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Climate Change Impacts on Hydrological Processes and Sediment Dynamics: Measurement, Modelling and Management

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Water Balance Assessment Using Swat Model. Case Study on Russian Subcatchment of Western Dvina River

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1 Introduction

The aim of this study is to create the hydrological model for Western Dvina (Russian part) catchment based on open-source global spatial and climatic data to calculate water balance components and estimate the amount of dissolved and suspended matter flow through the Russian Federation border. This investigation is a part of the MANTRA Rivers project between Russia, Ukraine, and EU.

The scope of the study is the Russian part of Western Dvina river catchment in the outlet of Velizh town (SRTM-based catchment area is 17250 km^2). Annual water yield at Velizh is about 4.45 km^3. Watershed is highly forested and swampy, rivers are not regulated, not exposed to high human activity impact and poorly studied as well. So to assess water balance components the combination of hydrological model, specifically processed wide climatic data and on-site measurements were implemented to calculate interannual actual evapotranspiration, snowmelt water yield, and river runoff and it's spatial distribution.

2 Methods

Modeling of different types of fluxes (water, dissolved and suspended matter) is based on calculations of the river discharge and its parametrization.

We have chosen the physically based semi-distributed hydrological model SWAT v.2012 (Gassman et al. 2007), it is the widespread tool to estimate water and sediment yield. Main advantages of the SWAT model are the availability of reliable and helpful documentation, the absence of limitations on catchment area, the open-source module of auto calibration SWAT-CUP (Abbaspour et al. 2007). The modeling process of different types of fluxes is based on calculations of the river discharge and its parameterization. Water discharge modeling in SWAT has the following stages:

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building the catchment model (using open-source medium resolution spatial data on relief, soil with wide database and land use), preparation of the plausible climatic database and calibration of parameters.

The catchment model was built with the ArcSWAT 2012 GIS-interface using following input open source data. Digital elevation models SRTM v.4 30 m res. (http://earthexplorer.usgs.gov) for monthly and ALOS PALSAR RTC 12.5 m res. (https://www.asf.alaska.edu) for the daily model time step. World Soil Database HWSD FAO (http://www.fao.org) was used as input soil layers data. Raster layers of land cover and land use GLOBCORINE, with a spatial resolution of 300 m (http://due.esrin.esa.int) and Global Land Cover, with 30 m spatial resolution (http://www.globallandcover.com) were used as input watershed coverage for monthly and daily time step respectively.

The meteorological data is the basis of the water balance equations to describe in-catchment hydrological processes. SWAT model needs some daily meteorological inputs such as min and max temperature (Tmin, Tmax), precipitation (PCP), relative humidity (HUM), wind speed (WND), surface solar radiation downwards (SSRD). The observed weather has many discrepancies to reanalysis data which is so attractive to use. Especially in relative humidity and precipitation. Daily precipitation has huge spatial diversity. So it was decided to prepare a special database mostly based on observations.

During preparation of the meteorological database we compared two different open sources of the daily meteorological data for the period 1981–2016: global atmospheric reanalysis ERA-Interim, observed station data of the GSOD NCDC/NOAA and ECA&D. The data were analyzed for the plausibility and outliers. Tmin, Tmax, PCP, HUM, and WND were analyzed using the methods of robust statistics.

From all meteorological data, the most unreliable is PCP. As for the comparison of reanalysis data with interpolated station data, it is highly variable in time and space (correlation between neighboring stations is extremely low). For WND, the reanalysis data overestimate wind speed comparing to the interpolated station data, in spite of the correlation coefficient is quite high. Plausibility analysis, regionalization of data and comparison of station data and reanalysis allowed to make a recommendation to use the values obtained by interpolated stations data with SSRD from ERA-Interim reanalysis.

3 Results

Initial runoff calculation is divided into a test of model performance due to catchment components and inner features of model setup. Then finding the sensitive parameters, developing of calibration approach and then – using the model.

The initial model shows quiet adequate performance – annual characteristics correspond well to measured evapotranspiration (ET) (MODIS) and river runoff (observed). For parameter calibration, we have used separate calibration for genetically different parameters, especially – for snowmelt parameters and runoff curve number. For model performance evaluation it was used popular criteria – Nash-Sutcliff, Kling-Gupta, square correlation, and PBIAS.

The most sensitive parameter is the rainfall-runoff curve number, which is also sensitive to land cover distribution. It is calibrated separately for forested and non-forested lands. Other sensitive group includes lumped parameters responsible for snow cover generating and melting (snowfall and snowmelt temperature, amount of snow decreasing dependent to air temperature, a snow temperature lag factor dependent to air temperature, maximum snow water content before melting). Soil water losses calibrated mostly with soil bulk density and available water capacity, groundwater losses – with groundwater flow delay, groundwater minimum depth, recharge to deep aquifers. Water flux transformation caused by canopy is calibrated mainly with plant evaporation compensation factor.

The results for calibration fall into good to very good (and very good to satisfactory depending on objective function) (Table 1). We can recognize, that extreme hydrological events are performed not very good. For example – enormous high spring flood and also enormous low spring flood following with heavy rainfalls. This kind of uncertainty most likely appears because of too rough soil database.

In the Western Dvina River catchment, the annual distribution of the river flow is genetically non-homogeneous. So the standard approach of the model auto-calibration was not successful. In this study 19–21 sensitive parameters (for monthly and daily runoff respectively) were chosen manually one by one. The parameters affecting the snowmelt runoff were grouped together and calibrated separately from the others.

Table 1. Results of daily and monthly runoff modeling.

Objective function	Definition	Monthly model	Daily model
R2	Square correlation	0.83/0.78*	0.77/0.78*
NS	Nash-Sutcliff coefficient	0.77/0.76*	0.72/0.76*
PBIAS %	Percent BIAS	−11.5/−15.5*	−11.7/−16.5*
KGE	Kling Gupta coefficient	0.8/0.78*	0.8/0.75*
Model quality		Good	Good

*Calibration (1992–1998)/Validation (1999–2004)

Results of calibration are good in general (and very good to satisfactory depending on objective function) – Table 1.

Rainfall distribution plays a significant role for this middle-size catchment and should be prepared very carefully. We recommend using interpolated data against reanalysis. Using detailed DEM (12.5 m) and LandUse/LandCover (30 m) brings better results for daily timestep, but almost does not have effect for monthly discharge calculations.

Calculated water balance components illustrate the interannual variability of river runoff, ET and snowmelt water yield. Maximum snow water yield absolutely corresponds and exceed river runoff, because of storing inside the catchment (Fig. 1).

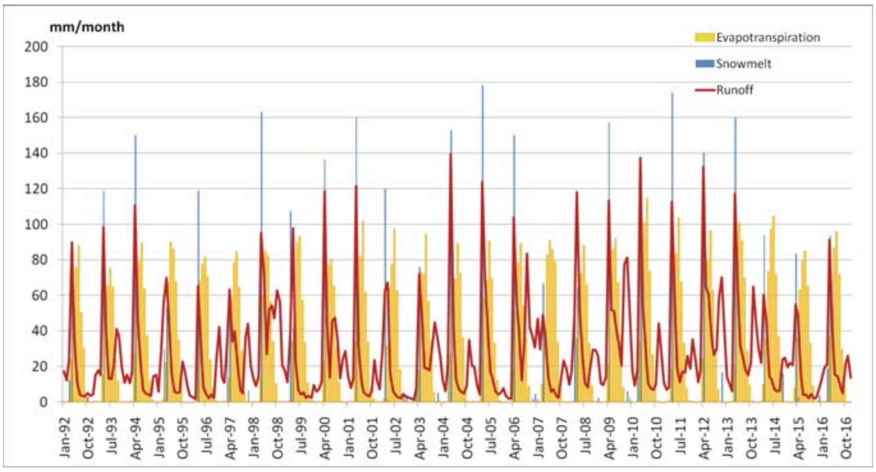

Fig. 1. Simulated monthly water balance components for Western Dvina Russian sub-catchment (at Velizh) – Evapotranspiration, Snowmelt water yield, and river runoff.

4 Conclusions

Modeling results gave valuable information about optimal input parameters of the river catchment and the method of defining elementary catchments. The results also include the estimation of the model parameters sensitivity and their calibration for river runoff calculation with daily and monthly temporal resolution. Every model, especially hydrological, has a lot of uncertainties. In Russia, we have sparse gauging network and many gaps in data. Global spatial data does not consider local features – wetlands and its temporal variability, local soil distribution (for example, alluvial soils in river valleys, peat soils). Likely reasons of uncertainties include the SWAT model disadvantages – it has lumped snowmelt parameters. Model equifinality caused by a huge number of calibrated parameters. The most important input data – precipitation meets the most data deficit because of low spatial distribution and data leakage for "in-catchment" scale. Authors recommend to use interpolated observed weather data against reanalysis (except downward solar radiation). Using detailed DEM (12.5 m) and LandUse/LandCover (30 m) significantly improve results for a daily time step, but almost does not have effect for monthly. The most sensitive are some "snow" and "groundwater" parameters, and also distributed "rainfall-runoff curve number" parameter. Calibration of "snow" parameters should be done separately from others. Evaporation is simulated well, but snow water equivalent is slightly overestimated (in comparison to observed). Soil database should be more detailed for daily time step calculations.

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