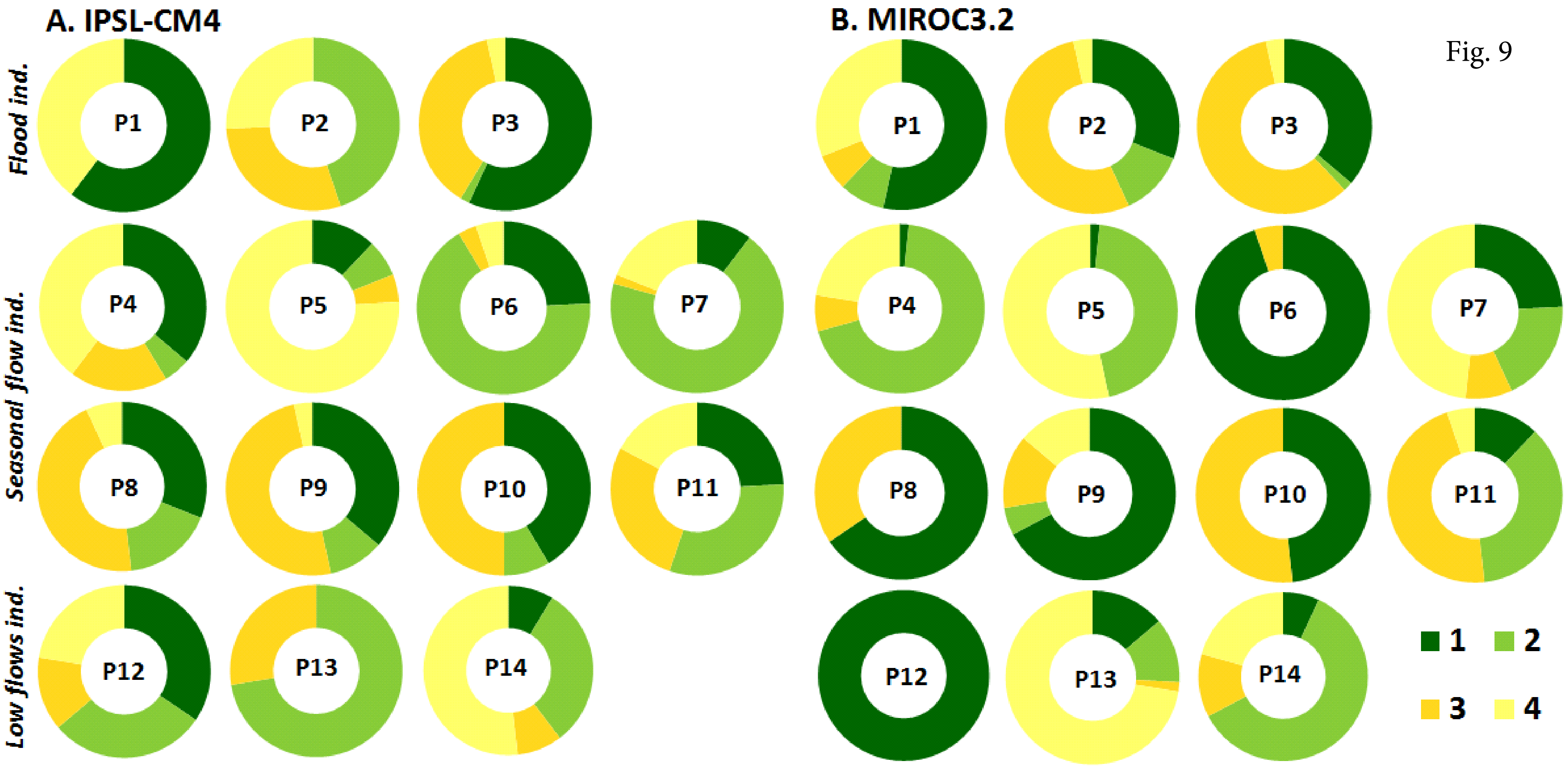
Fig. 7



IPSL-CM4
SWAT
WaterGAP
A.
B.
daily
C.
D.
monthly
MIROC3.2
SWAT
WaterGAP
E.
F.
daily
G.
H.
monthly
Impact
Low
Moderate
Large
Impact
Low
Moderate
Large
0
100 Km

Fig. 8


IPSL-CM4
A. FII
B. RHAI
MIROC3.2
C. FII
D. RHAI
Impact
No
Low
Moderate
Large
0
100 Km



A. IPSL-CM4
B. MIROC3.2
Flood ind.
Seasonal flow ind.
Low flows ind.
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
P13
P14
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
P13
P14
1
2
3
4

Fig. 9

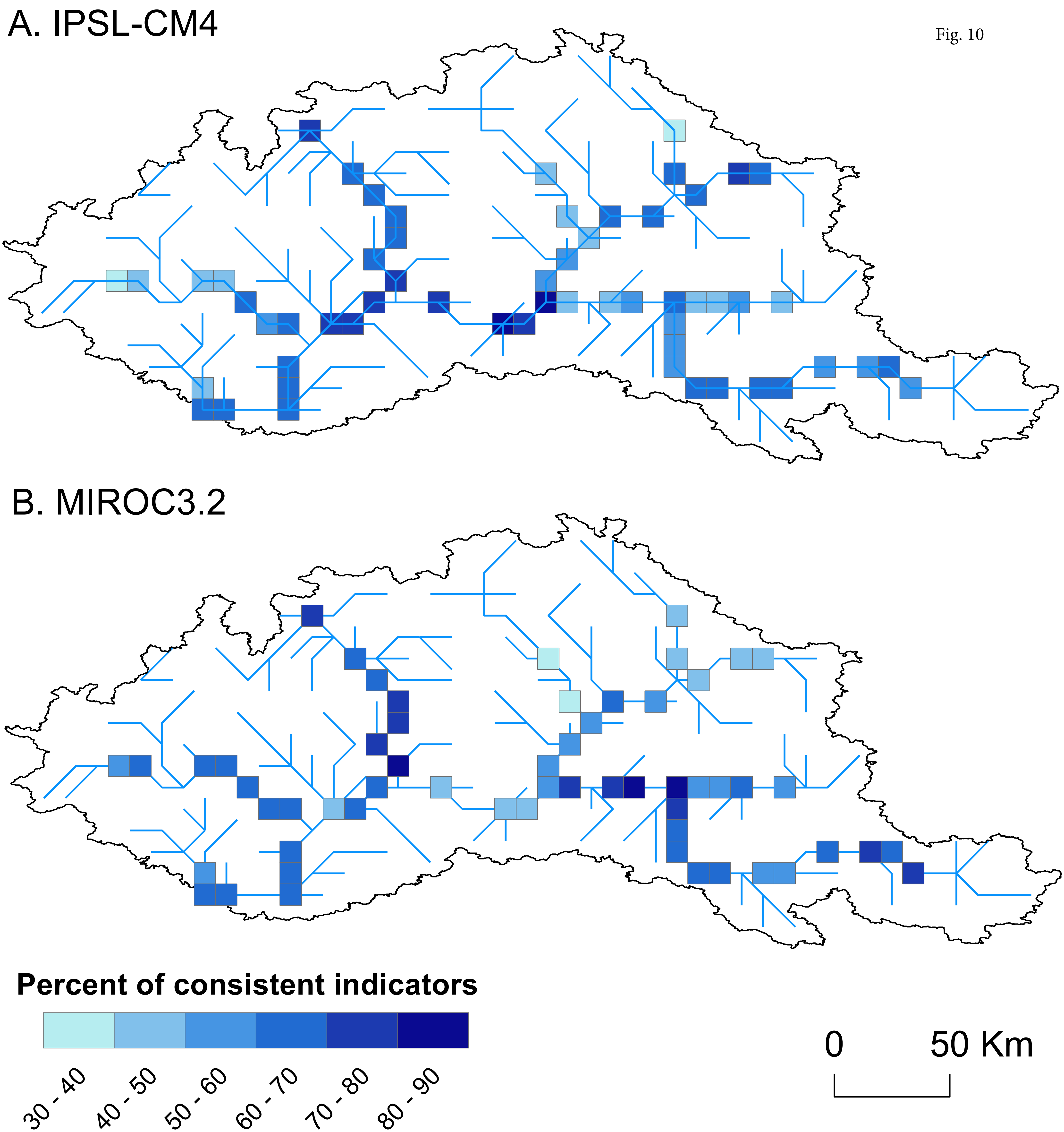


Fig. 10
A. IPSL-CM4
B. MIROC3.2
Percent of consistent indicators
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
0
50 Km