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RESEARCH ARTICLE - HYDROLOGY

Applicability of TOPMODEL in the mountainous catchments in the upper Nysa Kłodzka river basin (SW Poland)

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Abstract

River basins located in the Central Sudetes (SW Poland) demonstrate a high vulnerability to flooding. Four mountainous basins and the corresponding outlets have been chosen for modeling the streamflow dynamics using TOPMODEL, a physically based semi-distributed topohydrological model. The model has been calibrated using the Monte Carlo approach—with discharge, rainfall, and evapotranspiration data used to estimate the parameters. The overall performance of the model was judged by interpreting the efficiency measures. TOPMODEL was able to reproduce the main pattern of the hydrograph with acceptable accuracy for two of the investigated catchments. However, it failed to simulate the hydrological response in the remaining two catchments. The best performing data set obtained Nash–Sutcliffe efficiency of 0.78. This data set was chosen to conduct a detailed analysis aiming to estimate the optimal timespan of input data for which TOPMODEL performs best. The best fit was attained for the half-year time span. The model was validated and found to reveal good skills.

Keywords TOPMODEL · Hydrologic model · Discharge · Poland · Kłodzko land

Introduction

Better understanding of watershed dynamics is one of the key factors in solving water-related scientific and practical problems. This role becomes crucial for effective planning and management of water resources (Beven and Freer 2001a; Bastola et al. 2008) in areas endangered by extreme hydrological events. Key variables influencing the hydrological response of the catchment need to be estimated based on data recorded on gauges, and the limitations occur when data are poor or insufficient. Thus, the hydrological modeling of water cycle components is the essential tool which becomes necessary for extending hydrological data both in space and time (Bastola et al. 2008). Many researchers attempted to develop solutions that would model the complexity of processes and heterogeneity of factors influencing the hydrological system dynamics. The availability of spatial characteristics of the catchment that rose with the advent of geographic information systems (GIS) shifted the research interests from the traditional lumped models towards more complicated, distributed ones. The advantage of the latter is the possibility of having a spatial pattern of the modeling outputs, such as soil moisture or saturation zone extent (Sun and Deng 2004). One of the semi-distributed and physically based conceptual models is the TOPography-based hydrological MODEL, known also as TOPMODEL (Beven and Kirkby 1979; Beven et al. 1995; Beven and Freer 2001a). It combines the advantages of two above-mentioned approaches. The number of parameters is reduced, but they maintain their physical interpretation. Simplified model structure diminishes the data requirements. Thus, this conceptual model integrates the ability to simulate the spatial distribution of its results at any time step (Choi and Beven 2007) with the computational efficiency that allows multiple simulations (Peters et al. 2003). These features

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contribute to the model popularity and successful applications in numerous studies. Furthermore, recent increase of the TOPMODEL application is caused by access to more detailed data describing the watershed characteristics.

According to Beven et al. (1995), the TOPMODEL concept should not be considered as a hydrologic modeling package, but rather as a set of conceptual tools that can describe the catchment behavior. Hence, since its introduction in 1979 (Beven and Kirkby 1979), many versions have been developed and numerous studies have applied the TOPMODEL approach to a wide range of hydrology-related topics. The research problems investigated with the use of TOPMODEL include: flood frequency analysis (Beven 1986; Cameron et al. 1999), scaling theory in hydrology (Wood et al. 1988), examination of the influence of the digital elevation model (DEM) resolution on the simulation results (Brasington and Richards 1998), analysis of climate change scenarios (Romanowicz 2007), water table estimation (Merot et al. 1995; Moore and Thompson 1996; Lamb et al. 1997), testing the applicability to water quality problems (Wolock et al. 1990; Robson et al. 1992), and uncertainty analysis (Freer et al. 1996; Choi and Beven 2007; Bastola et al. 2008; Fisher and Beven 1996).

Although the initial TOPMODEL applications concentrated on examining the catchment dynamics in the humid temperate climate zone in the UK (Beven and Kirkby 1979; Beven et al. 1984; Quinn and Beven 1993), in the eastern USA (Beven and Wood 1983; Hornberger et al. 1985), the capability of providing good simulation results have been proven in the variety of environments in basins all over the globe. TOPMODEL has been successfully used in temperate cold climate in Norway (Lamb et al. 1997). Furthermore, the model performance has been investigated in drier Mediterranean regimes (Durand et al. 1992; Piñol et al. 1997), and in the monsoon region of China (Chen and Wu 2012). The research was also carried out in the humid temperate (Cameron et al. 1999; Bárdossy 2007; Choi and Beven 2007; Furusho et al. 2014) and Mediterranean (Gallart et al. 2008) climate zones. TOPMODEL has also been successfully utilized in the tropical climate zone in French Guiana (Molicova et al. 1997) and within the same climate zone, but in its antipodes, in one of the most hydrologically responsive forested headwater catchments, in Maimai in New Zealand (Freer et al. 2003). Sigdel et al. (2011) applied the model to watersheds in the Bagmati River basin in Nepal. It is worth noting that many researchers focused their studies on the TOPMODEL applications in the Nepal region: Brasington and Richards (1998) applied the TOPMODEL to a small headwater catchment in the Nepal Middle Hills, Shrestha et al. (2007) investigated its performance in different physiographic regions of Nepal, and Bastola et al. (2008) conducted a comparative study of 26 catchments across the globe, including 4 basins in Nepal. The vast majority of the TOPMODEL applications concern small- or medium-sized catchments (up to several dozen of square kilometers); however, the model demonstrated good performance for: very small basins of 0.75 ha (Lamb et al. 1997) and of 1.57 ha (Molicova et al. 1997) as well as very large basins of over 25 000 km^2 (Sun and Deng 2004; Chen and Wu 2012). High attention has been paid to the TOPMODEL capability of rainfall-runoff modeling in the mountainous regimes. Holko and Lepistö (1997) applied the model to the Jalovecky Creek catchment in Western Tatra Mountains, Blazkova and Beven (1997) investigated mountain wetlands in the Czech-Moravian highlands, and the research area for Nourani and Mano (2007) was watershed located 800–2178 m a.s.l. in the western Iran.

The model has been successfully applied to several catchments in Central Europe. Emphasis should be placed on the above-mentioned research of Holko and Lepistö (1997), focusing on the mountainous watershed in Slovakia, and on the investigation by Bárdossy (2007) into 16 lowland catchments in the German part of the Rhine basin. Applications of TOPMODEL for Polish basins were rare and focused rather on selected episodes than on the entire hydrologic years (Table 1). Szalińska et al. (2014) applied the model in question to simulate discharges in selected gauges installed within upper Nysa Kłodzka and Soła basins, with the emphasis placed only on selected high-flow events. Recent developments carried out in the Institute of Meteorology and Water Management—National Research Institute, Poland (Instytut Meteorologii i Gospodarki Wodnej—Państwowy Instytut Badawczy, IMGW-PIB) include the Hydropath framework, the platform that includes TOPMODEL (Orczykowski and Tiukało 2016). More recently, Niedzielski and Miziński (2017) used TOPMODEL as one of ensemble members in the multi-model hydrologic ensemble prediction, within the HydroProg system implemented in Kłodzko Land.

Even though these studies demonstrated good modeling results, the TOPMODEL performance has never been tested in Poland in longer time perspectives than single high-flow episodes. To fill this gap and fulfill a need of detailed analyses of the model in a variety of environments, postulated by Durand et al. (1992), in this study, TOPMODEL is applied to a few medium-sized catchments in the flood-prone areas of the Sudety Mountains in SW Poland. Hence, the aim of the modeling experiment was to test the applicability of the TOPMODEL for the purpose of discharge simulation at the outlets of four contributing catchments of Nysa Kłodzka river (gauges: Bystrzyca Kłodzka, Kłodzko, Bardo) and the river of Biała Lądecka (gauge: Żelazno). In addition, the aim of the study is also to estimate the time span of data (discharge/rainfall/evapotranspiration) for

Table 1 Applications of TOPMODEL for Polish basins and their sampling intervals

Basin	River	Institution	References	Data	Sampling interval
Nysa Kłodzka	Nysa Kłodzka (above Miedzylesie)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
	Nysa Kłodzka (above Bystrzyca Kłodzka)	UWr	This paper	Hydrologic years 2009–2012	15 min
	Nysa Kłodzka (above Kłodzka)	UWr	Niedzielski and Miziński (2017)	Selected episodes from 2014 to 2015	15 min
	Nysa Klodzka (above Kłodzka)	UWr	This paper	Hydrologic years 2009–2012	15 min
	Nysa Kłodzka (above Bardo)	UWr	This paper	Hydrologic years 2009–2012	15 min
	Bystrzyca (outlet unknown)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
	Biała Lądecka (outlet unknown)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
	Biała Lądecka (above Żelazno)	UWr	This paper	Hydrologic years 2009–2012	15 min
	Bystrzyca Dusznicka (above Szalejów Dolny)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
Sola	Sola (above Rajcza)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
	Woda Ujsolska (outlet unknown)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
	Zabniczanka (above Żabnica)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
	Bystra (outlet unknown)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
	Koszarawa (outlet unknown)	IMGW-PIB	Szalińska et al. (2014)	Selected episodes from 2010 to 2012	1 h
Kamienna	Kamieinna (above Jakuszyce)	IMGW-PIB	Orczykowski and Tiukało (2016)	Unknown choice of data span	1 h

IMGW-PIB Instyhit Mereorologii i Gospodarki Wodnej—Panstwowy Instytut Badawczy (Institute of Meteorology and Water Management—National Research Institute), *UWr* Univtersytet Wroclawski (University of Wroclaw)

which the TOPMODEL performance is optimal. Therefore, the novelty of the work presented in this paper is twofold: (1) it presents new results on discharge modelling in the upper Nysa Kłodzka river basin in time scales of a few hydrologic years, hence not only for selected high-flow episodes; (2) it shows first attempts to relate modelling skills with time span of input data.

The paper is organized as follows: the next section presents a simplified description of the model (its concept and features), based on the extended explanations of TOPMODEL theory given by Beven and Wood (1983) and Beven (1986). The second section also contains overview of methods used for the model assessment. The study area is presented in the third section, followed by the fourth section that focuses on description of data used in the research. The results of land surface parameterization, model calibration, sensitivity analysis, and validation of the TOPMODEL for four contributing basins located within the upper Nysa Kłodzka basin (SW Poland) are included in the fifth section. They are concluded in the last section, which also offers an overview of potential future research activities.

Methods

Concept of TOPMODEL

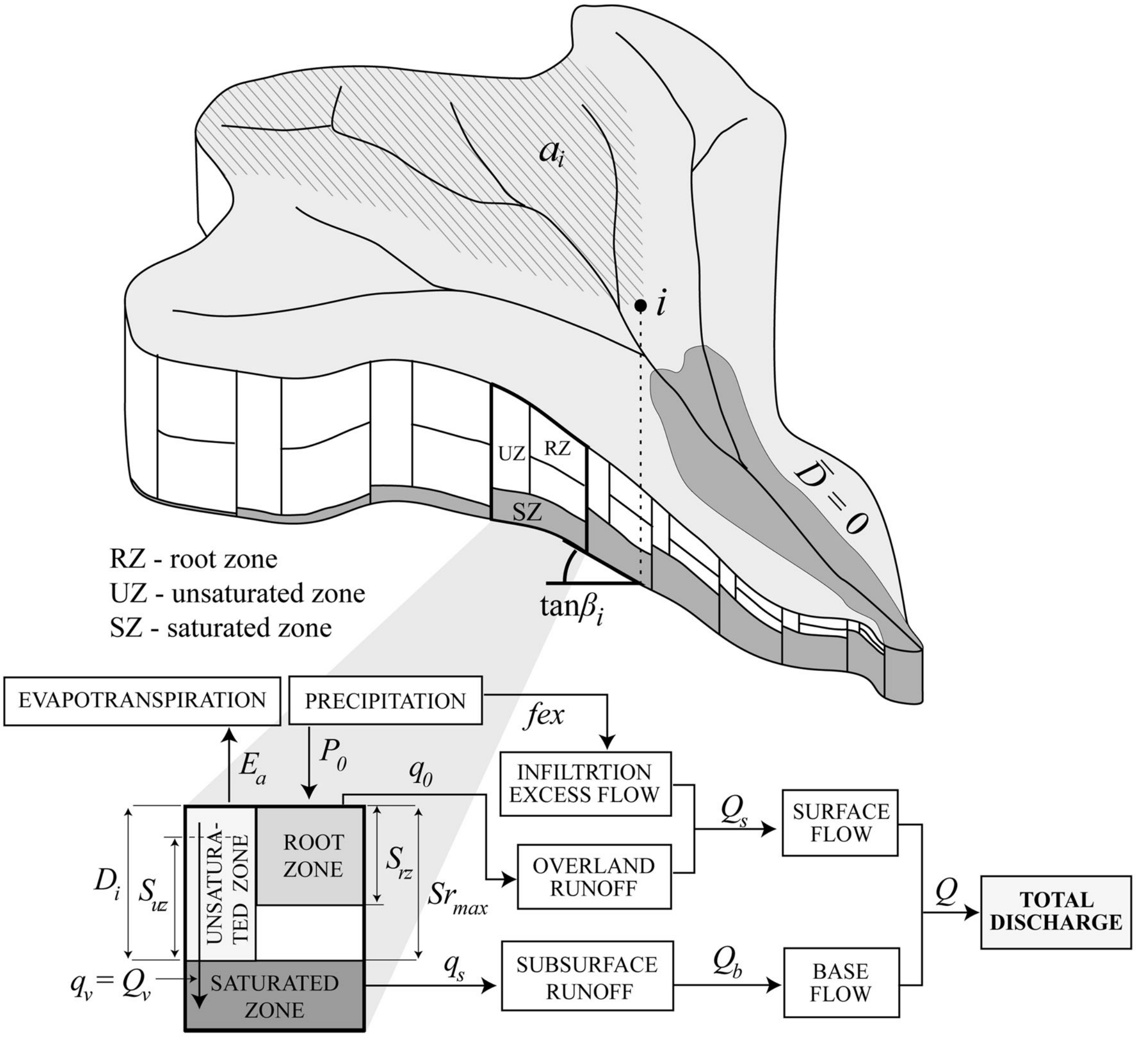
The idea that runoff is primarily a result of overland flow generated by rainfall when infiltration capacity of the soil is exceeded is known as Hortonian theory of infiltration excess overland flow. However, in recent studies, it is commonly superseded by the contrary concept that emphasizes the significance of saturation-excess overland flow and subsurface runoff generation. On the contrary to the Hortonian concept, stating that the occurrence of surface overland flow is possible when the soil is not fully saturated, the saturated-excess overland flow theory assumes that the overland flow is generated when the soil is fully saturated to the surface or if subsurface flow returns to the surface in saturated areas (Nourani et al. 2011). Among different applications of this concept in hydrological modeling, one of the most widely used is TOPMODEL (Beven and Kirkby 1979; Beven 1997; Beven and Freer

2001a). The predominant factors influencing the discharge generation in the model are topography of the basin and soil characteristics (Franchini et al. 1996). The topography is quantitatively expressed by the topographic index (also known as Topographic Wetness Index, TWI). Its value is computed from the basin topography using the following expression:

$$\mathrm{TWI}_i = \ln \frac{a_i}{\tan \beta_i}, \tag{1}$$

where a_i is the upslope contributing area of ith basin and $\tan \beta_i$ is slope of the ground surface of this basin. Upslope contributing area (Fig. 1) represents the area that can potentially produce runoff to the location of interest, i.e., to the outlet from the contributing basin (Erskine et al. 2006). In the raster representation of the terrain, it should be replaced by the upslope drainage area per unit of contour length (Moore and Wilson 1992; Moore and Burch 1986; Desmet and Govers 1996), which is equivalent to DEM grid cell size (Mitasova et al. 1996). Areas associated with high TWI values tend to saturate first and will, therefore, constitute potential subsurface or surface contributing areas (Gumindoga 2010; Beven 1997).

TWI refers to variable source area concept of runoff generation (Hewlett and Hibbert 1967) and is based on the following three simplifying assumptions regarding the



Q_v – total flux, q_v – the flux of water entering the water table locally (per unit area), A_i – area associated with topographic index class, E_a – actual evapotranspiration, Sr_{max} – maximum root zone deficit, S_{rz} – root zone deficit, S_{uz} – local water storage in the unsaturated zone, q_0 – overland runoff, P_0 – precipitation per unit width, *fex* – infiltration excess flow, Q_s – surface flow, Q_b – base flow, q_sz – subsurface saturated zone flux, Q – total discharge

Fig. 1 Basic concept of TOPMODEL scheme. Based and combined from schemes by Nourani et al. (2011); Franchini et al. (1996); Gumindoga (2010) and Fisher and Beven (1996) hydrologic system (Nourani et al. 2011; Gumindoga 2010; Brasington and Richards 1998; Beven et al. 1995; Holko and Lepistö 1997):

- dynamics of the saturated zone can be approximated by successive steady-state representations;
- hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope ($\tan \beta_i$), and thus, the groundwater table and saturated flow are parallel to the local surface slope;
- distribution of downslope transmissivity with depth is an exponential function of storage deficit or depth to the water table.

This approach implies that all points with the same value of TWI respond in the same way (Fisher and Beven 1996). Calculations need to be performed only for representative values of the index, what greatly simplifies the procedure and reduces the computational cost while maintaining the capability of the identification of water table levels and soil moisture within the catchment (Chairat and Delleur 1993; Fisher and Beven 1996). The results may be mapped back into space using knowledge of the pattern of TWI derived from a topographic analysis (Beven 1997).

Sigdel et al. (2011) pointed out that the above assumptions may be valid for small and medium catchments, with shallow soils and moderate topography, which do not experience excessively long dry periods. The quasi-steady-state dynamics concept has been criticized (Barling et al. 1994; Beven 1997; Peters et al. 2003), and it cannot be always safely accepted (Beven 1997).

According to the TOPMODEL concept, there are two main factors that account for runoff generation, namely the catchment topography and the transmissivity that diminishes with depth (Beven and Kirkby 1979). A soil column in TOPMODEL is defined as a set of three stores: root zone, unsaturated zone, and saturated zone. They behave like three interdependent repositories (Fig. 1). The detailed explanation of physical processes taken into account with TOPMODEL calculations can be found in Peters et al. (2003), Taschner (2003), Sun and Deng (2004) and Sigdel et al. (2011).

The extended interpretation of the TOPMODEL theory is given by Beven and Wood (1983) and Beven (1986).

Model performance measures

Assessment of the efficiency of the hydrological model is necessary not only for the estimation of its ability to reproduce catchment behavior, but also for modifying model structure. Apart from the subjective visual inspection of the simulated and observed hydrographs, there are numerous statistical measures which can be used for hydrological model assessment (Krause et al. 2005). In this study, two model performance measures have been chosen: root-mean-square error (RMSE) and Nash–Sutcliffe efficiency (NSE). The latter was created specifically to assess hydrological models (Nash and Sutcliffe 1970) and can be calculated using the formula:

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{N} (\mathrm{Qobs}_t - \mathrm{Qsim}_t)^2}{\sum_{t=1}^{N} (\mathrm{Qobs}_t - \overline{\mathrm{Qobs}_t})^2}, \tag{2}$$

where Qobs_t is observed discharge, Qsim_t is simulated discharge at time step t, and N is number of observations/simulations. Although its value has been questioned (Criss and Winston 2008), it is still most widely used criterion for evaluating TOPMODEL performance (Beven and Binley 1992). The main critic relates to its sensitivity to extreme values and, since the hydrological data often contain outliers, the measure can be misleading. Values of NSE vary from $-\propto$ (strong misfit) to 1 (perfect fit), and the situation $\mathrm{NSE} = 0$ occurs when model predictive skills are similar to performance of extrapolated mean of observations. According to Moriasi et al. (2007), there are several classifications of NSE and the corresponding interpretations, with a range of NSE intervals to describe a satisfactory model performance. Since the intervals vary significantly, NSE values greater than 0.6 are hereinafter assumed to describe a satisfactory fit (Beven and Freer 2001b).

Study area

The TOPMODEL performance was investigated using data from four gauges located in the Sudety Mountains in upper Nysa Kłodzka basin (SW Poland and the border region of Czech Republic). The following reasons led to the choice of the study area.

- The present research is associated with the HydroProg system (Niedzielski et al. 2014) in which TOPMODEL is used for predicting river stages in real time.
- Rainfall and water level data sets are available, and the access to date is courtesy of the authorities of Kłodzko County, the owner of the Local System for Flood Monitoring (Lokalny System Osłony Przeciwpowodziowej, LSOP).
- TOPMODEL has not been applied in the upper Nysa Kłodzka basin so far.
- TOPMODEL has been already shown to work well in small mountainous catchments in different parts of the world (e.g. Bastola et al. 2008; Cameron et al. 1999).

To investigate the performance of the model in different conditions, four gauges and the associated contributing basins were delimited (Bardo, Kłodzko, Bystrzyca Kłodzka, and Żelazno). The main features of the watersheds are presented in Fig. 2 and listed in Table 2.

Fig. 2 Investigated watersheds and precipitation stations

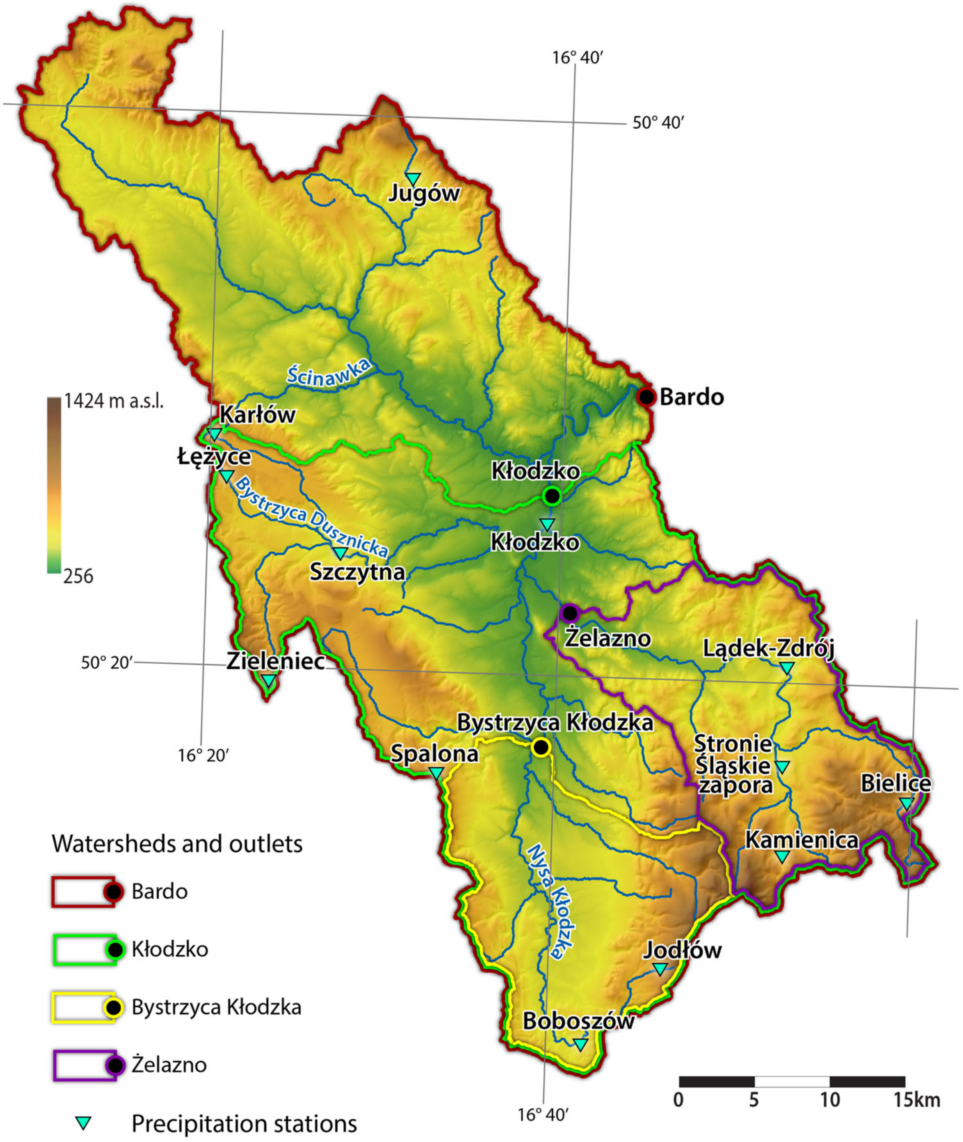


Table 2 Main characteristics of investigated watersheds

Catchment outlet (gauge)	Bardo	Klodzko	Zelazno	Bygtrzyca Klodzka
Altitude (m a.s.l.)	259	285	341	319
Area (km^2)	1744.1	1079.31	259.985	302.94
Mean altitude (m a.s.l.)	534.79	567.45	576.53	648.06
Elevation difference within the catchment (m)	1165	1139	1024	1106
Mean slope (%)	8.09	8.24	7.45	11.17
Flow distance from source (km)	78	58	47	36
Mean TWI	7.37	6.91	6.81	6.34
River	Nysa Kłodzka	Nysa Kłodzka	Biała Lądecka	Nysa Kłodzka
Mean observed flow (m^3/s)	19.19[a]	13.31[a]	4.8[a]	4.29[a]

[a] Based on: http://bip.umwd.pl/fileadmin/user_upload/woda_i_melioracja/Program_Malej_Retencji_Wodnej_tekst_jednolity_10_2006.pdf

The Sudety Mountains are a medium–high mountain range spread along the Polish-Czech boundary in Central Europe. A maximum elevation of the mountains is equal to 1603 m a.s.l. Sudety Mountains are an example of fault-block mountains which are characterized by fault-generated mountain fronts and structural basins attributed to up- and downfaulting in the late Cenozoic (Migoń and Placek 2014). Diverse tectonic structure is additionally enhanced by the lithological complexity. Highly complex and diversified landscape is a result of the mosaic of underlying geology and its polygenetic origin (Wieczorek and Migoń 2014). The structure has also significant impact on extreme events: meteorological, hydrological, and geomorphological ones (Migon and skutki 2010). Large elevation differences strengthen foehn effects and reinforce orographic rainfall that can lead to flood wave formation in mountainous steep-slope streams (Migon and skutki 2010).

The main river of the study area is Nysa Kłodzka, the left tributary of the Odra River. It is characterized by rapid water supplies in the spring and summer as a result of concentric arrangement of numerous tributaries, which are mostly mountain streams. Table 2 juxtaposes main characteristics of the studied basins, along with mean discharges measured at four outlets under study. Three of the investigated basins have outlet located along Nysa Kłodzka. The largest one, with the area of 1744 km^2, is the contributing basin above the gauge in Bardo. Further southward, 16 km upstream, located is the Kłodzko gauge which closes the second biggest of the investigated basins. The smallest one, still located along Nysa Kłodzka, is the basin above the gauge in Bystrzyca Kłodzka, with the area of nearly 260 km^2. However, the Żelazno gauge is located along Biała Lądecka which is the longest right tributary of Nysa Kłodzka in the study area. The contributing basin above Żelazno is a subcatchment of Bardo and Kłodzko basins.

The study area belongs almost entirely to Poland; only the NW parts of the Bardo catchment belong to Czech Republic. That division makes the data related to geographical characteristics of the entire investigated area (i.e., soil cover and land use) not compatible due to different national classification criteria. Thus, the detailed statistical data, that can be assumed as representative for the study area, are available for Kłodzko County which is the administrational unit covering 84.17% of the area of interest.

The topography of the research area, i.e., Kłodzko Valley and the upper Nysa Kłodzka basin surrounded by mountain ranges, is responsible for its distinct microclimate. Although the investigated catchments, as the entire Sudety Mountains, are located in the cool temperate climate zone with marked maritime influences (Schmuck 1969), diversity between the main climate components is noticeable. Average annual air temperature calculated for the entire area of Kłodzko County is 6.3 °C (Geographic Characteristic of Counties 2004). Allowing for the temperature drop with altitude, it is lower than 1 °C at the summits (Waroszewski et al. 2013). In contrast, in Kłodzko Valley (most of Bystrzyca Kłodzka and Żelazno subcatchments),, the annual average temperature rises to approximately 7.4 °C (Schmuck 1969). The altitude influence is also clearly seen in the annual precipitation sums, which vary from 590 mm in the lower parts of Kłodzko Valley to about 1500 mm at the summits (Godek et al. 2015). The mean annual precipitation rate calculated for the entire county is 803 mm (Geographic Characteristic of Counties 2004), and at the altitude of 800 m a.s.l., annual rainfall varies between 800 and 1000 mm (Latocha and Migoń 2006). While the storms with rainfall intensity 20–50 mm/day are not considered to be abnormal (Piasecki 1996), catastrophic rainfall episodes with daily precipitation exceeding 50 mm are observed rarely—a few times per decade (Pawlik et al. 2013). Snow cover is present in the Kłodzko station for average of 63 days (Bednorz 2011) with the first occurrence in November and last in April.

In the river valleys of Nysa Kłodzka, Biała Lądecka, Ścinawka, and lower reach of Bystrzyca Dusznicka, the groundwater level does not exceed 2 m (Geographic Characteristic of Counties 2004). It changes with the distance from the river, and 2–6 km from the channel, it deepens to 10 m. The lowest water levels occur within the mountain massifs and can reach depth of several tens of meters.

The soil pattern is homogenous in the studied catchments. The soil types of the region are mainly Brown Earths and Podzoles. The river valleys are covered with Fluvisoles (Geographic Characteristic of Counties 2004).

Data

The data which become inputs to TOPMODEL can be divided into two groups, i.e., hydrometeorological time series (temporal variability) and terrain characteristics (spatial variability). The next two subsections correspond to this classification. For the purpose of the experiment, 4 consecutive hydrologic years have been selected, abbreviated hereinafter as HYs (note that in Poland hydrologic year begins on 1 November and finishes on 31 October). These HYs are: 2009, 2010, 2011, and 2012. Only four contributing basins which are mentioned and characterized above are the focus of the study.

Hydrometeorological time series

Time series of discharge, rainfall, and potential evapotranspiration are needed to calibrate TOPMODEL. They all should be calculated in m/m^2 per time step. The observed river flow and precipitation data, sampled every 15 min, are obtained from the above-mentioned Local System for Flood Monitoring, known also as LSOP, courtesy of Kłodzko County. However, potential evapotranspiration is modelled empirically, and the same 15-min time step is kept.

Since LSOP observes only water level, and thus, no discharge is measured, there is a need to use rating curves to calculate discharge time series. This has been done using the tabulated rating curves for four gauges under study, obtained courtesy of IMGW-PIB. The validity periods of the rating curves were the following: for Bystrzyca Kłodzka (06/11/2012), for Kłodzko (01/02/2013), for Bardo (30/01/2013), and for Żelazno (09/12/2012). For a few model calibration exercises, the curves were slightly newer, but the adequacy of their performance in calculating discharges from LSOP-based water levels was confirmed by the comparison with discharges measured by IMGW-PIB. The tabulated rating curves, after applying the square-root transformation to the discharge data, have been approximated with high-order polynomials which have been fitted using the least-squares method. Attention has been paid to the uniqueness of the model solution, specifically for low flows. The models have used to compute discharge time series, expressed in m^3/s, for four sites under scrutiny, and sampling every 15 min have been inherited from river stages. Since discharge data should be expressed in m/m^2 per time step, for each gauge, so calculated discharge was multiplied by 15 × 60 (15 min between consecutive discharge data times 60 s in a minute) and divided it by basin area (expressed in m^2).

Rainfall is measured in LSOP at 13 automatic weather stations, and hourly precipitation rate is recorded every 15 min. The data have been recalculated to fit the 15-min time step, and millimeters of rainfall have been converted to m/m^2 per time step. Since no continuous information on precipitation field is provided, the Thyssen polygons have been applied to relate rainfall to a given contributing basin.

Potential evapotranspiration has been computed empirically, i.e., an averaged time series have been constructed. It is assumed to be valid for every year. In our exercise, the evapotranspiration data set is a combination (sum) of: the daily-averaged potential evapotranspiration data for the entire year (computed for each day of year as a mean potential evapotranspiration on the corresponding days in many years) and the diurnal harmonic variation computed on the basis of the true sunrise and sunset times.

Due to the fact that the daily evapotranspiration data are not available for Kłodzko Land, the daily potential evapotranspiration data for the nearest German site of Goerlitz have been utilized, they were computed using the Turc–Wendling method in frame of the NEYMO project. Since Goerlitz is located approximately 140 km from the center of Kłodzko Land, a scaling approach is proposed to account for change in evapotranspiration between Goerlitz and the considered sites in Kłodzko Land. Thus, the daily-averaged evapotranspiration data for Goerlitz have been multiplied by a constant number which was a ratio of: (1) mean annual potential evapotranspiration between 1966 and 1995 in a single site in Kłodzko Land (499 mm for Bystrzyca Kłodzka as well as 516 mm for Kłodzko, Bardo, and Żelazno); and (2) mean annual potential evapotranspiration between 1966 and 1995 in Zgorzelec which is equal to 570 mm (Zgorzelec is a Polish town that forms an entity with German town of Goerlitz). The resulting ratios, computed using values published by Drabiński et al. (2006), led to the calculation of daily-averaged potential evapotranspiration data for basins above gauges in Bystrzyca Kłodzka, Kłodzko, Bardo and Żelazno.

Diurnal harmonic variation was simulated on a basis of true sunrise and sunset times. It was assumed that evapotranspiration is equal to zero in the night and starts growing non-linearly after the sunrise, which reaches the daily maximum and declines to zero at sunset. In this paper, the day segment was modelled with a sinusoid and replicated many times to reveal the same length as the above-mentioned daily evapotranspiration data. The similar, but not entirely identical approach, was applied by Liu et al. (2005). In our exercise, the mean value of the diurnal components was subtracted, and such a procedure prevented extra evapotranspiration values to occur when integration over time was performed.

Subsequently, the data-based daily-averaged potential evapotranspiration data were added to the mean-corrected diurnal evapotranspiration component, leading to the ultimate estimate of potential evapotranspiration.

A note should be given here on why the above-mentioned approach for estimating potential evapotranspiration has been selected. The TOPMODEL configured as described in this paper is used in the experimental multi-model hydrologic ensemble prediction system, known as HydroProg (Niedzielski et al. 2014). It is, therefore, natural that for reference to the system itself and to the previously published work on the use of TOPMODEL in HydroProg (Niedzielski and Miziński 2017), the same settings of the model should be kept to allow comparisons. However, it is likely that the empirical method for estimating averaged time series which is assumed to be valid for every year may become one of the sources of calibration errors.

Terrain characteristics

Topography of the investigated watersheds, as a major factor influencing the TOPMODEL performance, was, in this study, a subject of scrutiny. Digital Elevation Model for the watersheds was interpolated to 25 m grid based on LiDAR data. The grid size was this is a compromise between using a lower resolution that causes a loss of information about hillslope flow pathways, and a high resolution that is influenced by noise (Nourani and Zanardo 2014). Based on the flow accumulation maps generated using GIS tools, the TWI value was assigned to each raster cell in the digital elevation models of the watersheds. The classification of the values into 16 classes (Blazkova and Beven 1997; Holländer et al. 2009) was performed to reduce the computation time, and thus, the calculations were carried out for the topographic index class instead of each individual value. Figure 3 shows the frequency and the spatial distribution of the TWI values. It is clearly seen that the highest values—which indicate potential subsurface or surface contributing areas (Beven 1997)—are associated with the bases of slopes and the stream valleys. These areas are characterized by large contributing areas and relatively flat slopes. The mean TWI for the watersheds varies from 6.34 for Bystrzyca Kłodzka catchment, through 6.81 and 6.91 for Żelazno and Kłodzko, respectively, to the highest mean value of 7.37 obtained for the Bardo catchment.

DEM was also used for the estimation of the delay function which represents the time for a particle of water to travel to the outlet. Based on the flow length map, each watershed was divided into five zones, grouping the similar values of the function. The simple matrix was prepared for the further computations, with the first column indicating average distance to the outlet and the second column representing relative cumulative area of each zone.

Results

Parameter estimation

Although the TOPMODEL assumptions require relatively small number of parameters that need to be estimated, the

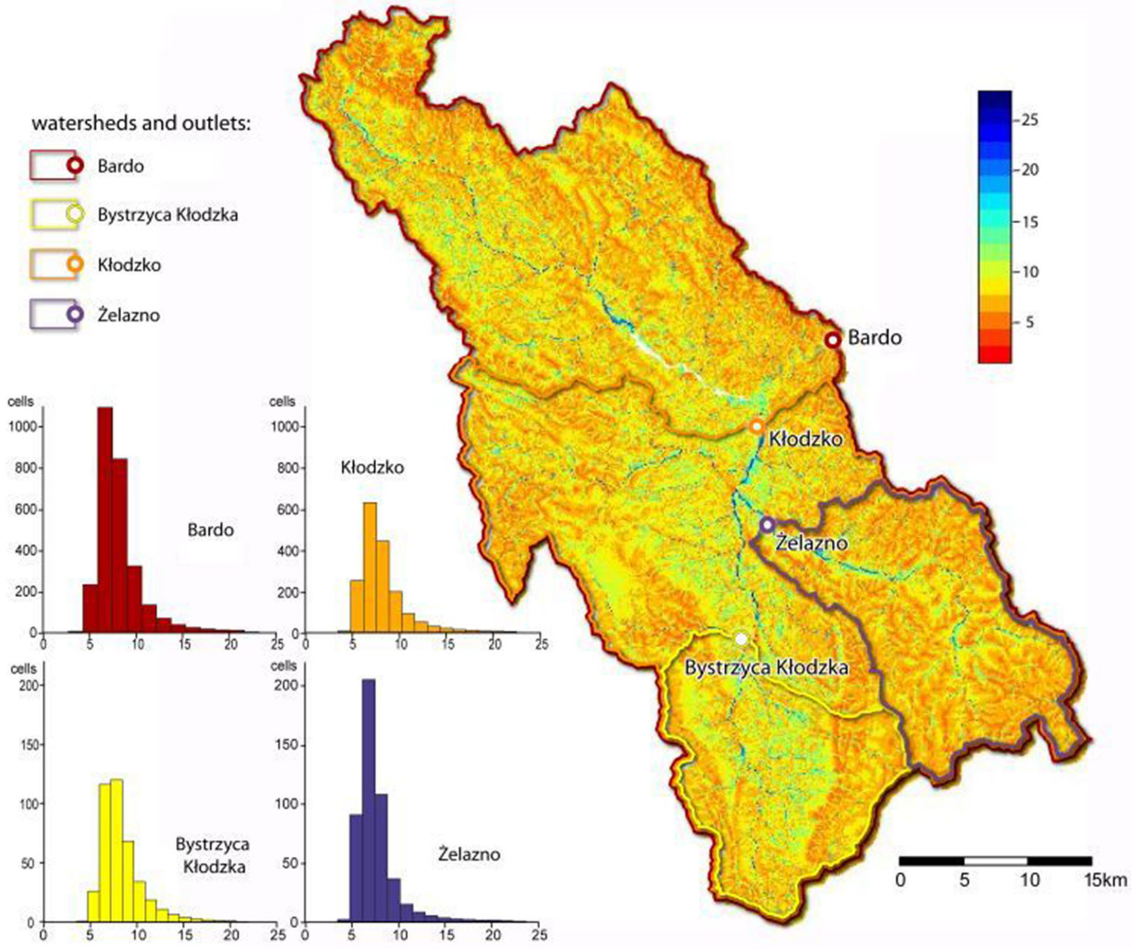


Fig. 3 TWI values and its distribution in investigated catchments

difficulty of the calibration is caused by the uncertainty of the parameters (Kuczera and Mroczkowski 1998). In addition, as Beven and Freer (2001b) stress out, a diverse set of possible parameter values can produce similar modeling results.

The Monte Carlo procedure, that has been proven to be particularly useful for hydrological studies (Romanowicz and Beven 2003), was carried out to estimate a set of parameters that offer the best model performance. In this paper, the Monte Carlo approach is used in association with the uniform distribution, i.e., random sampling across the specified parameter range is performed, assuming the same probability of sampling each element. Table 3 shows the ranges applied for each parameter based on the previous studies and manual calibration. The ranges of the parameters were kept wider than the expected possible values for the catchment (Freer et al. 1996). To enhance the certainty, the number of simulations was set to 10,000. Further increase of this number did not improve the final result and required a more time-consuming computation. The procedure was carried out for all above-mentioned catchments, in each case study for the period of 1 hydrological year, and the data from HY 2010, HY 2011, and HY 2012 were taken as an input. Table 3 confirms the statement that constraining the perfect parameter set is not possible and the modeling needs to rely on the best performing, not necessary actual, values. In the experiment, three independent calibration exercises (HY 2010, HY 2011, and HY 2012) are carried out to show the level of variability of model parameters and its impact on model performance.

Each parameter is equally important during the Monte Carlo sampling, although the manual calibration showed that four of the parameters—m, lnTe, $\mathrm{Sr}_{\max}$, and vch—are more meaningful, i.e., variation in their values influences the model performance and the shape of the simulated hydrograph most significantly. The highest sensitivity is associated with m parameter, which represents the change in the saturate hydraulic conductivity with depth. Small values of m imply the quick flow and insignificant subsurface runoff, while large values indicate that more rainfall can infiltrate the soil, and thus, less water reaches the outlet via surface route (Sigdel et al. 2011). For the investigated catchments, m parameter range was kept wide, assuming that the well-vegetated, deep-seated catchments of the study area can be well characterized by the large values of m. The next highly sensitive parameter, lnTe, influences directly the shape of hydrograph. The quick recession is associated with small values of the lnTe parameter, while low values result in gradual fall of the hydrograph limb after the peak, as a result of increasing saturated transmissibility that may cause runoff delay. This parameter draws a special attention in this study, since the shape of the recession limb in the modelled hydrographs often did not resemble the observed ones. Constrained allowable range for this parameter was set to be between − 2 and 1, and its value for the most efficient runs varies from − 1.37 (Bystrzyca Kłodzka catchment, simulation for 2011) to 0.99 (Żelazno catchment, simulation for 2012). The third parameter that was found to be sensitive, although not as much as the previous ones, is the maximum root zone deficit $\mathrm{Sr}_{\max}$. The value of this parameter indicates the influence of evapotranspiration on the hydrological behavior of the catchment. Small root zone deficit (low $\mathrm{Sr}_{\max}$ value) allows less water to be stored in the root zone and hence available for evapotranspiration (Sigdel et al. 2011) what can lead to the increased runoff. An extended knowledge of the catchment vegetation is necessary for the $\mathrm{Sr}_{\max}$ calculation. The difference of the water contents at field capacity and the permanent wilting point needs to be multiplied by the rooting depth of the soil (Beven and Freer 2001a). Due to the lack of such detailed data, $\mathrm{Sr}_{\max}$ parameter ranges were very wide (0–3 m). The best performing parameter sets for the simulations for different HY in the same catchment contained $\mathrm{Sr}_{\max}$ parameters with

Table 3 Parameter ranges applied for random sampling in the Monte Carlo procedure and their significance

Parameter		Range	Significance
qs0	Initial subsurface flow per unit area (m)	0 to 0.00004	Insensitive
lnTe	Log of the areal average of $T0$ (m^2/h)	− 2 to 1	More sensitive
m	Model parameter controlling the rate of decline of transmissivity in the soil profile	0 to 2	Highly sensitive
Sr0	Initial root zone storage deficit (m)	0 to 0.02	Insensitive
$\mathrm{Sr}_{\max}$	Maximum root zone storage deficit (m)	0 to 3	Sensitive
td	Unsaturated zone time delay per unit storage deficit (h/m)	0 to 3	Less sensitive
vr	Channel flow inside catchment (m/h)	800 to 1000	Sensitive
$k0$	Surface hydraulic conductivity (m/h)	0 to 0.01	Less sensitive
CD	Capillary drive	0 to 5	Insensitive

various values, and the estimation of the right span was difficult. Constraining the ranges for the last highly sensitive parameter did not cause such problems, since channel flow velocity can be estimated by dividing the observed discharge by the cross-sectional area of the stream. The channel velocity varies along the stream, but for all the investigated catchments, the best performed parameter sets were generated when the each parameter range was set to 800–1000 m/s.

There final parameter values' ranges presented in Table 4 which yielded the best overall fit of the model when executed for entire hydrograph for a HY.

Model performance

The calibration of the model was performed on all four watersheds for HY 2010, HY 2011, and HY 2012. The rainfall, discharge, and evapotranspiration data were converted to 15-min time steps, and the Monte Carlo procedure was performed to generate the best performing parameters set out of 10,000 individual sets. Table 4 shows the modeling results and the calibrated parameter values. Obtained efficiency statistics as well as the parameter ranges are not consistent for all catchments and all simulation periods. For all of the catchments, TOPMODEL achieved the best fit modeling the discharge in HY 2011. The topography, land use, soils, and other characteristics of terrain influencing the runoff generation were relatively steady, but model efficiency statistics varied between the modeling time periods, which proves that the model performance measures are strongly dependent on weather conditions.

The best performance of TOPMODEL was found for Bystrzyca Kłodzka catchment in HY 2011, with $NSE = 0.78$ and the correlation between observed and simulated discharge of 0.89 (Fig. 4). Slightly less skillful was TOPMODEL in Kłodzko catchment, with values of the above-mentioned statistics of 0.66 and 0.83, respectively. The model performance expressed by $NSE > 0.6$ is considered as satisfactory, also named as behavioral (Beven and Freer 2001b). For two remaining catchments, Bardo and Żelazno, TOPMODEL was unable to simulate the hydrograph with fair accuracy. In Bardo basin, the modelled discharge was, for each time period, less accurate as the mean of the observed data ($NSE < 0$). For Żelazno catchment, this situation occurred for the HY 2012 data, and the results for the remaining modeling periods, HY 2010 and HY 2011, were also not satisfactory, with $NSE = 0.31$ and 0.42, respectively.

Based on the results of calibration using the yearly data, the watersheds were categorized into three categories: "good"—all obtained $NSE > 0$, "acceptable"—all obtained $NSE \geq 0$, and "unacceptable"—some obtained $NSE < 0$ (Blazkova et al. 2002). The third category, containing two watersheds—Żelazno and Bardo—was excluded from further analysis and the emphasis was put on finding the underlying causes of model bad performance in these basins.

Bardo is the biggest of the investigated catchments (Fig. 2) and includes the basin of the left Nysa Kłodzka river tributary—i.e., Ścinawka. Within this watershed, there is only one meteorological station with rain gauge. Hence, due to numerous local anomalies in the precipitation field in the study area (orographic precipitation, rain shadows), the precipitation measurements weighted by Thiessen polygons are imprecise representation of real spatial variability of rainfall. Both dense distribution of measurements in the mountainous areas and relatively small number of stations located on the plains and in the NW part of Bardo watershed lead to the difficulty in adjusting model parameters and, as result, in accurate simulating discharge. Żelazno is a watershed with the most diverse topography; hence, the local anomalies in precipitation occur more frequently and have greater impact on model misrepresentation of the spatial rain pattern. It is also considered that the soil properties in this forested watershed (forests compose over 63% of land use) can exhibit seasonal variability which is more significant than in remaining watersheds. Further investigation into the latter problem is needed, because Polish digital soil maps provide information about soil properties only for agricultural land (Drzewiecki et al. 2014), and thus, there are no data for forested areas.

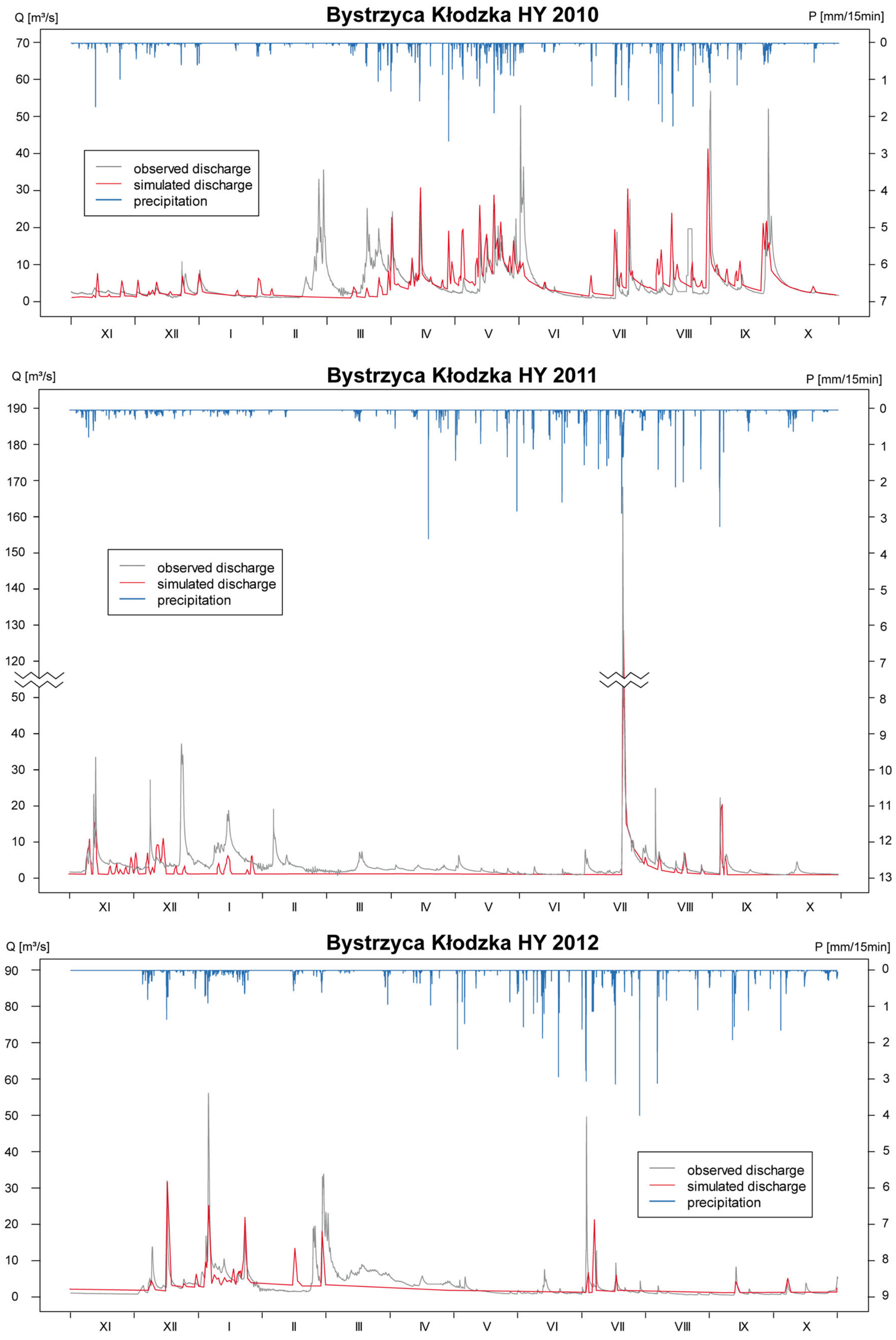
For Bystrzyca Kłodzka and Kłodzko watersheds, TOPMODEL performed better in predicting discharge than the observed mean. The only exception is associated with Kłodzko watershed in HY 2010, for which the model predictions were exactly as accurate as the mean observed discharge ($NSE = 0.03$). In the watershed where TOPMODEL performance was superior over the remaining basins, i.e., Bystrzyca Kłodzka, the model obtained the highest efficiency for HY 2011, what is consistent with other watersheds investigated in HY 2011. It may hypothesized that meteorological conditions in this HY differed significantly from the remaining calibration HYs, and the processes involved in these conditions can be better represented by the model. This may be confirmed by the analysis of rainfall and discharge patterns in Kłodzko station (Table 5).

The primary difference in the shapes of hydrographs for HYs 2010–2012 is the existence of a large mid-summer peak as a result of major storm event occurring on 24/07/2011. The peak was reconstructed well by the model—its underestimation by over 20% is acceptable taking into

Table 4 Modeling results and the calibrated parameter values

	Bardo			Bystrzyca Kłodzko			Kłodzko			Żelazno		
	2010	2011	2012	2010	2011	2012	2010	2011	2012	2010	2011	2012
NSE	− 0.49	− 0.01	− 0.10	0.29	0.78	0.32	0.03	0.66	0.32	0.31	0.42	− 0.18
RMSE	23.884	20.561	14.458	4.502	3.485	3.264	16.103	7.831	6.974	5.644	2.947	2.889
Cor	0.07	0.29	0.14	0.59	0.89	0.58	0.59	0.83	0.64	0.70	0.66	0.06
Best performing parameter set												
qs0	3.99E−05	3.99E−05	3.95E−05	1.75E−05	3.99E−05	3.21E−05	5.79E−06	3.91E−05	3.96E−05	2.04E−05	3.90E−05	2.47E−05
lnTe	0.898	0.400	0.872	− 0.345	− 1.964	− 0.542	0.366	− 0.576	0.278	− 1.332	0.023	0.989
m	1.932	0.956	0.453	0.022	1.605	0.096	0.037	1.875	0.175	0.030	1.268	1.971
Sr0	0.004	0.018	0.011	0.007	0.009	0.002	0.007	0.008	0.001	0.018	0.015	0.006
Sr_{max}	2.647	2.810	2.619	0.002	0.464	2.409	0.000	0.275	2.979	0.019	0.021	0.355
td	0.839	2.391	1.948	0.855	1.212	0.485	1.127	1.371	2.446	1.211	1.731	0.502
vch	811.5	860.2	895.4	877.0	876.0	851.7	825.3	898.3	815.7	824.5	965.6	848.4
vr	891.9	934.5	980.7	958.0	841.5	903.5	987.8	999.1	970.1	809.3	878.5	983.0
*k*0	0.006	0.006	0.003	0.005	0.003	0.005	0.003	0.008	0.007	0.004	0.009	0.003
CD	2.471	4.101	1.256	1.038	4.434	2.313	3.332	1.852	1.577	4.921	2.209	1.735

NSE Nash–Sutcliffe efficiency, *RMSE* root-mean-square error (m^3/s), *cor* Pearson's correlation coefficient, *qs0* initial subsurface flow per unit area (m), *lnTe* log of the aerial average of *T*0 (m^2/h), *m* model parameter controlling the rate of decline of transmissivity with the soil profile, *Sr0* initial root zone storage deficit (m), Sr_{max} maximum root zone storage deficit (m), *td* unsaturated zone time delay per unit storage deficit (h/m), *vr* channel flow inside the catchment (m/h), *k0* surface hydraulic conductivity (m/h), *CD* capillary drive



Bystrzyca Kłodzka HY 2010

Bystrzyca Kłodzka HY 2011

Bystrzyca Kłodzka HY 2012

Fig. 4 TOPMODEL simulation results for the Bystrzyca Kłodzka watershed account the magnitude of the event. The well-fitted parts of the hydrograph include also recession curve after the main peak, and modelling such situations is perceived as one of the most problematic responses to be reconstructed by the TOPMODEL (Sigdel et al. 2011). The model was able to predict smaller peaks after the event and the estimation of the base flow also improved after the main peak. The biggest discrepancies between observed and simulated runoff occur in the winter season. This is due to the limitation of this simple version of TOPMODEL which does not account for the water accumulated in snow cover. Because the model uses the same parameters to estimate the discharge during the whole simulation period, its values need to be calibrated to produce the smallest overall prediction error, for different hydrological settings. In such a case, the model seems to provide superior fit to the large peaks rather than to other hydrological situations. The evaluation of model performance on a basis of NSE itself can be misleading due to the inclination of this measure to place emphasis on the larger errors, while the smaller ones tend to be neglected. The acceptable performance of the model during one extreme event contributes to good statistical performance for entire hydrograph and poor results in the representation of the base flow. Although this discrepancy occurs during long periods of simulation for low flows, its impact on the overall efficiency measure is rather small. The model parameters estimated with support of this criterion produce a hydrograph that recreates peaks with reasonable accuracy, but fails to match the observed hydrograph during low flows. In 2011, despite the high 0.78 NSE, the model underestimated the mean discharge by over 40%, similar to the HY 2012 with much lower NSE of 0.29.

The same pattern can be observed in Kłodzko catchment. In this case, the recession curve was not reproduced as accurately and the overall model performance is lower (NSE = 0.66) than in Bystrzyca Kłodzka catchment (Fig. 5). The model does not provide a good representation of hydrograph during the winter season, when discharge is impacted by snow-melt and water can be stored in snow cover. Similar situation was detected also on other hydrographs for all the catchments, i.e., simulations for period December–April were found to be inaccurate. This leads to the conclusion that snow component should be included in the model structure to properly reconstruct the hydrological behavior of the investigated catchments in winter seasons. To confirm the impact of this misrepresentation of the hydrograph, the model was tested on the shorter periods and the following section contains the results of this simulations.

Table 5 Rainfall and discharge patterns in Kłodzko station and the NSE values obtained in the simulations

	2010	2011	2012
Mean observed discharge (m^3/s)	3.11	3.82	4.81
Mean simulated discharge (m^3/s)	3.61	2.27	2.92
NSE	0.29	0.78	0.32
Precipitation (mm)	748	758	836

Optimal time span for simulations

The best performing watershed—Bystrzyca Kłodzka—was chosen to conduct a detailed analysis of the model ability to reproduce hydrological response during periods of different lengths. It was assumed, based on the shape of the simulated hydrograph for entire year in relation to the observed one, that the model performance during the winter season will exhibit the lowest accuracy expressed by the NSE. To determine the most optimal time span for the model simulations, the periods of 1 week, 2 weeks, 3 weeks, 1 month, 2 months, 3 months, and 6 months were taken into account. Table 6 shows the results for HY 2011, where a given time span (e.g., 1 week of data) was iteratively moved forward by 1 day (which corresponds to 96 observations) to rerun simulations and get a set of statistics. Figure 6 depicts the variability in achieved NSE values for 2-week, 1-month, and 6-month periods.

The overall performance of a model for particular time period was judged subjectively by comparing the efficiency measures obtained by each simulation independently. To shorten the time-consuming calculations, the number of simulations in the Monte Carlo procedure has been reduced from 10,000 to 1000. It was impossible to find the timespan that would give satisfactory results for all hydrological settings, and this is clearly seen when analyzing winter seasons. The mean NSE, calculated for a window of a given length moved in a stepwise way through the entire year, is severely impacted by the low values representing the periods in winter season. Most sensitive to this effect, and thus producing dispersed values, were shorter periods—standard deviation of NSE for the 1-week period exceeds 2 m^3/s. The NSE of the best-fitted parameter set in all periods is very high, namely of 0.95–0.97, but these values relate mostly to the time spans when the discharge rate is stable and this stability is expressed properly by the model. To avoid the positive bias, percentage of the parameter sets that can be considered behavioral (NSE > 0.6) and percentage of the parameter sets that perform better than the mean of observed values (NSE > 0) have been calculated. The variability of the mean NSE among the investigated periods is high, but the ratio of behavioral parameter sets and especially parameter sets with NSE > 0 is much more stable. The NSE decreases rapidly after each peak caused by the snow-melt

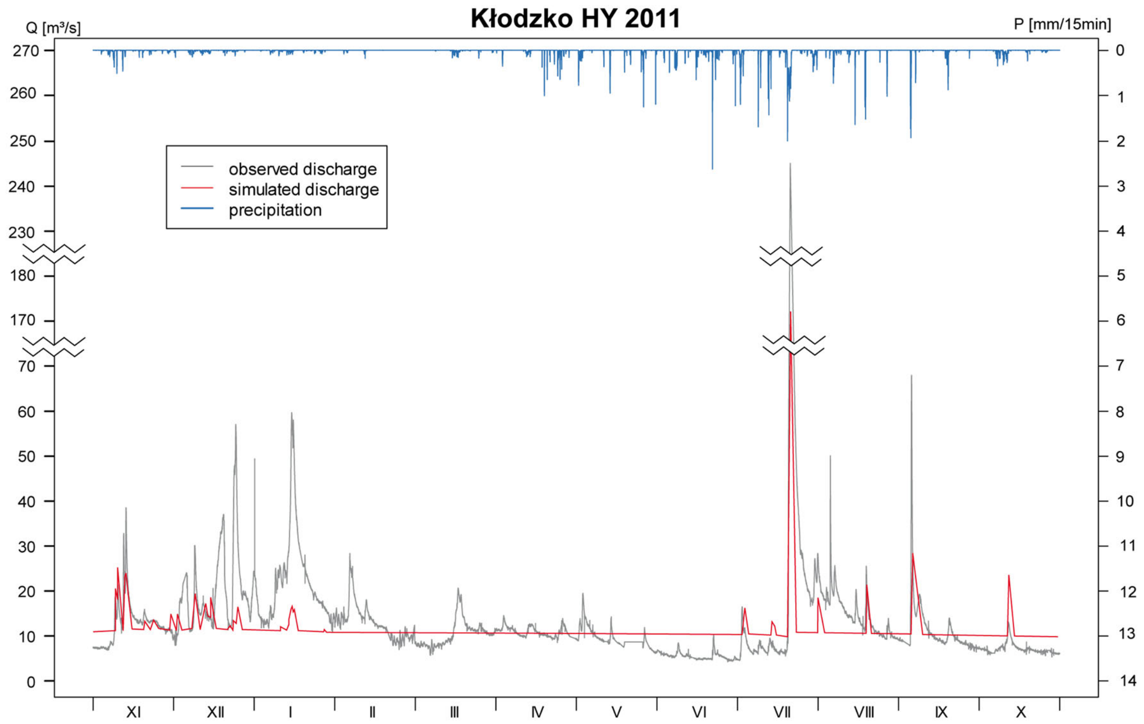


Fig. 5 TOPMODEL simulation results for the Kłodzko watershed in HY 2011

Table 6 Comparison of simulation results for chosen period lengths for Bystrzyca Kłodzka catchment in HY 2011

Time span	1 week	2 weeks	3 weeks	1 month	2 months	3 months	6 months
Number of simulations	359	352	345	336	306	276	246
Number of time steps in each simulation	672	1344	2016	2880	5760	8640	11,520
Mean NSE	− 0.52	0.09	0.22	0.28	0.34	0.39	0.41
Std dev. NSE	2.22	5.25	0.53	0.48	0.43	0.44	0.44
Best NSE	0.98	0.97	0.95	0.96	0.96	0.96	0.95
NSE > 0.6 (%)	25.07	26.42	25.79	26.78	30.06	32.97	42.27
NSE > 0 (%)	62.67	67.04	70.14	72.32	70.26	73.18	75.61
Mean RMSE	1.69	2.00	2.18	2.34	2.74	2.90	2.92

NSE Nash–Sutcliffe efficiency, *RMSE* root-mean-square error (m^3/s)

as indicated in Fig. 6. Another major dip corresponds to the storm from 24 July 2011, when the underestimation of the main peak flow affects the NSE value. The best performance of the model was noticed for the 6-month period. Just after the winter season, the NSE values rise gradually and reach a plateau of NSE > 0.9 beginning with the simulations starting at the end of March. It has been noticed that for the longer time spans, the model was able to simulate the major peak from 24 July 2011 with higher accuracy.

Further analysis of the impact of the snow component was performed by limiting the modeling to period without snow cover: April to October for HY 2010, 2011, and 2012. Univariate analysis of the simulated discharge in comparison to the calculations for entire HY as well as NSE values confirms that the model performance is highly influenced by the snow-melt component (Table 7). For the best performing HY 2011, as predicted in optimal time span analysis, the NSE value was as high as 0.93 for the months without snow cover in comparison to 0.78 for entire year. The goodness-of-fit for simulations in HY 2010 and 2012 was also significantly enhanced by limiting modeling to the April–October period. NSE value for HY 2010 increased from 0.29 to 0.62 reaching the behavioral threshold; and in HY 2012, the value of NSE raised from

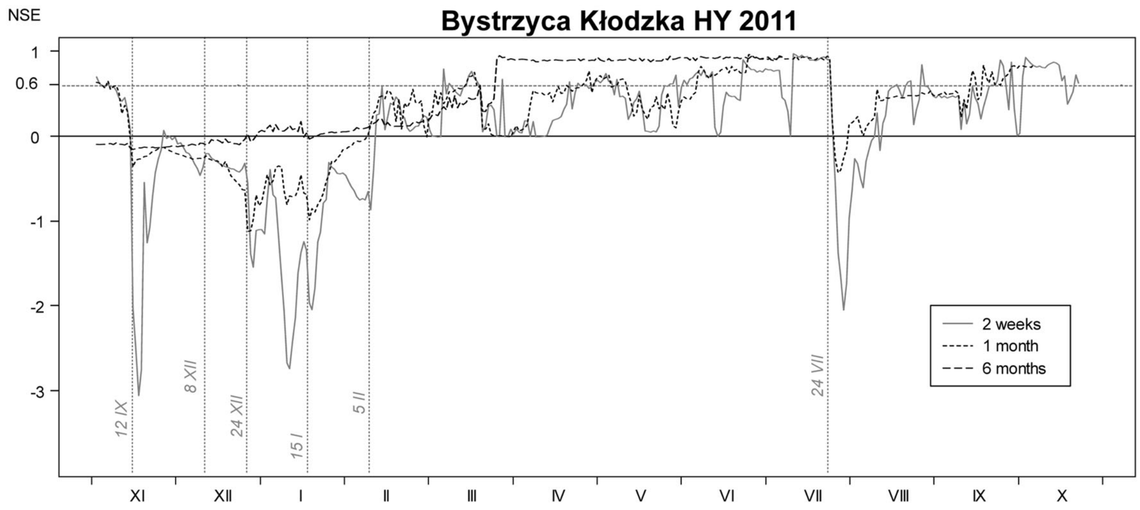


Fig. 6 Performance of TOPMODEL as a function of span of data used to calibrate the model

Table 7 Comparison of statistics for model performance in Bystrzyca catchment for entire HY and for months without snow cover (April–October)

	HY			IV–X		
	2010	2011	2012	2010	2011	2012
NSE	0.29	0.78	0.32	0.62	0.93	0.57
Standard dev.	3.19	5.91	4.01	6.12	7.32	7.01

0.32 to 0.57. It should also be noted that for the experiment limited to the April–October period (Table 7).

Finally, it is worth noting that there were applications of TOPMODEL in temperate cold climate for which snow-melt component was not included (Lamb et al. 1997). This supports our approach and the comparison presented in Table 7.

Model validation

The optimized parameter set from HY 2011 in the best performing watershed Bystrzyca Kłodzka was applied to the same watershed for the HY 2009 to validate the model. In the validation exercise, the 6-month time span was used as it was shown to be the data length for which model skills were the superior over all the studied cases (Table 6). Thyssen polygons for spatial distribution of rainfall data were recalculated because of the lack of precipitation data in one of the station used for HY 2010–2012. Precipitation data from station located 8 km away were used as a substitute.

Validation performed for entire 2009 HY showed that the hydrograph fails to match with the observed one at the beginning of the year, during the snow-melting period. Following the procedure described in "Optimal time span for simulations", the simulations were limited to the shorter time spans, focusing on the period without snow cover and using the best performing parameter set calibrated for Bystrzyca catchment for the months without snow cover.

Model performed best for the summer and fall months, with the exception of the period from mid-June to mid-July, where the simulated hydrograph failed to match the observed one. Figure 7 shows the results of the validation preformed on the late summer months of the 2009 HY. The NSE value obtained for depicted time span was 0.73; and limiting the simulation period to only the months of August and September, the NSE value reaches 0.87 and predicts accurately the recession curve. Despite the high value of NSE and relatively accurate representation of the first peak, the hydrograph significantly underestimates the second peak in the period of simulation.

Validation showed satisfactory results also for the month of May 2009 (Fig. 8). The NSE of 0.63 is above the 0.6 threshold for being classified as behavioral. Similar to the above described period, the peaks of the hydrograph are underestimated and the model fails to predict accurately the last peak in the period showing only a slight rise in the discharge rates, when the observed values form the largest peak in this time span.

The poor performance of the model for the validation period of entire 2009 HY as well as the months without snow cover can be explained by the uniqueness of conditions in the best performing 2011 HY, when the intense precipitation and very high discharge rates in the major peak from 24 July 2011 resulted in calibration of the parameters performing best in this unique conditions and failing to simulate the hydrograph in less extreme circumstances. Despite that, there were time spans in the validation period that the model demonstrated satisfactory results, only slightly lower than the values obtained during calibration period.

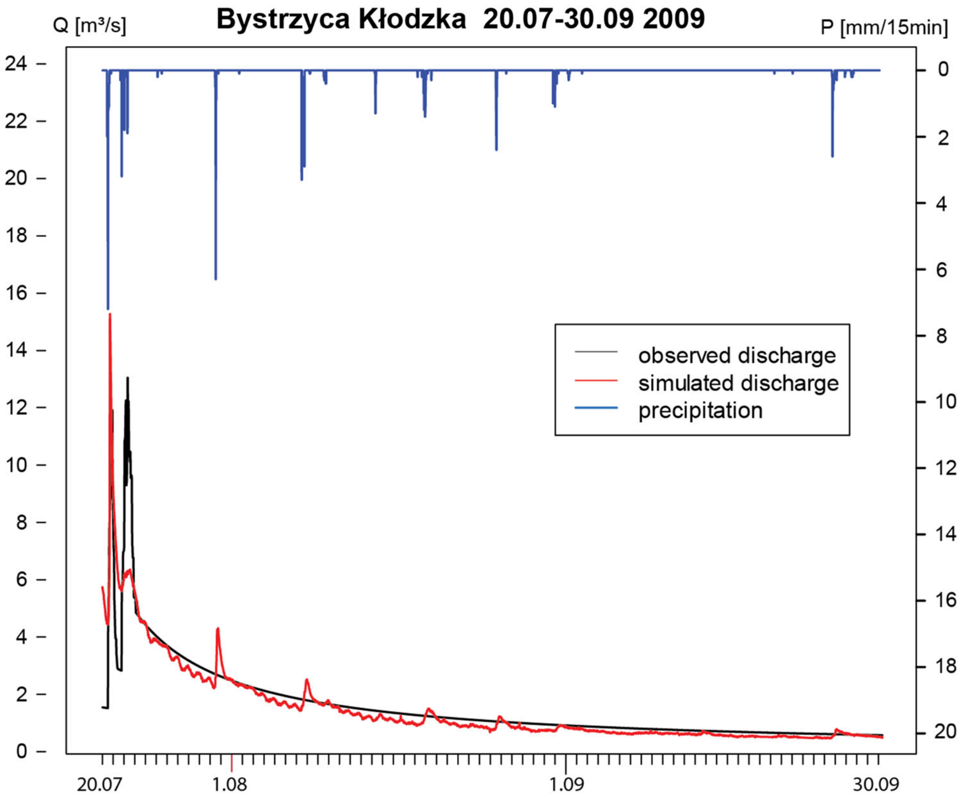


Fig. 7 Validation of TOPMODEL for the Bystrzyca Kłodzka watershed

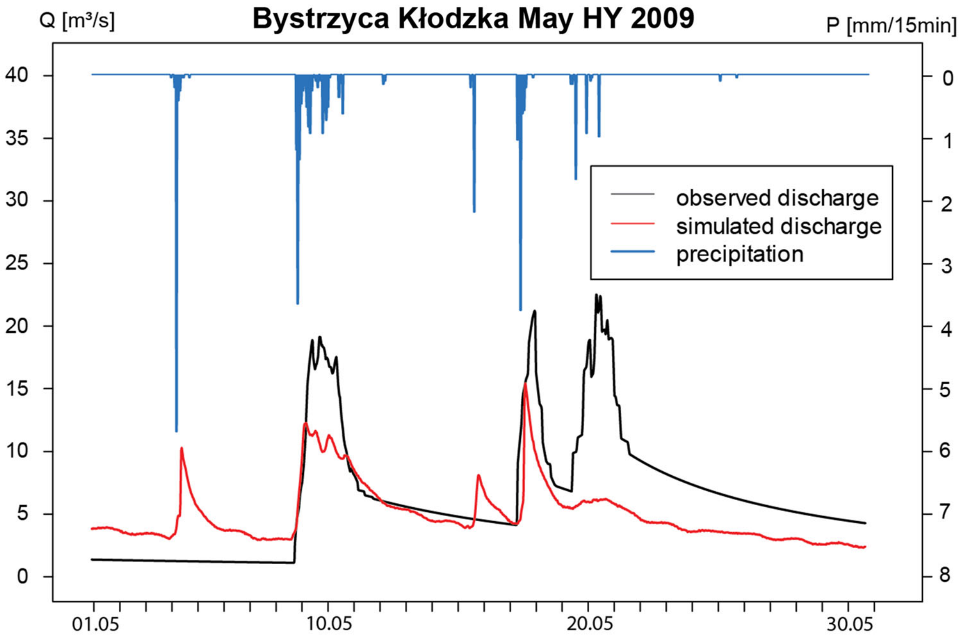


Fig. 8 Validation of TOPMODEL for the Bystrzyca Kłodzka watershed in the month of May 2009

Conclusions

TOPMODEL was successfully applied to four subcatchments of the upper Nysa Kłodzka river basin, but was able to reproduce the main pattern of the hydrograph with acceptable accuracy only for two of them. The conclusions are the following.

1. Poor performance of the model in two catchments can have variety of reasons, including input data error, calibration inaccuracy, parameter uncertainty, and model structure. The most probable cause of

misrepresentation of hydrograph lies in the snow-melt component that is not included in this basic version of TOPMODEL. A more sophisticated structure of the response function needs to be used to improve the TOPMODEL performance in all of the investigated watersheds. Low accuracy of the model can also be effect of the model inability to represent distributed rainfall pattern.

2. Complicated environment and lack of soil data make the calibration of parameters challenging. The Monte Carlo simulation produces the most suitable parameter sets, but they may not correspond to the actual conditions in the watershed.
3. It has been found that the goodness-of-fit increases along with time span of data used for TOPMODEL calibration, and among the studied periods, the half-year solution produces the best agreement between data and model simulations. However, such estimates cannot be treated as global ones, since they are highly dependent on hydrological settings and weather conditions.
4. Simulations that do not include winter season provided promising results, the NSE for nearly half of the simulations using 6-month time span of data for Bystrzyca Kłodzka catchment are higher than 0.6.
5. Snow cover was found to impact the model performance, i.e., when the analysis is limited to snow-free months, the NSE values are considerably higher than for the entire year which includes periods of snow cover occurrence.
6. Validation performed using the best set of parameters obtained during calibration for the best performing watershed was found to demonstrate satisfactory results (obtained just slightly lower NSE values than during calibration period), but only for shorter time spans and failed to simulate the hydrograph for the entire HY used as validation period.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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