Natural streamflow simulation for two largest river basins in Poland: A baseline for identification of flow alterations

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Abstract. The objective of this study was to apply a previously developed large-scale and high-resolution SWAT model of the Vistula and the Odra basins, calibrated with the focus of natural flow simulation, in order to assess the impact of three different dam reservoirs on streamflow using the Indicators of Hydrologic Alteration (IHA). A novel spatial calibration approach was proposed, in which calibration was focused on a large set of relatively small non-nested sub-catchments with semi-natural flow regime. These were classified into calibration clusters based on the flow statistics similarity. After performing calibration and validation that gave overall positive results, the calibrated parameter values were transferred to the remaining part of the basins using an approach based on hydrological similarity of donor and target catchments. The calibrated model was applied in three case studies related to the effect of dam reservoirs (Włocławek, Siemianówka and Czorsztyn Reservoirs) on streamflow alteration. Both the assessment based on gauged streamflow (Before-After design) and the one based on simulated natural streamflow showed large alterations in selected flow statistics related to magnitude, duration, high and low flow pulses and rate of change. Some benefits of using a large-scale and high-resolution hydrological model for the assessment of streamflow alteration include: (1) providing an alternative or complementary approach to the classical Before-After designs, (2) isolating the climate variability effect from the dam (or any other source of alteration) effect, (3) providing a practical tool that can be applied at a range of spatial scales over large area such as a country. Thus, presented approach can be applied for designing more natural flow regimes, which is crucial for river and floodplain ecosystem restoration in the context of the European Union's policy on environmental flows.

1 Introduction

The Vistula and the Odra basins (VOB), whose total area in Poland, Germany, Czech Republic, Slovakia, Ukraine and Belarus amounts to 313,000 km^2 are among the five largest river basins in the European Union. To date, the VOB has not been modelled in a comparable manner as the remaining three basins from the EU's top five: the Danube (Pagliero et al., 2014), the Rhine or the Elbe (Huang et al., 2015). The VOB is covered by larger-scale applications, e.g. for the Baltic Sea Basin Donnelly et al. (2014) or entire Europe Abbaspour et al. (2015), but they offer much coarser resolution than it would be desired to address locally specific water resource problems. Such problems can be more accurately addressed by a large-scale and high-resolution model that is tailored for this area.

The overwhelming majority of large river basins in the world are currently to some extent impacted by human pressure that usually causes departures of discharge from natural to altered conditions (Richter et al., 1997). The largest impact on streamflow regime is usually attributed to dam reservoirs, although the irrigation systems, inter-basin transfers, point source discharges and withdrawals can also have a considerable effect. The degree of flow alteration in the VOB is moderate compared to western Europe or other worlds regions (cf. Milliman et al. (2008)) and it is possible to identify both a subset of near-pristine benchmark catchments and heavily-regulated catchments.

Assessment of anthropogenic streamflow alteration and identification of baseline streamflow conditions and their range of variability across different scales, is fundamental to water resources management, understanding subsequent ecological effects, and designing environmental flows (Poff et al., 2010). Flow gauge-based approaches to assessing streamflow alteration are popular, but their large-scale applicability is limited due to a low density of gauging stations or missing data records. An alternative approach is to apply a hydrological model that can prove useful in diverse ways. For example, a model that does not account for water management but is targeted at simulation of natural flows can serve as a tool providing a rapid estimate of the baseline hydrological conditions, which is the first step in a popular framework for asessing environmental flows called ELOHA (Ecological Limits of Hydrologic Alteration) framework (Poff et al., 2010).

The main objective of this study is to apply a previously developed large-scale and high-resolution SWAT model of the VOB, calibrated with the focus of natural flow simulation, in order to assess the impact of three different dam reservoirs on streamflow using the Indicators of Hydrologic Alteration (IHA).

2 Natural streamflow simulation with SWAT

A detailed description of the model setup, calibration protocol and model evaluation has been published elsewhere (Piniewski et al., submitted). The corresponding simulation output data have been stored in an open online data repository (Piniewski et al., 2015). Here we provide a short summary essential for better understanding of the core part related to the assessment of flow alteration.

2.1 Model inputs and calibration approach

SWAT is a process-based, semi-distributed, continuous-time hydrological model that simulates the movement of water, sediment and nutrients on a catchment scale with a daily time step (Arnold et al., 1998).

The 40 m resolution Digital Elevation Model (DEM) was hydrologically corrected using stream network data from the Hydrographic Map of Poland (MPHP) in scale 1:50,000 prior to watershed delineation. The whole area of the VOB was divided into 2633 sub-basins. An overlay of land cover, soil and slope maps within SWAT sub-basins resulted in 21,311 units. The median sub-basin and HRU areas were thus 147 and 10.7 km^2, respectively.

The 1951-2013 daily minimum and maximum temperatures [°C] and precipitation totals [mm] were obtained from the CHASE-PL Forcing Data (CPLFD-GDPT5), the gridded daily temperature and precipitation dataset (Berezowski et al., 2015a, b). This dataset was interpolated onto a 5 km grid based on station data from six countries and five institutions, of which the most important was the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB) in Poland, who provided the majority of data. The applied interpolation methods were kriging with elevation as external drift for temperature and indicator kriging for precipitation. Cross-validation of this dataset gave an overall positive result, indicating that the errors are correlated with the density of gauging stations changing over time. Gridded daily data were aggregated at SWAT sub-basin level prior to their direct use for modelling in the VOB.

The SUFI-2 algorithm (Abbaspour et al., 2004) within the SWAT-CUP software package was used for model calibration, validation, sensitivity, and uncertainty analysis. We used Kling-Gupta Efficiency (KGE) as the objective function (Gupta et al., 2009). KGE is easy to interpret as it consists of three components: correlation term r, variability term α and bias term β and its value always gives the lower limit of r, α and β. We selected 1991-2000 as the model calibration period and 2001-2010 as the validation period.

A novel spatial calibration approach accompanied by a parameter regionalisation scheme that leads to simulation of natural (unimpaired) streamflow in the whole model domain was used. The first step of the calibration protocol was selection of small, non-nested (i.e., independent) catchments located in the VOB, with relatively undisturbed flow regimes, the so-called "benchmark" catchments. From 111 "candidate" catchments 31 were excluded based on spatial analyses including the assessment of reservoirs, dams, point sources, water withdrawals, urban land cover, and drainage. Location of 80 benchmark catchments is shown in Figure 1.

In the next step benchmark catchments were grouped into clusters of similar flow regime properties. The rationale was to derive a smaller number of homogeneous calibration areas, each of which would have its own parameter set. In order to group benchmark catchments into clusters, we have followed the statistical approach applied in previous works on natural flow regime classifications (Mackay et al., 2014). Eight flow regime clusters showed in Figure 1 were distinguished.

The total area of 80 benchmark catchments constitutes only 25% of the VOB. Therefore a regionalisation strategy was necessary to transfer calibrated parameter values across the entire VOB. We used the hydrological distance approach (He et al., 2011), in which hydrological similarity was evaluated based on a set of climatic-physiographic properties of the donor and target catchments. This approach was evaluated by validating the model at two most downstream gauging stations on the two investigated rivers.

2.2 Model performance evaluation

The model performance at 80 benchmark gauges as well as at two most downstream basin outlets is illustrated in Figure 2. Median KGE across all benchmark catchments was equal to 0.7 and 0.63 for calibration and validation period, respectively. Median KGE is also higher than 0.5 for each cluster in both calibration and validation. Even though there are individual catchments with rather poor results (KGE below 0.4), the majority of KGE values falls into a satisfactory range. Typical reasons for poor results are low quality of precipitation input, mis-classification in cluster analysis, or human-impaired streamflow (despite the benchmark catchment selection process).

Figure 2 B and C also shows that the parameter regionalisation approach worked very well: calibration results at two most downstream gauges are significantly better than the average results for the benchmark catchments. One of the main issues is underestimation of flows in certain periods, more visible for the Vistula (by 15 %) than for the Odra (by 6 %).

The calibrated SWAT model of the VOB was then used to run a simulation for the whole period of availability of CPLFD data. The resulting output dataset CPL-NH (CHASE-PL - Natural Hydrology), consisting of monthly sub-basin water balance components and daily (natural) streamflow records for 2633 sub-basins and reaches, for the time period 1954-2013 is stored in an open online research data archive 3TU.Datacentrum (Piniewski et al., 2015).

3 Assessment of flow alteration caused by dams

In order to illustrate the effect of dam reservoirs on downstream streamflow alteration we selected three reservoirs situated in different parts of Poland (Fig. 1) and having different characteristics (Table 1). Selected reservoirs differ with respect to upstream catchment area, dam height, construction year, capacity and dominating functions. All of them were associated with the nearest flow gauge situated downstream of a dam and with respective model outlet for which simulated daily flows were available. The Nature Conservancy's IHA program (Mathews and Richter, 2007) was applied to calculate 33 flow statistics based on pre-dam and post-dam observed and modelled streamflow data. A number of comparisons were made, each of which served a different purpose:

1. Comparison of pre-impact and post-impact flow statistics using gauged flows provides an estimate of the magnitude of flow alteration due to dam effect. This can be referred to as the Before-After (BA) design (Peñas et al., 2016).

2. Comparison of pre-impact and post-impact flow statistics using simulated flows provides an estimate of the flow alteration due to climate effect.

3. Comparison of pre-impact gauged and simulated flow statistics is a way of model validation.

4. Comparison of post-impact gauged and simulated flow statistics is an alternative to the BA design. It can be referred to as the Control-Impact (CI) design (Peñas et al., 2016), where modelled flows serve as a control.

Thirty three IHA statistics refer to different aspects of flow regime (magnitude, duration, timing, high and low flow pulses, rate of change). For illustrative purposes three example statistics selected for each reservoir are discussed below.

3.1 Włocławek Reservoir

Constructed in 1970, Włocławek Reservoir with a surface area of 70 km^2 is the largest reservoir in Poland. It also has the largest upstream catchment area of 171,000 km^2. Since the ratio of capacity to inflow is relatively low, reservoir operation does not strongly affect such parameters as seasonal flows, extreme flows or timing. However, the parameters related to the rate of change (rise rate, fall rate and number of flow reversals) are affected, as shown in Figure 3 A-C. The analysis based on gauged flows demonstrates that after dam construction all these parameters have at least doubled, on average. At the same time there is no significant change in the same parameters assessed using modelled flows, which shows that the natural climatic variability did not affect them. Comparison of pre-dam observed and simulated data shows on the other hand that the SWAT-based rate of change parameters, particularly fall rate and number of reversals, are underestimated. Thus, the effect of Włocławek dam assessed following the CI design is presumably over-estimated.

3.2 Siemianówka Reservoir

Constructed in 1992, Siemianówka Reservoir with a surface area of 32.5 km^2 is the third largest reservoir in Poland. It also has relatively small upstream catchment area of 1,100 km^2. This is a lowland catchment situated mainly in Belarus. Due to a relatively large ratio of capacity to inflow, a long list of flow parameters are affected by this dam. Three of them showing significant impacts were selected for illustrative purposes: mean December flow, 1-day maximum flow and high pulse number (Fig. 3 D-F). The analysis following the BA design demonstrates that post-dam period was not homogeneous, i.e. the pattern of streamflow indices for the periods 1992-1999 and 2000-2007 was considerably different. For example, an abrupt increase in December flows after dam construction lasted until approximately year 1999, after which December flows were generally lower than in the pre-dam period. As with Włocławek Reservoir, there is no significant change in the studied parameters assessed using modelled flows, which shows that the natural climatic variability did not affect them. Visual comparison of pre-dam observed and simulated data shows on the other hand a moderate agreement between SWAT-based and gauge-based parameters. The effect of Siemianówka dam assessed by comparing post-impact observed and modelled data is different in different sub-periods. For example, high pulse number was significantly lower for the observed flows than for the simulated flows in the sub-period 1992-1999, while in the later period they were similar.

3.3 Czorsztyn reservoir

Constructed in 1997, Czorsztyn Reservoir with a storage capacity of 232 millions m^3 is the third largest reservoir in Poland (with respect to capacity). In contrast to Włocławek and Siemianówka it is situated in the mountains, on the River Dunajec characterised by a more dynamic flow regime. Three parameters showing relatively large impacts related to dam construction were selected for illustrative purposes: mean August flow, 1-day maximum flow and 7-day minimum flow (Fig. 3 G-I). The analysis based on gauged flows demonstrates that August mean flows and 7-day minimum flows increased and 1-day maximum flows decreased (including their variability) after dam construction. In contrast to two previous examples, the natural climatic variability seems to have affected streamflow as well. For example, simulated mean August flows were significantly lower, while simulated 1-day maximum flows had a considerably lower variability in the post-dam period as compared to the pre-dam period. Visual comparison of pre-dam observed and simulated data shows on the other hand a high agreement between SWAT-based and gauge-based August flows, and an underestimation of minimum and maximum flows by SWAT. The effect of Czorsztyn dam assessed in the CI design suggests a higher dam impact than when assessed in temporal comparison, in particular for August flow and 7-day minimum flow. While in the first case this statement seems to be true (because of good performance of SWAT in simulating August flows), in the latter it is probably wrong (because of underestimation of minimum flows by SWAT in the pre-dam period).

4 Discussion and Outlook

The spatial calibration approach developed here in order to simulate natural discharge over two large river basins is applicable in other geographical settings, particularly for areas in which the degree of flow alteration is moderate (as in Poland), i.e. it is possible to identify both a subset of near-pristine benchmark catchments and heavily-regulated catchments. An approximate indication of such regions over the world can be made based on the global distribution of deficit watersheds of Milliman et al. (2008) or on the global distribution of aging of continental runoff in response to large reservoir impoundment Vörösmarty and Sahagian (2000). For river basins that are entirely near-pristine this approach would not bring much benefit, as the gauged hydrology is already natural. In contrast, for extremely regulated river basins, this approach would not work because of insufficient number of unaltered benchmark catchments.

This study showed that three different reservoirs caused alteration of different flow regime characteristics. The added value of using the large-scale high-resolution hydrological model for assessing flow alteration is manifold. The assessment using gauged flows is probably more accurate, but in many cases gauges can be situated far downstream from a dam (or another source of alteration, such as point source or abstraction), and thus the direct effect is dampened. A common issue with gauged flows are missing data, which can be supplemented by simulated streamflow. Finally, comparison of pre-dam and post-dam gauged flow data (BA design) carries the danger of ignoring the effect of natural climatic variability. In this respect, the modelled flows can serve as the proxy of a control gauge (CI design) within the full Before-After-Control-Impact (BACI) design, the preferred design of assessing flow alteration Peñas et al. (2016). As shown in this study, care needs to be taken as far as the reliability of modelled flow statistics is concerned. If the model is able to predict the variability of a given parameter in the pre-impact period, it can be reliably used in the Control-Impact design. As with the August flow for Czorsztyn Reservoir, there was a good agreement for this parameter during the pre-impact period, and thus one could conclude that the dam effect assessed using the BA design was underestimated. The reason was that this design neglected the fact that post-impact streamflow was naturally lower than the pre-impact streamflow in August.

In Poland, environmental flows have been for a long time identified with minimum low flow thresholds. Due to the EU Water Framework Directive and its environmental flow policy (Acreman et al., 2009) this situation is gradually changing, and more importance is given to flow requirements of valuable ecosystems such as riparian wetlands (Piniewski et al., 2014). It is anticipated that designing environmental flows from dams will sooner or later become an important topic in Poland. Thus, a model simulating baseline (natural) hydrology in 90 % of the country may be a useful tool in guiding this process, since a similar analysis as performed here for only three reservoirs can be easily extended over all major sources of flow alteration.

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Table 1. Main features of investigated reservoirs

Reservoir	River	Gauge	Catchment area [10^3 km^2]	Dam height [m]	Construction end year	Capacity [10^6 m^3]	Power plant capacity [MW]	Dominating functions
Włocławek	Wisła	Włocławek	171	20	1970	408	160	energy, recreation
Siemianówka	Narew	Bondary	1.10	9	1992	79.5	0.16	nature protection, irrigation, recreation
Czorsztyn	Dunajec	Sromowce Wyżne	1.3	56	1997	232	92	flood protection, energy

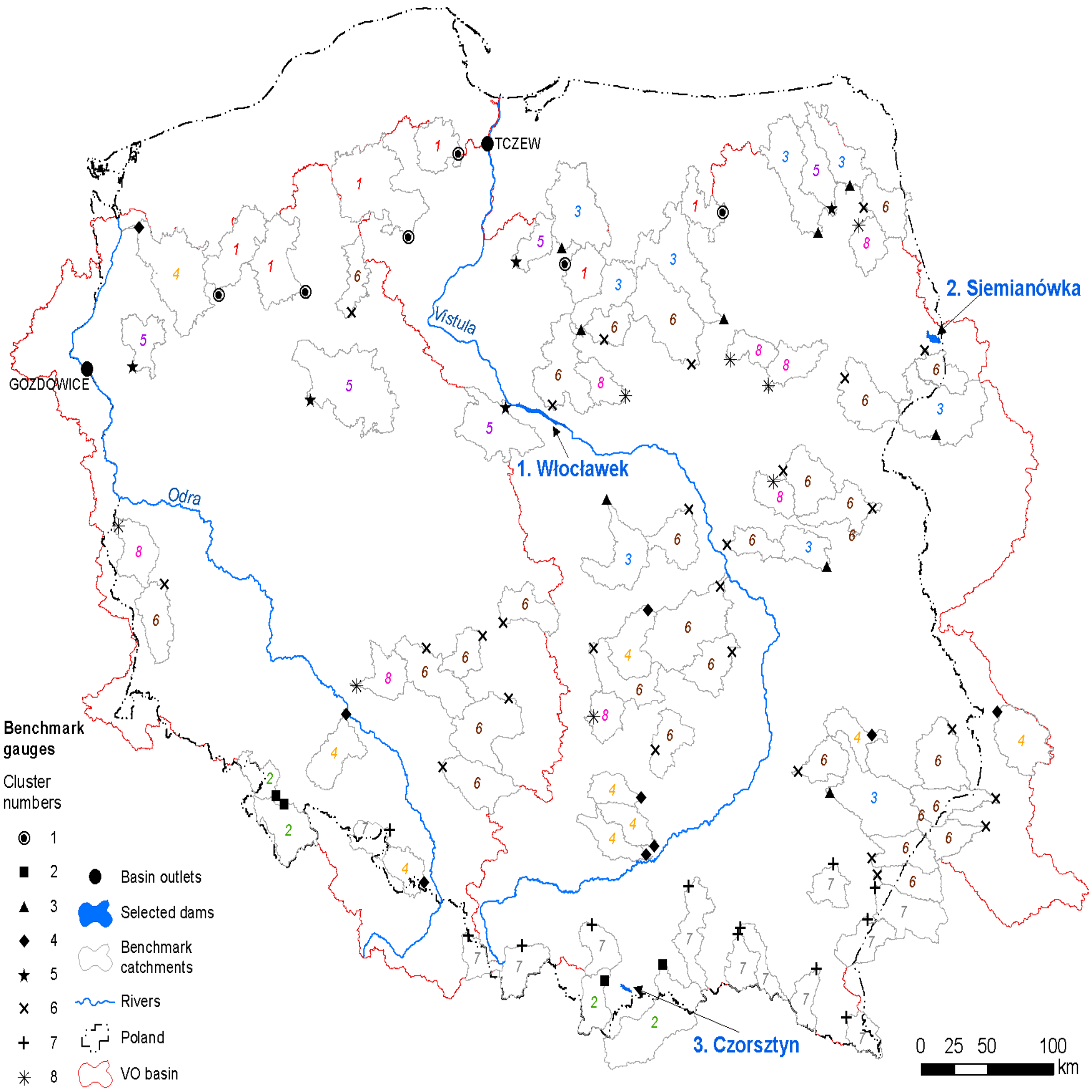

Figure 1. Division of benchmark catchments into 8 clusters and location of three studied dam reservoirs

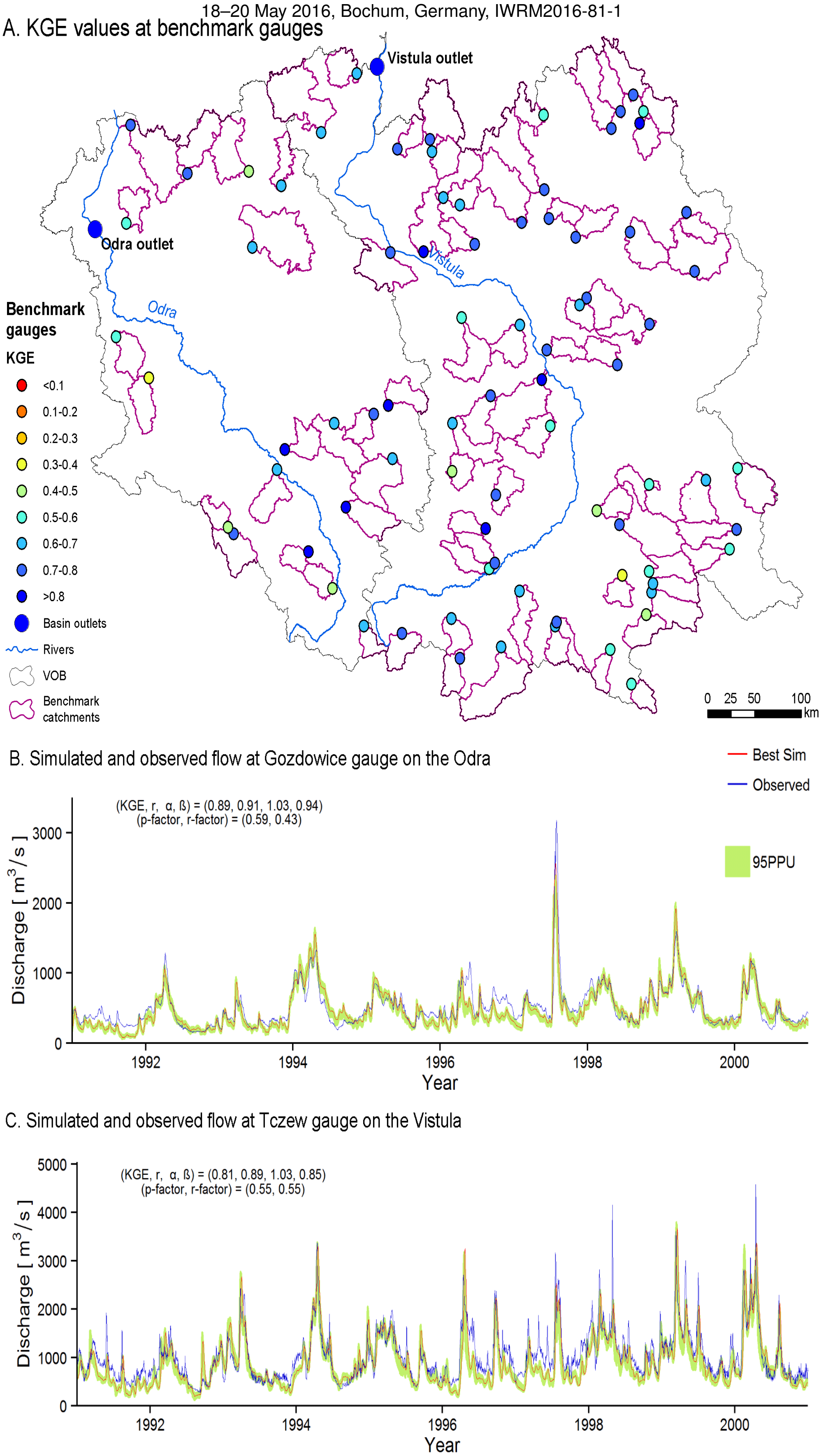

Figure 2. Calibration results: KGE values at benchmark gauges (A), simulated and observed flows at Gozdowice gauge on the Odra (B) and at Tczew gauge on the Vistula (C).

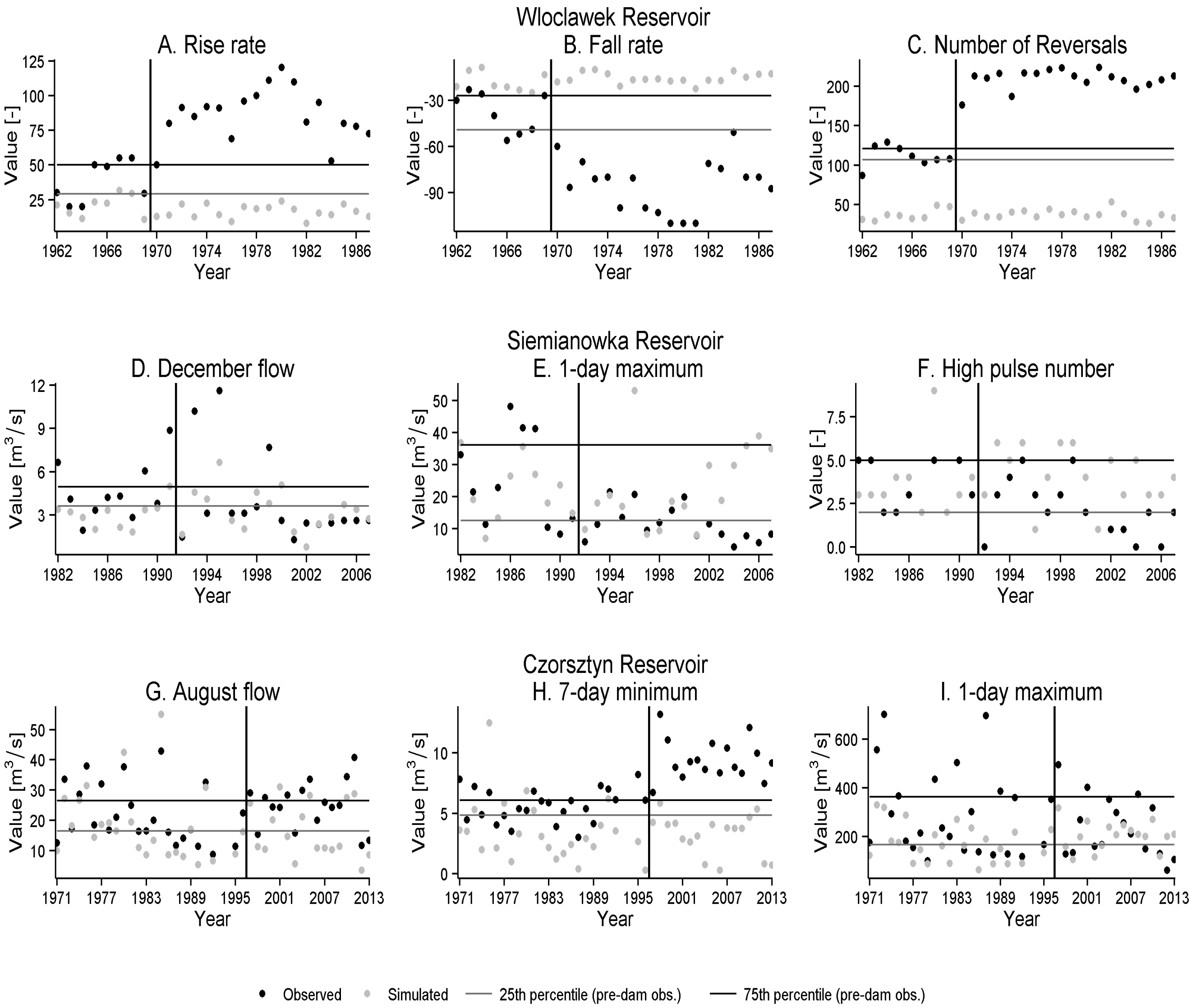

Figure 3. The effect of three dam reservoirs: Włocławek, Siemianówka and Czorsztyn on streamflow alteration assessed using observed and simulated flows. Black vertical line denotes the construction year of each reservoir. The 25th and 75th percentiles of the flow statistics were calculated based on pre-dam observed flows and delineate the likely interval of natural variability of a given statistics.