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Modeling the Hydrological Regime of Small Testbed Catchments Based on Field Observations: A Case Study of the Pravaya Sokolovka River, the Upper Ussuri River Basin

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Abstract—The aim of this study is to apply mathematical modeling to describe the hydrological regime of small testbed catchments located in the territory of the Verkhne-Ussuriisky Biocenological Experimental Station (Federal Scientific Center of the East Asia Terrestrial Biodiversity, Far Eastern Branch, Russian Academy of Sciences). The experience in data preparation and the calibration and application of two hydrological models, based on field observations, is presented. The interpretation of the results was based on the analysis of modeling errors, calibrated model parameter values and physical means, and simulated water balance elements. For all applied models and cases, the average and high flow values are close to the measurements, but the base flow is overestimated. A noticeable result is that the models parameters kept their physical sense and calculated water balance elements are comparable for both models used.

Keywords: testbed catchments, hydrological modeling, rain floods, SWAT, Flood Cycle Model

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INTRODUCTION

Experimental catchments and physically based hydrological models form a scientific toolset for investigating the effects of climate, soil, and topography on runoff generation mechanisms. The well-known international project aimed to develop techniques for a priori estimation of model parameters and their transferability—Model Parameter Estimation Experiment (MOPEX [6]), water balance investigations on different time and space scales—NOrthern hemisphere climate Processes landsurface Experiment (NOPEX [21]), Euromediterranean Network of Experimental and Representative Basins (ERB, [16]) can be mentioned among others. The same investigations were performed on the network of former experimental water-balance stations in the USSR [19].

Using in-situ observations made on testbed catchments for calibration of physically based hydrological models allows a more efficient investigation of the runoff formation features on a watershed scale. In this context, applying and comparing results of hydrological models with different physical substantiation of the structure is an objective reason for regionalization of model parameters and methods to subgrid process parametrization. The simulation of high spatial-temporal variability of hydrological processes in small catchments is very sensitive to measurement quality and spatial representativeness of landscape hydrologic properties, i.e., the small area cannot compensate for errors and uncertainty in the model input and parameters. In addition, it would be worth noting that the water balance components can be more or less reliably estimated only on relatively small catchments where the sources of measured fluxes could be known or implicitly determinable.

Initially, the hydrological models were developed based on pioneering studies of water balance in the testbed catchments using the lumped-parameter approach. Then the lumped models were gradually extended to the so-called semi-distributed models reflecting basin-scale spatial patterns of water balance. By now, the spatial structure of most these models is based on the concept of representative elementary area (REA) or watershed (REW) [28, 33], i.e., it splits a river basin into spatially uniform units for determining lumped, average hydrological behavior of the respective sub-domains. In this regard, numerical modelling based on experimental observations in the areas, where the major portion of runoff is generated (as a rule, these are hard-to-reach headwater areas) is cru-

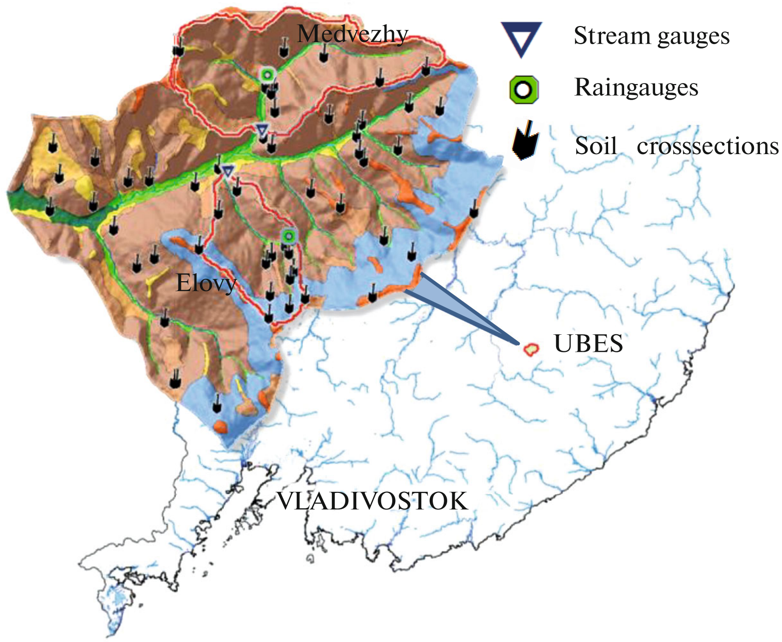

Fig. 1. The Upper-Ussuri Biocenological Experimental Station location (UBES); relief hillshade; soil areal map; Medvezhy (7.6 km^2) and Elovy (3.5 km^2) creeks catchments.

cial to solve the problem of extending the obtained parameters to ungauged area using hydrological similarity framework. This is of particular importance for the poorly gauged regions with very diverse runoff generation conditions like the Russian Far East.

In this study, the hydrological regime of two experimental catchments located in the Sokolovka River basin (the southern part of the Primorsky Krai, Russia) was investigated (Fig. 1). The watercourses are rain-fed predominantly; the summer–autumn floods are the main phase of the water regime. Two different hydrological models were used: the first one is a well-known open-source SWAT (Soil and Water Assessment Tool) 2012 model [1], and the second one is FCM—an original model of the flood cycle in a small river basin [7, 8]. The field survey data [9], standard observation from monitoring operating network of Primorye Administration for Hydrometeorology and Environmental Monitoring (PAHEM) [3], the results of the operative numerical weather model WRF [14], and high resolution SRTM30 DEM, soil and vegetation geodatabase were used for simulation preparation.

TESTBED CATCHMENTS

The objects of test simulation were small catchments, located within the Pravaya Sokolovka River basin—Medvezhy (7.6 km^2) and Elovy (3.5 km^2) creeks. This territory belongs to the Ussuri River basin and to the Upper-Ussuri Biocenological Experimental Station (44°02′ N, 134°11′ E), Federal Scientific Center of the East Asia Terrestrial Biodiversity, Far Eastern Branch of the Russian Academy of Sciences. The relief of the studied territory is mid-mountainous; hillslopes are moderately steep, locally very steep, the range of the altitude is 450–1100 m a. s. l. The average annual air temperature is +0.7°C, the absolute minimum is –45°C (in January) and the maximum is +38°C (July–August) [20].

The analyzed catchments are characterized by monsoon climate with unstable intra-annual and long-term precipitation regimes. The average annual precipitation is 780 mm, of which more than 80% falls in the warm period (April–October). Maximum daily rainfall during tropical cyclonic activity season (August–September) is about 100–200 mm. The snowpack is seasonal; it usually appears in November, grows up to 52–102 cm by March–April, and accumulates 100–200 mm of water. The average soil freezing depth is 5–120 cm.

The Medvezhy creek catchment is formed on Jurassic metamorphic basic rocks (gabbroids etc.) while Elovy creek, on scattered Cretaceous volcanites (tuffs) and subvolcanic acid and intermediate rocks (granites, ryolite, porphyrites, and diorites) [13]. At the bottom of the valleys, the water-deposited alluvium is well developed. Groundwater is of fracture type; its resources are insignificant [18].

A digital soil map 1 : 10000 (Fig. 1) was compiled using the techniques outlined in [4]. Soil hydrological characteristics for each genetic horizon were collected from a fair number of profiles [22, 29]. The database prepared in SWAT format includes: layer depth, bulk density, moisture capacity, infiltration coefficient, and grain-size composition. The transition from Russian to international grain-size classification [17] was carried out using the cumulative curve [30].

The vegetation–soil cover (Fig. 1) of the examined catchments is dominated by mixed coniferous–broadleaved forests and mountainous brown forest soils (the Cambisol group [17]) with high rock fragments content (up to 60–90% of volume even for the upper layer) and infiltration capacity. The parent rocks are highly water-permeable loose eluvium and eluvium–deluvium [12]. In the case of intensive rains, most precipitation does not reach groundwater and feeds the channel network in the form of lateral inflow, which significantly exceeds the normal rate of base flow leakage. More detailed physical characteristics of the experimental catchments are given in some previous publications [2, 9, 20].

Intensive field measurements were carried out during the warm season from late May to early October of 2012–2018. The precipitation, wind speed, air temperature and humidity were measured with 15-min resolution by two automatic weather stations (Delta-T WS-GP1) located on the Elovy creek catchment at the elevation of ~750 m and in the valley of the Medvezhy creek at the elevation of ~650 m a. s. l. The observation sites of Medvezhy and Elovy creeks were equipped with hydrostatic digital loggers (Solinst 3001) continuously recording water level at 15-min resolution. The water discharges were measured using magnetic inductive flow sensor (SEBA FlowSens): daily, during periods of water abundance; twice a day during the floods; and once per 2–4 days during rainless period. To obtain series of daily discharges, the rating curves $Q = f(H)$ for every year and for every discharge measurement site were used. After data quality control, the simulation periods were selected as 2011–2014 for Elovy creek and 2014–2017 for Medvezhy creek. In addition, to complete the SWAT input database for the cold part of the year and to fill gaps at periods of in-situ sensor malfunction, the standard observations from the PAHEM Chuguevka weather station (31939), located 35 km to the NW from the observation site, were used. The output of numerical mesoscale atmosphere model WRF-ARW was used to obtain daily solar radiation data series interpolated from closest computational grid nodes.

HYDROLOGICAL MODELS

Two hydrological models were used to simulate the hydrological regime of the studied catchments. These models differ greatly in their structure, theoretical background, and the basic concepts of describing the main hydrological processes and the input data requirements. The first one is a well-known open-source SWAT (Soil and Water Assessment Tool) 2012 model [1] and the second one is FCM (Flood Cycle Model)—an original model of the flood generation in a small river basin [7].

SWAT Model (Soil and Water Assessment Tool), is a free open-source model used widely by hydrological scientific community [11, 27]. SWAT is a semi-distributed, continuous in time model, which describes the main processes of the land hydrological cycle: infiltration, evaporation, thermal and water regimes of soil, formation and melting of snow, generation of surface, subsurface, and groundwater runoff.

The natural configuration of the hydrographic network is used to divide a watershed into subbasins and then into Hydrologic Response Units (HRU). Each HRU is characterized by the homogeneity of soil cover, relief, land use, and vegetation cover. The simulation of hydrologic cycle within each subbasin is separated into two phases. The first one is the land phase, which controls the amount of water loadings to the main channel in each subbasin. The second is the routing phase, which simulates water flow through the channel network to the watershed outlet. The surface runoff is formed if the precipitation rate exceeds the infiltration capacity. The empirical SCS CN method is used to calculate the daily volume of surface runoff. The kinematic wave approximation is used for calculating channel routing.

Only the meteoforcing data are used as the model input: precipitation, air relative humidity and temperature (daily maximum and minimum), wind speed, and solar radiation. At the first step, SWAT splits the input precipitation on rain and snow using the average daily air temperature. The snowmelt process is described as a linear function of air temperature, snow depth, and the degree of snow cover. Then a part of precipitation may be intercepted by the canopy or evaporate. At the soil top boundary, the precipitated water may infiltrate into the soil profile or turn into the surface flow.

The soil water may evaporate or be redistributed between lateral and groundwater runoff. The downward flow is allowed only if the layer temperature is above 0°C, its field capacity is exceeded, and the underlying layer is not saturated. The lateral flow velocity is controlled by the layer saturated conductivity. The water percolating past the last soil layer is proportionally split between unconfined and deep aquifers (losses). The amount of groundwater ascent to the zone of capillary fringe is calculated as a linear function of potential evaporation.

Flood cycle model is a lumped water-balance model of a small river basin that simulates the dynamics of the basin's storage near full moisture conditions [7, 8]. The model is used to simulate the rain floods in the warm season (June–September) only. The precipitation and the measured flow are used as input. The daily potential evapotranspiration is considered as an initial condition calibrated for every simulated season. The main feature of the FCM is the use of outlet discharge as an indicator of the basin storage state. Five basic hypotheses are used: (1) there is a critical discharge value Q_{cr}, at which the total basin capacity is full; (2) each part of basin storage has characteristic volumes associated with $Q = Q_{cr}$; (3) the free dynamics (recession) of each basin storages is described by exponential law; (4) the outlet discharge functionally depends on both the gravitational storage and the channel storage; (5) when the discharge is Q_{cr} and the effective precipitation is zero, the dynamics of the channel and gravitational storages are identical in terms of the equivalence of their first and second derivatives.

At the first stage, FCM splits precipitation between the gravitational and non-gravitational (capillary-bound water) components. The gravitational capacity and the related channel capacity of the basin are the most important elements of the model. The streamflow volume is treated as a part of gravitational storage, and their ratio varies with its total capacity. If the discharge at the outlet is below Q_{cr}, the model calculates the runoff volume (effective precipitation). The non-gravitation storage balance is calculated from the precipitation portion received and the evaporation at a simulation time step. Once the flow exceeds Q_{cr}, all precipitation recharges the basin gravitational storage. The water exchange with the deep aquifer is set constant for the entire simulation period.

Thus, the main parameters of the FCM are the characteristic values of basin capacity, i.e., the total moisture capacity (TMC), the field moisture capacity (FMC), and the gravitational critical moisture capacity (GCC). FCM is essentially nonlinear due to the power-law functions applied for approximating the dynamics of basin storage components and threshold effect of critical discharge insertion. As a result, three different runoff generation modes are presented in FCM: the internal (lateral flow prevails), surface (overland flow prevails), and the so-called "outburst", which is predicted rather hypothetically for very rare extraordinary floods. These modes are switched by specifying critical (Q_{cr}) and supercritical ($Q_{scr} = f(Q_{cr})$) discharge values, respectively. This results in a substantial dependence of the runoff generation intensity on the current state of the basin storage even at close values of the input precipitation.

MODELLING RESULTS

While preparing the numerical experiments, due to fragmentation in the field observations (periods of sensors malfunction, difficulties with site visit, etc.), two available 4-year datasets were prepared—the period of 2011–2014 for the Elovy creek and 2014–2017 for the Medvezhy creek. Since FCM supports only daily interval, all numerical modelling is conducted with a daily time step. The input data for the FCM model are the measured daily precipitation and daily discharges at basin outlet. Extra to the above-mentioned FCM input, SWAT model requires entering daily data on the air relative humidity and temperature (maximum and minimum), wind speed, and solar radiation. To maintain the experimental integrity, the parameters of every model were calibrated manually and quite independently from each other. The coefficient of determination R2, the Nash–Sutcliffe (NSE) efficiency [26], and the relative bias (BIAS) were used as objective functions.

The SWAT 2012 model v.637 was applied. The simulation was prepared using the ArcSWAT 2012 GIS interface for ESRI ArcGIS. Following the concepts of the natural characteristics of hillslopes and watercourses (relating to their lengths and slopes) [5], the examined watersheds were divided into subbasins with the size of 1–3 km^2. The Penman–Monteith method was applied to compute the potential evaporation, and the variable travel time method was used to calculate channel routing.

The parameters of equations for surface, subsurface, and groundwater runoff were calibrated (Table 1). The values of the curve number (CN2) for all soil types was set in accordance with the Soil Conservation Service (SCS) recommendations [32] to soil groups "*A*" characterized by high infiltration capacity. The value of soil evaporation compensation factor (ESCO) is proposed to allow the forest cover extract moisture from the whole soil profile, including the lower soil horizons. The depth of the impervious layer (DEP_IMP) is aligned with the supposed base of geological substrate. Note, the parameter LAT_TTIME for the Medvezhy creek was set equal to zero, which means that SWAT will calculate the lateral travel time itself based on soil hydraulic properties, while its value for the Elovy creek was calibrated.

The main parameters of FCM—Q_{cr}, R, and TMC—were deduced from the analysis of measured precipitation and discharges according to the method proposed in [7, 8]. The groundwater depletion rate k_D and deep aquifer exchange G were determined by calibration. The remaining FCM parameters were adjusted for each warm season (each year). The essence of this adjustment was to select the optimal values of non-gravitational stored moisture and evaporation.

The values of the modeling efficiency criteria for the two models are given in (Table 2). Motovilov et al. [25] categorized the NSE as *unsatisfactory* (if NSE < 0.36), *satisfactory* (if 0.36 < NSE < 0.75) and *good* (if NSE > 0.75). Depending on the value of criterion BIAS, the results of runoff hydrograph simulations can be assumed good at |BIAS| < 15%, satisfactory at 15% < |BIAS| < 25%, and unacceptable at |BIAS| > 25% [23]. According to the above criteria, most of the results are considered satisfactory or good with the

Table 1. SWAT and FCM parameters: a short description and calibrated values

	Parameters	Elovy	Medvezhy
SWAT	Moisture condition II curve number, CN2	35	45
	Overland roughness, OV_N	0.1	18.0
	Soil evaporation compensation factor, ESCO	0.4	0.5
	Lateral flow travel time, LAT_TTIME, days	3.5	0.0
	Depth of the impervious layer, DEP_IMP, m	5.2	5.2
	Baseflow recession constant, ALPHA_BF	0.15	0.04
	Time to reach the groundwater, GW_DELAY, days	1.4	31
	Return flow threshold GWQMN, mm	60	100
	Deep aquifer percolation coefficient, RCHRG_DP	0.05	0.5
FCM	Critical discharge, Q_{cr}, mm/day	9.0	10.0
	Streamflow depletion rate, R	0.19	0.1
	Total moisture capacity, TMC, mm	185	220
	Deep aquifer exchange, G, mm	0.02	–0.02
	Groundwater depletion rate, k_D	0.38	0.68

Table 2. Modelling efficiency criteria (SWAT/FCM) and measured seasonal (June–September) runoff, Q_{sn}

Objects	Year	R^2	NSE	BIAS, %	Q_{sn}, mm
Elovy creek	2012	0.88/0.94	0.76/0.94	10/–2	73
	2013	0.71/0.69	0.54/0.67	–24/–8	95
	2014	0.86/0.76	0.31/0.73	–10/–10	69
Medvezhy creek	2015	0.72/0.78	0.57/0.75	38/16	30
	2016	0.91/0.94	0.90/0.93	–25/–8	276
	2017	0.43/0.63	0.38/0.61	13/–19	36

exception of 2014 (NSE) and 2015 (BIAS) years for SWAT model. The simulation results for 2017 are worse for all three estimates. All fault cases correspond to the years characterized by low flow and are most likely due to the poor quality of observation data.

The annual values of the water balance elements were obtained using the SWAT model alone. The comparison of the SWAT and FCM water balance components was made only for the warm season according to FCM applicable period.

The annual (all simulation periods) values of water balance elements are as follows. For the Elovy creek: the total precipitation is 809 mm (188 as snow); the evaporation is 440 mm; the sublimation is 24 mm; the surface, subsurface, and groundwater runoff values are 65, 27, and 144 mm, respectively. The loss for the deep aquifer recharge is 6 mm. For the Medvezhy creek: the total precipitation is 785 mm (125 as snow); the evaporation is 425 mm; the sublimation is 27 mm; the surface, subsurface, and groundwater runoff values are 20, 90, and 0 mm, respectively. The loss for the recharge of deep aquifer is 125 mm.

The following seasonal values of the water balance elements calculated by two hydrological models were obtained. The total precipitation on the Elovy creek is 489 mm. The evaporation is 322 mm; the surface, subsurface, and groundwater runoff values are 0, 155, and 6 mm, respectively; the deep aquifer recharge is 4 mm as produced by FCM. SWAT results are: the evaporation is 331 mm; the surface, subsurface, and groundwater runoff values are 46, 14, and 110 mm, respectively. The deep aquifer recharge is 6 mm. The total precipitation on the Medvezhy creek is 487 mm. FCM estimates water balance as follows: the evaporation is 390 mm; the surface, subsurface, and groundwater runoff values are 23, 50, and 8 mm, respectively. Deep aquifer recharges equal to 10 mm. SWAT: the evaporation is 304 mm; the surface, subsurface, and groundwater runoff values are 15, 55, and 10 mm, respectively. The loss for the recharge of deep aquifer is 125 mm. The obtained results reflect the variety of hydrological situations for the specified years alone and the difference in the concepts of the models used. For more reliable estimates, analysis of longer observations is required.

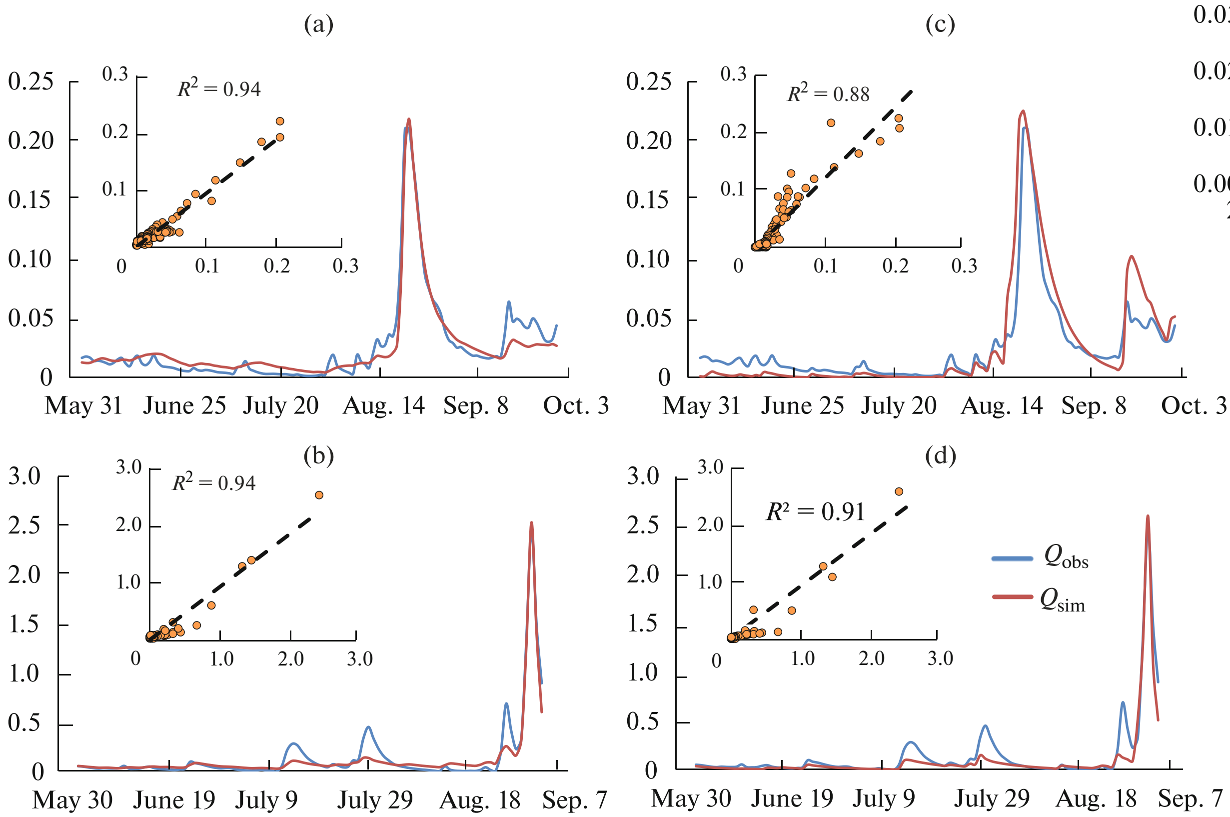

Fig. 2. Observed (Q_{obs}) and simulated (Q_{sim}) discharges, m^3/s; (a), (c) FC-model; (b), (d) SWAT model, (a), (b) 2012 (Elovy creek); (c), (d) 2016 (Medvezhy creek).

DISCUSSION

The applied models are characterized by very different approaches in terms of hydrological process descriptions. However, in totality, both models reproduce the main features of the hydrological regime for the test basins quite well; the simulated and measured hydrographs demonstrate a good agreement. Examples of calculated hydrographs for the high floods of 2012 and 2016, caused by typhoons activity, are given in Fig. 2.

As expected, SWAT describes low-water periods better than the FCM model, which uses a very rough description of soil moisture exchange, evaporation, etc. SWAT is more accurate in calculating daily evapotranspiration by Penman–Monteith method and modelling the dynamics of soil moisture and groundwater more precisely as well. Both models show a good agreement between the calculated and observed hydrographs during the flood periods, with a slightly better results of FCM in the flow volume and the peak time.

It is worth noting that the runoff generation (effective precipitation) concepts in the models considered are both deduced from extensive empirical data and are definitely strongly correlated. Similar to SCS CN method, adopting different CN value for the dry, normal and saturated soil condition, FCM uses two critical discharge values for tree different runoff generation modes. The variable runoff coefficient K_{pq} used in FCM for calculating the effective precipitation proportion (when flow is below Q_{cr}) corresponds to calibrated SCS CN2 values used for dry and medium soil moisture conditions. At the discharge at the outlet above Q_{cr}, only SWAT still calculates the runoff losses. FCM approach, based on region runoff researches, demonstrates better results compared to SCS CN method based on generalized empirical data.

The basin average field capacity values calculated by SWAT, that is the sum of the wilting point (calculated from soil clay content) and the available water capacity, are 145 and 43 mm for the Elovy and Medvezhy, respectively. The correlatable FCM basin-scale non-gravitational storage values are 145 and 183 mm, respectively. The high difference between SWAT and FCM for Medvezhy creek is due to the above noted difference between the storage concepts used. We emphasize that the soil parameters have not been calibrated in this study. Additionally, it would be worth discussing the subjectivity in the determination of soil layer depths and especially that of the lowermost

C horizon by different soil scientists. Underestimation of this layer's capacity not only leads to a bias in water capacity estimation, but also affects the other model parameters as well.

The results of physical simulation for the two models confirm the earlier field studies that have found out that the basin of the Elovy creek is more heterogeneous in terms of runoff generation conditions than that of the Medvezhy, a feature which is due to the heterogeneity of the former's geological and landscape structure [9, 15]. For instance, the models give similar surface and lateral runoff components for the Medvezhy creek, while they differ significantly for the Elovy. The components of water balance obtained from FCM and SWAT simulations for Medvezhy creek differ by 120 mm, which is equal to the deep aquifer recharge in SWAT. If the soil data are reliable (about 600 mm depth and 80–90% of stones, i.e., 10–20% of fine water-retaining material), then the result of SWAT is physically justified and vice versa. So, with parallel model calibration it is assumed that this discrepancy can be compensated for by either an increase in the soil capacity characteristics in SWAT or the adjustment of the appropriate (gravitational or non-gravitational) storage capacity and deep aquifer exchange parameter G in the FCM.

During flood events, the discharge at outlets varied within two orders of magnitude at one model time step, and the flow rate (validated by the measurements) might reach 600 L/(s km^2) for the Elovy and 350 for the Medvezhy. The fixed effective values of the channel and overland roughness for the whole amplitude of discharge and precipitation rates essentially reduce SWAT model efficiency while FCM still benefits from applying simple linear reservoir approach (in the context of the considered case).

The high value of OV_N (overland roughness in SWAT) calibrated for the Medvezhy catchment corresponds to Befani's ideas [31] of the subsurface (contact) runoff formation over a relatively impermeable layer. In this case, the roughness is considered as a total resistance of the hillslope to the water flow through all runoff mechanisms realized under the specific conditions. It is widespread in mountain territories mostly occupied by brown mountain forest soils with a highly skeleton profile and a good drainage [5, 10]. In the case of Elovy creek, the surface runoff clearly dominates during intense rainfalls and the value of OV_N corresponds to the interval of tabulated values commonly used in hydraulics for natural slopes covered with dense bushes. Meanwhile, the much higher OV_N value for the Medvezhy means that floods are mainly formed by subsurface flow, i.e., during a flood event, stormwater runs to a drainage network through the system of subsoil drains where the resistance is an order of magnitude higher than that for hillslope overland flow [5, 10].

The SWAT was insensitive to groundwater parameters in the calibration for the Medvezhy creek. Groundwater parameters for the Elovy creek were specified during model calibration—the baseflow recession constant (ALPHA _BF), the time to reach the groundwater level (GW_DELAY), and return flow threshold (GWQMIN) show the significant role of groundwater for this catchment. The difference in groundwater behavior was partially explained above by the properties of the models and the uncertainty in the soil characteristics, but the influence of flow control dams installed on the Elovy Creek must be noted as well. The cut-off walls screen subsurface flow in the river alluvium and divert water back to the channel. FCM k_D parameter of perched water storage depletion can be roughly assumed comparable with SWAT ALPHA _BF. Both parameters are indicating fast subsurface water dynamics.

The analysis of the observed water discharges against precipitation measured both at the in-situ rain gauge and at Chuguevka meteorological station, located 35 km apart, allowed estimating the potential problem in field equipment malfunction and the effect of spatial distribution of precipitation on hydrological modelling result. Some diagnostics patterns are shown in Fig. 3. In the first case discussed (June 30, 2015–July 12, 2015), the in-situ rain gauge obviously malfunctioned. Drawing up the rain records from the Chuguevka meteorological station shows modelling results to agree with the measured hydrograph. The second case illustrates the effect of precipitation spatial pattern on modelling result. The total amounts of rain that formed the peak discharge differ by about 100 mm at two control meteorological stations. Using the incorrect rain data from the meteorological stations located aside gives the visible error in simulated hydrograph. Without in-situ rain gauge data, such error may lead to considerable errors in model parameter estimates and degrade simulation results. The nonuniformity of precipitation rate over calculation time step and related problem with effective hydraulic conductivity [24], among other reasons, can significantly affect the calculation results, especially for small catchments.

CONCLUSIONS

In this study, the field observation data, collected on two experimental catchments, located in the south of the Russian Far East in 2011–2017, were used to calibrate the well-known SWAT and original FC models. These models differ in the structure, basic concepts, and input data requirements. The interpretation of the results was based on the analysis of modeling errors, calibrated model parameter values, its physical meaning, and simulated water balance elements. Both models are elaborate enough to simulate the low (few liters per second) flow stage as well as the sharp two-order rise in the flood hydrograph. Individual discrepancies

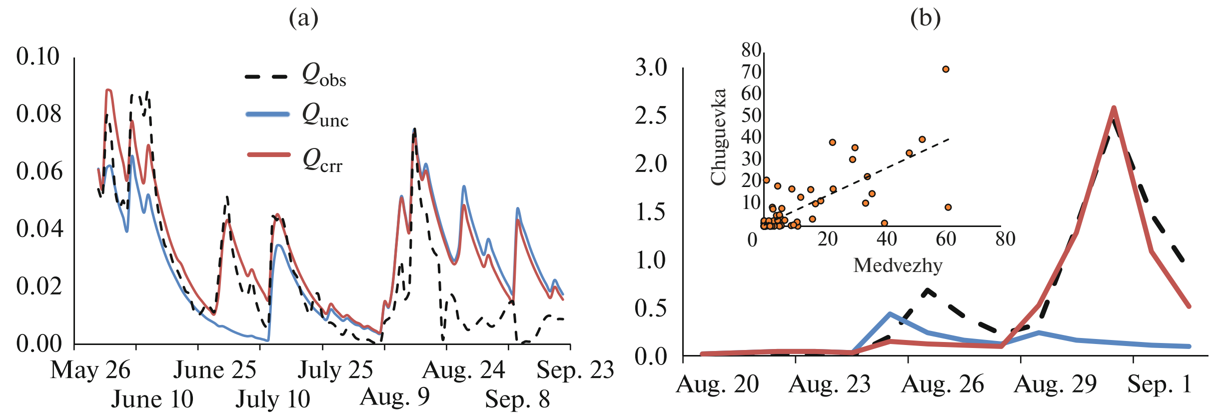

Fig. 3. Observed (Q_{obs}), uncorrected (Q_{unc}) and corrected (Q_{crr}) SWAT modelling result discharge m^3/s, for Medvezhy creek: (a) 2015, (b) 2016. Daily precipitation scattering diagram (VI–IX, 2016) for Chuguevka and in situ Medvezhy weather stations.

between the calculated and observed hydrographs are evidently related to the high spatial variability of precipitation and its intensity. FCM model slightly outperforms SWAT model in the simulation of flood hydrograph, and SWAT shows better performance during medium and low flow stages. Both models tended to overestimate the base flow and showed poor modeling efficiency at low flow. The shape of flood hydrograph and peak discharges are reproduced quite well. The numerical experiments revealed some limitations associated with the simplification of the empirical description of runoff generation processes. The obtained model parameters and water balance elements are in satisfactory agreement with the published data and the general concepts of runoff formation in the region. Finally, research perspectives in experimental measurements and applying a range of numerical models for testbed basins can clarify our basic assumptions, improve the validity, and make results more physically sound.

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