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River flow hydrograph simulation using the HBV-light model (an example of small rivers in Tomsk city, Western Siberia, Russia)

V.A. Zemtsov[1], S.G. Kopysov[1], H. Matsuyama[2], S.V. Negrul[1]

[1]*Tomsk State University, Lenina Ave. 36, 634050, Tomsk, Russia*
[2] *Tokyo Metropolitan University, Tokyo, Japan*
Corresponding author E-mail: zemtsov_v@mail.ru

The goal of this paper is to study the applicability of the conceptual model to simulate and predicting the small river flow hydrographs and maximum water discharges produced by meteorological factors in the context of climate change and land use modifications. Three small rivers, tributaries of Ob (the Bolshoy Tatosh River at the Bolshoy Tatosh gauge station) and Tom (the Basandayka River at Basandayka and the Poros River at Zorkaltsevo) are studied by means of flow hydrograph modeling based on the HBV-light model. The study area in the city of Tomsk and its vicinity is considered as a zone of compound extremes of flooding. Initial information for flow modeling includes open data of hydrometeorological observations for 2008-2017. Results of flow hydrograph simulation are of a good quality and might be useful for flow prediction in unaffected catchments, monitoring and management of flood situation in the Tomsk area and similar regions.

Keywords: Compound extremes, flood, small rivers, hydrograph simulation.

Introduction

Floods are the most important and hazardous events taking into account of their magnitude and consequences in the life of Siberian rivers (Taratunin, 2008; Zemtsov et al., 2014). In the city of Tomsk and its vicinity, people almost every year deal with 'compound extremes', that is, 'the simultaneous or sequential occurrence of multiple extremes at single or multiple locations' (Hao et al., 2018, p.1). Especially hazardous is the flood situation that includes the following dangerous processes: (1) floods in the large river of Tom, associated with a rapid increase in its water flows due to intensive snow melt and rainfalls in the river basin; (2) floods in the city and its environs, arising from ice jams, the frequency of which tends to increase (jams can also occur in years with relatively low flood water flow; they often lead to the most dangerous rises in water level and flooding in the Tom valley); (3) floods with probable destruction of river banks in small tributaries of Tom; (4) the rise in groundwater levels in the city and its environs due to abundant atmospheric precipitation and (5) dangerous hydrogenic processes, such as landslides (Matsuyama et al., 2021) on steep slopes of river valleys.

Taken together, all of the above determines the complexity of the flood situation, which should be predicted in advance, and adequate measures should be taken to reduce risks and eliminate the consequences of floods.

The goal of this paper is to study the applicability of the internationally recognized conceptual HBV light model for simulating and predict small river flow hydrographs and maximum water discharges produced by meteorological factors in the context of climate change and land use modifications. In this regard, our recent experiments in hydrographs and daily maximum water flows modeling for Arctic rivers of western Siberia based on the HBV-light model have shown encouraging results (Kopysov et al., 2020).

Study area

The study area (Fig. 1) is located in the middle course of the Ob River, within the southeastern part of the Tomsk administrative region, around the city of Tomsk. Ob is the third largest northward flowing river in Siberia with headwaters in the Altai and Sayan Mountains. Tomsk is situated on the Tom River, the largest right tributary of the Ob. A transitional position of the study area between the mountain structures of Altai and Sayan and the west Siberian Lowland predetermines a complicated combination of hills and lowlands in the region.

The rivers in the area are characteristic of a high snowmelt flood and summer to autumn rain floods; a winter low flow period when the rivers are covered by ice lasts about six months. Maximum water levels are usually produced by a passage of peak spring-summer flood flow peak water discharges. The most common are snow melt floods that occur every year during spring (in medium size and small rivers, or spring to summer high water in large rivers. The flood flow hydrograph of the Tom River in Tomsk have several peaks, produced in different landscapes of its watershed basin.

Climate warming accelerates snowmelt in the headwaters of large rivers Ob and Tom rivers that run north from the mountains. In spring, melt water quickly destroys the winter ice pack in the river channel, and ice-jam-induced floods are becoming more frequent in transition areas between hills and lowlands. During spring floods, in river mouth areas of the tributary lowland rivers backwater

effects occur (Fig. 2), significantly worsening the drainage conditions of the watershed areas, increasing groundwater levels, and inducing destructive processes in the river valleys (Zemtsov et al. 2014).

We study three small rivers (Table 1) that flow into the large rivers of Ob (the Bolshoy Tatosh River at the Bolshoy Tatosh gauge station) and Tom (the Basandayka River at Basandayka and the Poros River at Zorkaltsevo). Despite geographical proximity, the physiographical characteristics of these catchments, including the water flow rate and regime, are quite different and influenced by anthropogenic activities. As a result, the water budget of such small catchments is also different (Savichev et al., 2010).
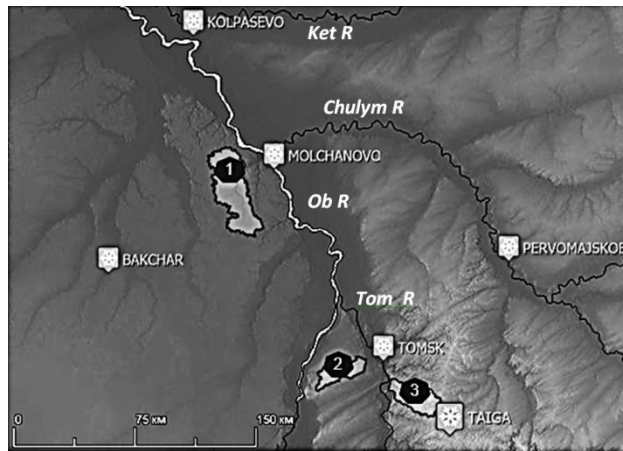

Fig. 1. Study area, weather stations and modeled small river basins in the middle course of the Ob River: 1-Bolshoy Tatosh, 2-Poros, 3-Basandayka.

Fig. 2. Backwater in the Ushayka river mouth at the Tomsk city center during a snow-melt-driven flood, dammed by the ice jam at the large river of Tom in the end of April, 2010 (Territorial Center, 2020).

Table 1. Localities of the gauge stations and accuracy of the flow hydrograph simulation using the HBV-light model.

River-Gauge Station	Catchment Area, km²	Weather Stations	Catchment Center Coordinates	Calibration Period	Coefficient of Determination R²	Model Efficiency Reff	Efficiency of Flood Flows Estimation Reff_flood
Bolshoy. Tatosh-Bol. Tatosh	1140	Kolpashevo, Bakchar	57°29' N 83°21' E	2008-2017	0.89	0.82	0.88
Poros-Zorkaltsevo	316	Tomsk	56°28' N 84°32' E	2011-2016	0.80	0.76	0.91
Basandayka-Basandayka	402	Tomsk, Taiga	56°20' N 85°11' E	2012-2018	0.89	0.89	0.92

Materials and Methods

For modeling river flow hydrographs with daily resolution, we apply rather simple conceptual semidistributed reservoir-type models, such as the HBV-light model (Seibert and Vis, 2012), one of new versions of the HBV model developed in the Swedish Meteorological and Hydrological Institute (Bergstrem and Forman, 1973), and the Tank Model (Sugawara et al., 1995) developed in the National Research Center for Disaster Prevention in Tokyo, Japan. After appropriate testing procedures, both the HBV and the tank model were recommended for practical use by the Hydrological Operational Multipurpose System (HOMS) established at the World Meteorological Organization for the transfer of technology in hydrology and water resources (Guide, 2009).

The HBV-light contains (1) snow routine, (2) soil moisture routine, (3) response function, and (4) routing routine (Seibert, 2005). Simulating flow hydrographs in the model with daily resolution consists of initial data preparation and selection (calibration) of the

model parameters that allow calculation of the daily runoff depth based on daily air temperature and precipitation at the nearest weather stations. We carried out the parameter calibration by using manual trial and error technique as recommended in (Seibert, 2005).

Initial data for flow modeling, namely, daily precipitation, daily air temperature data for the Roshydromet period 2008 to 2017 at the weather stations of Roshydromet nearest to the modeled river basins, were taken from databases of the All-Russia Research Institute of Hydrometeorological Information-World Data Center (RIHMI-WDC) (http://meteo.ru/data). Daily river water discharges at river gauge stations used in the study were obtained from the Automated Information System for State Monitoring of Water Bodies (https://gmvo.skniivh.ru/).

Results and Discussion

The results of the river flow modeling are shown in Table 1-3. All criteria that evaluate the fit of the simulated daily water discharges to the observed flows are high (Table 1). The best fit quality was obtained for 2015 with the greatest water flow rates from the watershed areas of the study catchments (Table 2). In Table 3, calibrated values of the parameters of the HBV light model parameters are presented. Different values of the same parameter are characteristic for different study basins.

Table 2. Accuracy of the 2015 maximum floodwater discharge estimation using the HBV-light model.

River-Gauge Station	Date of Qobs	Qobs, mm day^{-1}	Date of Qsim	Qsim, mm day^{-1}
BolshoyTatosh at Bolshoy Tatosh	04/26/2015	6.9	04/28/2015	6.8
Poros at Zorkaltsevo	04/24/2015	5.9	04/27/2015	5.2
Basandayka at Basandayka	04/25/2015	15.7	04/25/2015	15.4

The most severe flood situation was observed in spring 2010. At the end of April 2010, there was a coincidence in time of three characteristic flood events (Sidorenko and Romantsov, 2010): (1) intense flood in small rivers (Ushayka, Basandayka), (2) powerful ice drift with the formation of ice-jams and dams in the river of Tom near Tomsk, and (3) rapid rise in the Tom water level due to hot weather in the Tom river basin. Usually, the time interval between these separate consecutive events in ordinary years reaches up to one to two weeks. The water level in the Tom River near the Basandayka mouth has risen by more than 2 m, the flow of the Basandayka has actually stopped, and a vast backwater zone has formed in the small river channel. 'Observed' water discharges were more than twice overestimated due to the calculation of Qobs using its dependence on the water level, constructed for natural conditions, without the backwater effect (Fig. 3). It was proven that the situation in 2010 was favorable for the formation of landslides due to the high intensity of snow melting and atmospheric precipitation (Matsuyama et al., 2021).
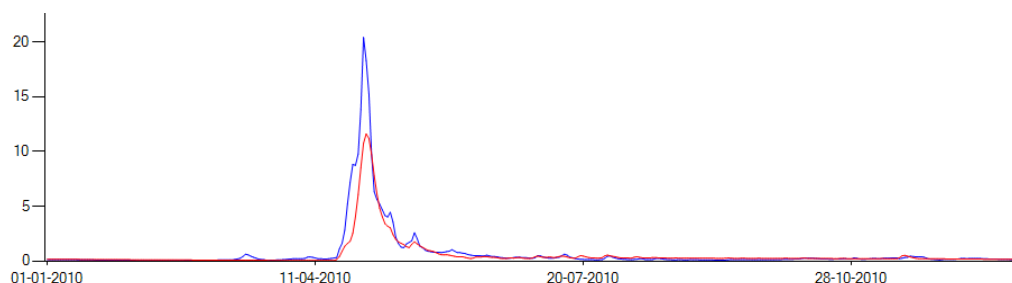

Fig. 3. Observed Qobs (blue line) and simulated in HBV-light Qsim (red line) water discharges from the Basandayka River at Basandayka, mm day^{-1}.

Table 3. Values of calibrated parameters of HBV-light for maximum daily specific discharge simulation.

Parameter	Notation	Unit	Bolshoy Tatosh-Bolshoy Tatosh	Poros-Zorkaltsevo	Basandaik-Basandaika
Threshold temperature between snow and rain	TT	ºC	2.3	1.5	0.5
Degree-day factor	CFMAX	mm ºC^{-1} day^{-1}	1.3	1.05	2.8
Correction factor for snow	SFCF	-	1	0.8	1
Refreezing coefficient	CFR	-	0.05	0.05	0.05
Proportion of melt water in snow pack	CWH	-	0.1	0.1	0.1
Maximum soil moisture storage	FC	mm	120	300	380
Threshold value of soil moisture	LP	-	0.2	0.4	0.1

Parameter, determining the relative contribution to runoff from rain or snowmelt	Beta	-	0.99	1.5	0.7
Recession coefficient	K_0	day^{-1}	0.4	0.4	0.1
Recession coefficient for upper reservoir	K_1	day^{-1}	0.1	0.1	0.1
Recession coefficient for lower reservoir	K_2	day^{-1}	0.09	0.09	0.009
Storage in upper zone	UZL	mm	35	15	20
Max. percolation to lower zone	PERC	mm day^{-1}	2	0.3	0.5
Parameter of transformation function	MAXBAS	day	5	5	2

Conclusion

The results of the study show that the conceptual HBV light model is applicable to simulate and predicting the small river flow hydrographs and maximum water discharges produced by meteorological factors in the context of climate change and land use modifications. Important advances of the model are its ability to reproduce flow hydrographs of ungauged small rivers using only observational data from the nearest weather stations and landscape characteristics of watershed areas. The results of our study also show that the calibrated values of the model parameters differ considerably differ for different small catchments within the study area. This fact complicates the determination of model parameters for small ungauged catchments. However, the model might be useful for reconstructing/correcting time series of hydrological observations containing missing (or rejected) values such as at Basandayka gauge station (or Poros at Zorkaltsevo) in April-May 2010. In general, the results of the flow hydrograph simulation are of good quality and might be useful for the prediction of flow prediction in ungauged basins, monitoring and management of flood situations in the Tomsk area and other regions.

Acknowledgements

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