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Hydrological Modeling in Studies of Mountain River Basins of Central Asia

Olga Kalashnikova[1,*], Jafar Niyazov [2] Aliya Nurbatsina[3]

[1]Department of the "Climate, Water and Geoecology"/ Central-Asia Institute for Applied Geoscience, Bishkek, Kyrgyz Republic

[2] Laboratory of Climatology, Glaciology and modeling of water resources / National Academy of Tajikistan Institute of water problems, hydropower and ecology, Dushanbe, Republic of Tajikistan

[3] Laboratory of Water Resources/Institute of Geography and Water Security, Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan, Almaty, Republic of Kazakhstan

* Corresponding author: o.kalashnikova@caiag.kg

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Abstract

Nowadays, hydrological modeling is widely used both in the scientific and practical studies of mountain river basins. The purpose of this study is to review the developed and adapted hydrological models in Central Asian countries. The models have different methodological approaches and peculiarities in data requirements, which the authors describe in more detail in the paper. Model calibration and testing results are given for mountain rivers located in Kyrgyzstan, Kazakhstan, and Tajikistan. For the high-mountain river basins with small river basin areas (in our study, the average catchment elevation is 2,652-4,170 m.a.s.l. and river basin area starts from 6.6 to 13.7 thousand km^2) and availability of the representative meteorological stations, the use of whole hydrological models such as HBV light and HBV-EHT show good quality (NSE=0.65-0.94, R=0.82-0.97) and practical applicability for rivers runoff estimation. However, such models have a loss of accuracy as they consider the basin a single unit. The Snowmelt Runoff Model (SRM) also performed well (R = 0.71), but requires additional input information on snow cover area from satellite images. The Soil and Water Integrated Model (SWIM), as a distributed type of model, uses a partitioning of the basin into hydrotopes, which complicates the calibration of the river basin model but allows a more accurate description of the processes in its basin (has good calibration quality for a river basin NSE = 0.88). The Water Evaluation and Planning system (WEAP) has a user-friendly interface and good calibration quality (NSE = 0.61, R = 0.88) for large river catchments (in our case 52.2 thousand km^2) and can be applied for water management purposes both at national and regional levels. The paper outlined the main conclusions on the application of these models for research purposes.

Keywords: hydrological modelling, Central Asia, mountain river, SRM, HBV, WEAP, SWIM

Introduction

Central Asia is particularly vulnerable to climate change, as this region is mainly irrigated agriculture, which depends on river runoff formed mainly by snowmelt and glacial waters.

Mathematical modeling in Central Asia has been developed since the 1970s at SANIGMI (Central Asian Scientific Research Hydrometeorological Institute) in Tashkent (Borovikova, 1972). Mathematical modeling made it possible to move from the use of indirect characteristics of runoff-forming factors used in physical-statistical methods to approximate calculations of these factors. Water reserves in snow cover, their distribution by height, and other factors influencing the formation of mountain river runoff began to be determined by mathematical expressions.

Studies have shown that in the Tien Shan, snow accounts for up to 70 % of the total precipitation and provides 60% of the total river runoff (Aizen, 1995). The use of remote sensing data, AVHRR satellite images (Baumgartner, 1988), and MODIS has provided information on snow reserves in inaccessible mountainous areas of Central Asia (Gafurov & Bárdossy, 2009). Over the following decades, hydrological models were developed by various scientific institutes and applied to the different Central Asian river basins. Research work has been carried out for the Syr Darya and Amu

Darya river basins, ranging from small river basins such as the Ala-Archa (Hagg, 2006) to rivers with significant basin areas such as the Tarim (Duethmann, 2016) and Ak-Shyirak in the High Tien Shan (Hagg, 2018). Modeling has been applied both to calculate intra- and inter-annual variability of the streamflow (Gafurov, 2017) and to calculate individual streamflow components, mainly glacial runoff (Hagg, 2007). In addition to research purposes, some hydrological models are used by state organizations (national hydrometeorological services) for practical purposes. For example, HBV light is actively used for river basins in Kazakhstan (Bolatova, 2018), and in the 2000s SRM for rivers in Uzbekistan (Baumgartner, 2000).

Several different types of hydrological models have been created so far. These models can predict changes in streamflow with varying levels of accuracy and consider both natural and human-caused changes in the environment.

This paper presents hydrological models implemented and tested in various organizations and institutions in Central Asia (national hydrometeorological services, research institutions, etc.). The authors evaluated the success of these hydrological models on the example of Central Asian river basins. The presented hydrological models were tested by the authors in previous studies and published in scientific journals and reports for the river basins of Kyrgyzstan (Kalashnikova, 2023), Kazakhstan (Nurbatsina, 2019) and Tajikistan (Niyazov, 2020). The publication presents the main methodological approaches, a brief characterization of hydrological models, and the main conclusions and recommendations obtained by the authors when using them.

Methods and Materials

River basins of Central Asia with basin area from 6,602 km^2 to 52,187 km^2 with an average catchment elevation of 240 - 4170 m.a.s.l. were selected as the main study sites. Most of the studied rivers (Naryn, Gunt, and Chatkal) have the snow-glacial type of feeding, with a glaciation area of 0.6 - 4.6 % of the basin area as estimated by Konovalov in 1985 (Konovalov, 1985) and Shabunin in 2018 (Shabunin, 2018), with flood peak in June. In addition, two river basins were selected, the headwaters of the Naryn River up to the Naryn and Kyzyl-Suu (western, headwaters of the Vakhsh River), with glacial-snow type of feeding, with a glaciation area of 7.7-11.9 % of the basin area (Konovalov, 1985) with flood peak in July-August, the Oba and Buktyrma rivers are belonging to the basin of the Ertis River (Irtysh). Basic information on the river basins is presented in Table 1.

Table 1. Basic information about the river basins under study.*

№	Name of the gauging station	Catchment area in km^2	Mean elevation in m.a.s.l.	Glacier area		Mean annual water discharge in m^3/s
				in km^2	percentage of the basin area	
1	Naryn river – tributary to the Toktogul reservoir.	52,187	2,851	1063*	2.0	404
2	Gunt river – Khorog town	13,700	4,170	634	4.6	104
3	Naryn river - Naryn town	10,500	3,570	511*	4.9	92.9
4	Oba – Shemonaiha village	8,550	1,228	-	-	173
5	Kyzyl-Suu river - Dombrachi	8,470	3,540	578*	6.8	76.2
6	Bukhtyrma – Lesnaya Pristan	10,700	-	-	-	218
7	Chatkal river – Khudoydodsay	6,602	2,652	42.3*	0.6	110

Note: *- glacier area according to Landsat images for 2013-2016 (Shabunin, 2018).

The most widely known hydrological model is HBV. *Hydrological model HBV light 2.0* were used for runoff model calibration for the upper Naryn (Naryn town) and Gunt river basins. Also were used *hydrological model HBV3-ETH9* for runoff model calibration for the Kyzyl-Suu and Chatkal river basins. The HBV model was developed in 1973 at the Swedish SMHI (Swedish Meteorological and Hydrological Institute) (Bergstörm, 1992), has been tested for regions of Switzerland (Braun, 1992), Alpine mountain basins (Hottelet, 1993) and further it was improved at the ETH Zurich. The model has been modified many times, and there are various versions in many countries. Currently, the model has a user-friendly interface that allows to visualize data and retrieve them both in graphical form and in the form of tables. The "runoff – precipitation" model HBV3-ETH9 we use to calculate runoff of high mountain rivers is an advanced model HBV, which allows us to calculate the daily runoff hydrograph based on meteorological and hydrological ground observation data. The HBV3-ETH9 model has a simple non-deterministic structure and does not require a large set of meteorological parameters. Another model that we use is HBV light 2.0 with semi-distributed parameters, which includes subroutines for meteorological interpolation, calculation of snow accumulation and snowmelt, total evaporation, soil moisture, and runoff generalization to calculate the transformation of water movement across rivers and lakes.

Data preparation, work with the model, and model optimization were carried out according to the HBV ligh 2.0t user manual (Seibert, 2005). The authors of the article used the allowable ranges of the model parameters given in the manual and the materials of previous studies for the mountain rivers of Kazakhstan (Bolatova, 2018). Data preparation, work with the model HBV3-ETH9, and model optimization were also carried out according to the HBV3-ETH9 user guide (Konz, 2003). Parameter ranges for model optimization were taken from previous studies prepared for the Enylchek of the Central Tian-Shan River (Mayr, 2014).

The Snowmelt Runoff Model (SRM) was developed by J. Martinec (1975) first for small European basins and is intended for modeling and predicting daily runoff in mountain basins where snowmelt is a major factor in the runoff. The SRM has been successfully tested at WMO for runoff modeling (WMO, 1986) and is partially used for simulated conditions of real-time runoff forecasts (WMO, 1992). The WinSRM provides the user with a complete modeling environment in which snowmelt is simulated for mountain basins where snowmelt provides a significant contribution to that runoff.

The SRM can be used for the following purposes:

1. Modeling of daily runoff in a snowmelt season, a year, or a series of years. Results can be compared with measured runoff to evaluate model performance and verify model parameter values. Modeling can also serve to evaluate runoff patterns in unmeasured basins and under hypothetical climate change.

2. The short-term and seasonal runoff forecast. The microcomputer program includes the formation of upgraded recession curves, which are the ratio of snow-covered areas and cumulative snowmelt depths when SRM is calculated.

These curves provide the ability to extrapolate snowpack area values manually by the user several days ahead from temperature forecasts so that this input of values is available for runoff forecasts. Modernized recession curves can also be used to estimate snow resources for seasonal runoff forecasts. Model performance may deteriorate if predicted air temperature and precipitation differ from actual values, but errors can be reduced by periodic upgrades.

The SRM calibration parameters include: runoff coefficient from snow, runoff coefficient from rainfall, degree-day factor (swarming factor), temperature gradient, critical temperature, rain coverage area, regression coefficient, and run-up time.

The SRM parameters are not calibrated or optimized with historical data. They can be obtained either by measurement or estimated by hydrologic judgment, considering basin characteristics, physical laws, and theoretical or regression relationships. Random successive fits should never exceed the range of hydrologically or physically acceptable estimates.

The German hydrological *model SWIM (Soil and Water Integrated Model)*, which was developed at the Potsdam Institute for Climate Impact Research (Germany) by Krysanova et al. in 1996, was tested in this study (Krysanova, 1996). The hydrological model SWIM performs calculations using the GRASS GIS software, which is freely available online (Geographic Resource Analysis Support System GRASS GIS, 2023). The user manual GRASS 4.1 was used for working with hydrological modeling (GRASS 4.1 Reference Manual, 1993). At the heart of the calculations is the division of the entire study basin into hydrotopes - areas with relatively homogeneous conditions and flow indicators, including unified characteristics of soils and land use.

In order to put the model into operational practice, it is necessary to thoroughly test it and verify the quality of the results. The following tasks were addressed during the testing: adaptation of the SWIM hydrological model to the conditions of the studied river; obtaining predictive meteorological information and processing data format in RStudio; conducting model calibration and verification; development of automatic procedures for making forecasts; evaluation of forecast quality.

The following meteorological parameters were used in SWIM for hydrological modeling: maximum, minimum, and average air temperature, precipitation amount, relative humidity, total solar radiation, and average wind speed.

The main methodological approach for modeling hydrology in *WEAP (Water Evaluation and Planning system)* is the soil moisture method. This method uses a one-dimensional equation that calculates the water balance for the surface soil profile (upper bucket, shallow soil zone) and the deep soil profile (lower bucket, deep soil zone) (User's Manual WEAP, Integrated water and energy modeling for the Syrdarya River basin).

The method considers the effect of soil water-holding capacity on runoff, evapotranspiration (ET), intermediate runoff, percolation (infiltration), and baseflow. Each watershed is delineated based on land use, soil types, and topography. Automatic watershed delineation separates catchments based on land use and elevation. Land use type and climatic parameters in the soil moisture method together determine how much water infiltrates into the ground, evaporates, or drains to the river. Meteorological parameters of the weather stations were used in WEAP for hydrological modeling: average air temperature, precipitation amount, relative humidity, and average wind speed.

The following optimization parameters were considered when evaluating the model calibration for the basin:

1. Pearson's correlation coefficient (R) is an index of the degree of linear relationship between observed and simulated data. It ranges from −1 to 1. If R = 0, no linear relationship exists. If R = 1 or −1, a perfect positive or negative linear relationship exists;
2. Pearson's coefficient of determination (R^2) also compares simulated and measured data; it describes the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance; typically, values greater than 0.5 are considered acceptable.
3. The Nash-Sutcliffe Efficiency (NSE) coefficient is commonly used in hydrological modeling to evaluate how well modeled stream flow matches observed streamflow. The ideal value is 1, Values of 0.5 are acceptable; most modelers aim for values that are at or above 0.7.
4. The ratio of the root mean squared error to the standard deviation (RSR) is a measure of how much simulated flows deviate from observed hydrographs. An ideal value is zero, but values less than 0.7 are considered acceptable.
5. Percent bias (PBIAS) is a measure of the model's ability to match the total volume of flow. An ideal value is zero, but PBIAS of plus or minus 25% of the observed streamflow is considered acceptable.

In our study, first of all, the main two parameters were taken into account to evaluate the calibration results of all presented hydrological models for streamflow - Nash-Sutcliffe Efficiency (NSE) and Pearson's correlation coefficient (R). Additionally, two morindicators—therratioio of throotomeanasquaredeerroror to the standard deviation (RSR) anpercentnt bias (PBIAS) are considered. The ideal values and interpretation of these ten embedded statistics are summarized in Table 2.

Table 2. Optimize calibration based on visual and statistical assessment.

Statistical measure Ideal and acceptable values Interpretation	Statistical measure Ideal and acceptable values Interpretation	Statistical measure Ideal and acceptable values Interpretation
Pearson's correlation coefficient, R	If R = 1 a perfect positive linear relationship exists	describes the degree of collinearity between simulated and measured data
Pearson's coefficient of determination, R^2	The ideal value is 1, values of 0.5 to 1 are considered acceptable	is an index of the degree of linear relationship between observed and simulated data
Nash-Sutcliffe Efficiency (NSE)	The ideal value is 1; values > 0.5 = acceptable > 0.6 = desired > 0.7 = good > 0.8 = very good	how well modeled stream flow matches observed streamflow
Ratio of the Root Mean Squared Error to the standard deviation (RSR)	An ideal value is zero, but values less than 0.7 are considered good.	a measure of how much simulated flows deviate from observed hydrographs
Percent bias (PBIAS)	An ideal value is zero, but PBIAS of plus or minus 25% of is considered acceptable	tendency of consistent over or underestimation of flows / match of simulated to observed total volume

Result

The calibration of the HBV-light model. The authors have used data for the Naryn river (Naryn town) period2010-201919 and for the Gunt river (Khorog), 2012-2016*For thehe calibration of the*

HBV-EHmodell, for the Chatkal and Kyzyl-Suu rivers we used data periods 2012-2016. The data from gauging stations Khudoydodsay for Chatkal river, Dombrachi for Kyzylsu river, Khorog for Gunt riv,er and Naryn town for Naryn river were used as input data. The weather stations Tien-Shan, Javshangoz, Chatkal and Sary-Tash, which were used focalibration, wereon mainly located in the upper reaches of the rivers. The gauging stations should be located at the exit from the mountain gorge, as well as located above the points of water intake for irrigation and communal services.

The data for the calculations were obtained from the historical data archive of the national hydrometeorological services under existing agreements with scientific institutes. Preparation of data in GIS required a digital elevation model with a spatial resolution of 30 meters (https://earthexplorer.usgs.gov) and shapefiles of modern glaciation, digitized for 2013-2016 using Landsat 8 images and Randolph Glacier Inventory 6.0 (2017) (Shabunin, 2018). There was a division into altitudinal zones for all watersheds above 200 meters. Model HBV3-ETH9 calculates in MATLAB and has the same set of input data as well as glacier mass balance data. We used input data on the simulated mass balance of the Abramov glacier for 2012-2016 (Barandun, 2018).

The HBV-light and HBV-EHT models were calibrated for the selected basins. The calibration showed the following results for river basins (Fig. 1): Naryn NSE = 0.84, R = 0.91 (R^2 = 0.83); Gunt NSE = 0.65, R = 0.82 (R^2 = 0.67); Chatkal NSE=0.94, R=0.97 (R^2 = 0.95); Kyzyl-Suu NSE = 0.74, R = 0.91 (R^2 = 0.82).

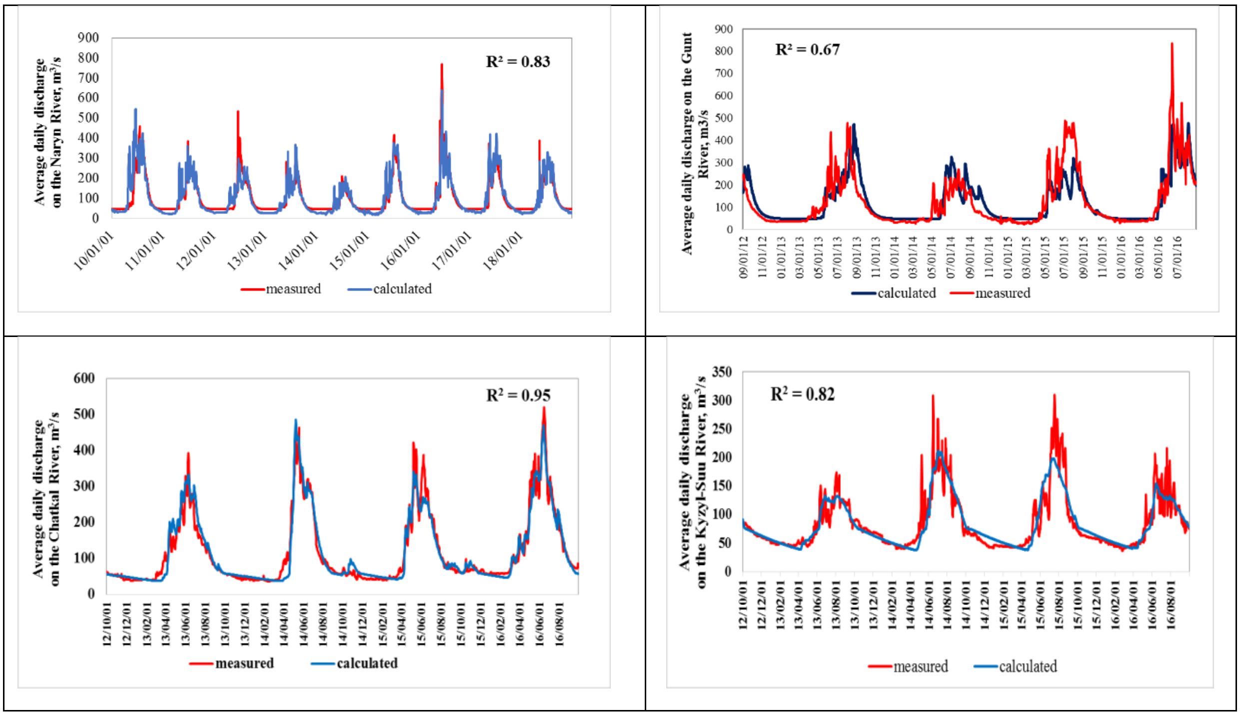
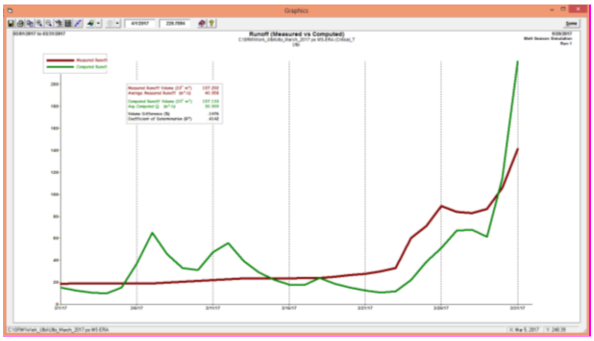
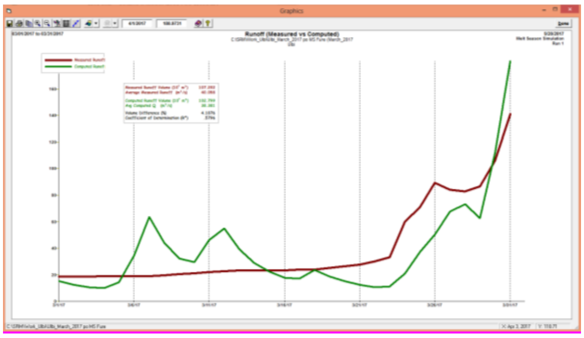


Figure 1. The HBV-light model calibration for the Naryn river (SG Naryn town) and for Gunt river (SG Khorog); the HBV-EHT model calibration for Chatkal river (SG Khudoydodsay) and Kyzyl-Suu River (SG Dombrachi).

To work with the Snowmelt Runoff Model (SRM) necessary to prepare the basin area and altitude zones, for this purpose the basin boundary is defined by the location of the stream gauge on the river and the watershed is identified from the topographic map. For meteorological parameters are needed the air temperature, precipitation and snow cover area data, and for hydrological parameters is needed a water discharge. For the SRM model calibrati,on we used hydrological data of the river Oba (SG Shemonaiha) and meteorological data (MSs Leninogorsk and Ust-Kamenogorsk) of the period 2014 - 2017. The result of calibration is R = 0.71 (fig. 2).



The comparison of March 2017 flood volumes using the annual analog method.



The comparison of March 2017 flood volumes by Fourier analysis

Figure 2. The calibration of the SRM model for the Oba river basin.

To prepare input information for Soil and Water Integrated Model *(SWIM)*, maps of elevation zones, soil types, land use, and vegetation were prepared. A digital elevation model SRTM with a spatial resolution of 30m was used to prepare the map of elevation zones. The soil types map was prepared based on data from the FAO Soils Portal (Food and Agriculture Organization of the United Nations, 2023). The land use/vegetation maps were based on data from the "Global Land 30" project for 2014, which used satellite images from the Landsat project with 30 m resolution for a multi-year series for the period 2009-2011. In digital format, as of the end of 2015 (www.globeland30.org) land use maps became fully available and contained more detailed division into classes (Globeland30. Publicly available global geoinformation product, 2023). To calibrate the model SWIM, we used hydrological data of the river Bukhtyrma (SG Lesnaya Pristan) and meteorological data (MSs Katon-Karagai, National Park Markakol, Ulken Naryn, Leninogorsk, Seleznevka) for the period 2001 - 2010. The calibration result is a NSE = 0.88 (fig. 3).

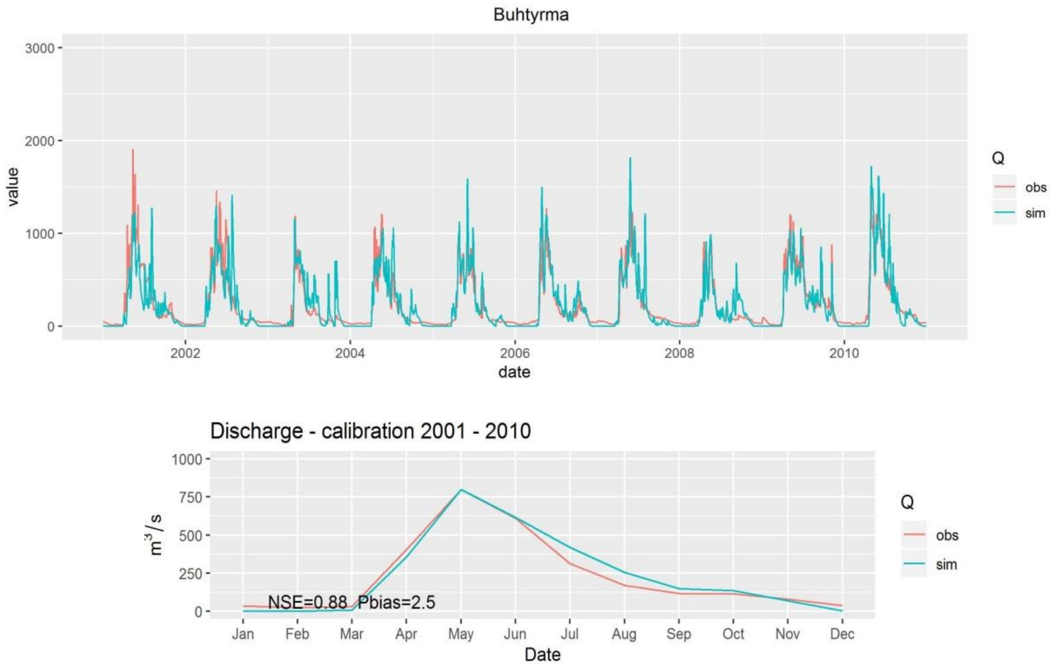


Figure 3. The SWIM model calibration for the Bukhtyrma river basin

To build the model for the Naryn River in the *WEAP software*, initial data from the Stockholm Environment Institute (SEI) from the water-energy model for the entire Syr Darya River basin and Kyrgyzhydromet data for the Naryn River basin were used. The basis for modeling was spatial data from the Stockholm Environment Institute (SEI) - the HydroSHEDS digital elevation model with a spatial resolution of 500 meters, glacier area from Randolph Glacier Inventory 6.0 (2017), glacier extent and land use data from the European Space Agency (ESA).

Climatic data for the Naryn River basin were interpolated using a temperature and precipitation gradient from weather stations located at the three altitude zones of Toktogul (at 983 m.a.s.l.), Naryn (2039 m.a.s.l.), and Tien Shan (3614 m.a.s.l.). Water inflow to the Toktogul reservoir, data on water discharge and volume were used according to the data of the site of JSC "Electric Power Plants". Calibration of the model was carried out in PEST tools.

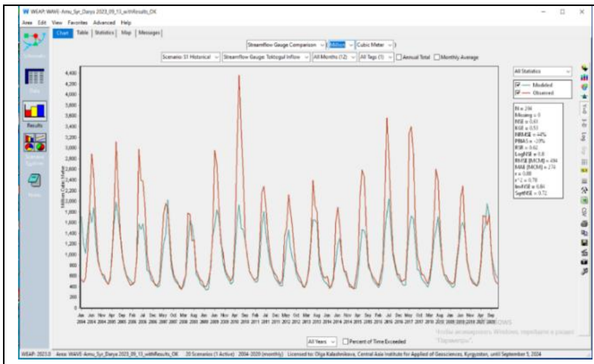
There are four charts we recommend considering in the process of calibration:

1) The monthly time series for observed and modeled streamflow. This chart allows us to observe how well the modeled flow matches base flows, wet weather flows, and seasonality for a range of dry and wet years.

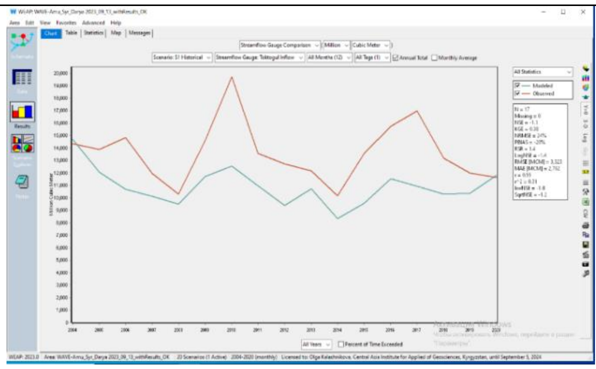
2) Annual total of observed and modeled streamflow. The annual total provides a good sense of the general fit of the model over time and of how well the modeled total annual volume of runoff matches observed values. 3) Monthly average of observed and modeled streamflow. The monthly average shows how the modeled flow values deviate from the historical record, on average, each annual cycle.

4) Exceedance Probability for observed and modeled streamflow. The exceedance probability chart ranks each flow measurement by value, the lowest on the right and the highest on the left, for both the modeled and observed streamflow. The values on the x-axis show the percentage of flows that exceed the values of flow. The modeled and observed streamflow should show a close match of exceedance percentages for the two flow records.

The monthly time series for observed and modeled streamflow were NSE=0.61 and R=0.88. Figure 4 shows the results of WEAP model calibration.



A



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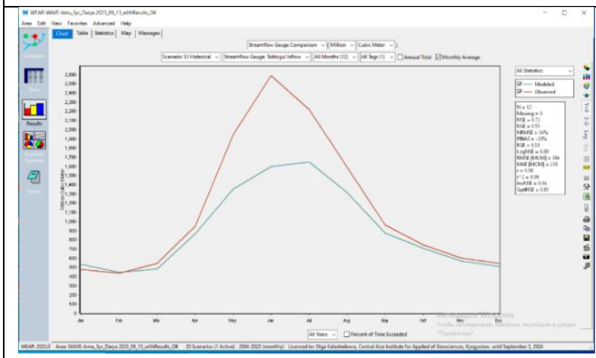

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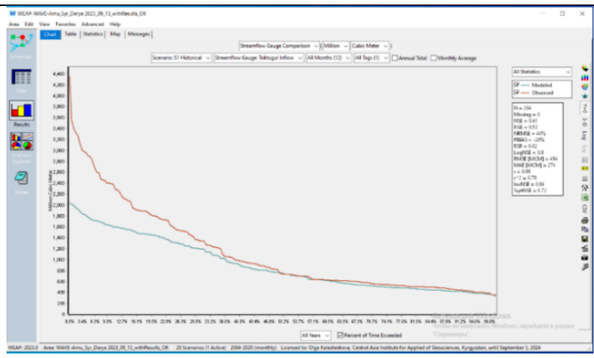

D

Figure 4. Calibration of the WEAP model for the Naryn river basin – inflow to Toktogul reservoir. A: The monthly time series for observed and modeled streamflow, B: Annual Total of observed and modeled streamflow, C: Monthly average of observed and modeled streamflow; D: Exceedance probability for observed and modeled streamflow. Blue color: modeled, red color: observed.

Thus, the study covered 5 main hydrological models (HBV light, HBV-EHT, SRM, SWIM and WEAP) with different methodological and model calibration approaches for the river basin.

Discussion

The choice of hydrological models HBV light 2.0 and HBV-EHT was due to the fact, that they are freely available and do not require a license. The model has a simple interface and a small set of input data: daily data on air temperature, precipitation and evaporation from a weather station representative of the watershed, and average daily water discharge from a gauging station with natural flow. To prepare the data in HBV-EHT, also are needed data on the mass balance of glaciers and the area of modern glaciation in the shape file. Calibration of models for small river basins (up to 13,000 km^2) with representative meteorological stations in Monte-Carlo and Gap-Optimization tools appears to be the simplest and can be successfully supplemented by manual calibration.

In contrast to HBV models, the SWIM hydrological model requires a large amount of incoming spatial data and complete calibration but is flexible in interpreting different situations introduced during scenario preparation. For example, changes in land cover, land use, etc. can be additionally considered.

The SRM hydrological model, like the HBV models, considers the river basin (as a whole), but requires input information on the spatial distribution of snow cover. The creation of the MODSNOW-Tool program (Gafurov, 2016) greatly simplifies the acquisition of this data for elevation zones of 200 meters or more. The SRM model has a simple interface and does not require a license.

The WEAP software has a user-friendly interface and models river runoff well for large river basins (in our case 52,000 km^2), which cannot be modeled in other simpler models, such as HBV, showing low statistical calibration performance. The WEAP software works in integration with QUAL2K, MODFLOW, MODPATH, PEST, Excel, and GAMS programs. It is currently actively integrating with LEAP, NEMO, MABIA, and MACRO programs. This integration allows for an integrated approach to the planning of water resources management activities, considering the full range of possibilities of their multipurpose use.

Conclusion

The main task of hydrological modeling is to obtain reliable hydrological forecasts of future water resource change. In the arid conditions of Central Asia, when irrigated agriculture requires significant water resources in the summer, advance forecasting is important for planning water allocation between upstream and downstream countries. An advance forecast of low water availability during the growing season, to carry out preventive measures for rational water use by water and energy companies, is the most important.

Assessment of hydrological models' efficiency, carried out by the authors based on long-term experience, allows using in practice the best models depending on the goals set by users (stakeholders).

Water availability forecasts based on the developed methods in the presented hydrological models and software, which have good quality and high efficiency, should be used in hydrometeorological services and water management.

Reliable and early forecasts will allow ministries and agencies to plan water use measures for the growing season, as well as to take timely preventive measures to avoid consequences of low water (water shortage, hydrological drought) and high water (mudflows/floods).

Authors' contribution

Kalashnikova O.Yu.: Conceptualization, methodology, formal analysis, writing original draft, visualization, writing, reviewing and editing, data collection, investigation. Niyazov J.B.: conceptualization, methodology, writing original draft, visualization, investigation, data processing. Nurbatsina A.A.: conceptualization, methodology, formal analysis, writing original draft, writing, reviewing and editing, data collection, investigation.

ORCID iD

Olga Kalashnikova https://orcid.org/0000-0002-6920-8067
Jafar Niyazov https://orcid.org/0000-0001-7723-3142
Aliya Nurbatsina https://orcid.org/0000-0002-4978-5377

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