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Possibilities of Flood Forecasting in the West Caucasian Rivers Based on FCM Model

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Abstract—The West Caucasus is the only Russian region where disastrous floods cause a great number of victims regularly. Developing the automated monitoring networks in the Kuban River Basin and Krasnodar Krai has improved the quality of hydrological information over the last years; however, its use for flood forecasting has to be more effective. The paper presents methods of short-term flood forecasting for West Caucasian rivers with rain floods prevalence during the warm season. They are based on applying the Flood Cycle Model (FCM), which has been tested for the first time in the region (the case study of the Tuapse, Psekups, and Pshish rivers). The presented forecasting methods, whose quality completely conforms to the criteria of the Russian Hydrometeorological Service, can enhance the existing hydrological forecasting systems. To further develop the flood forecasting methods for the West Caucasian rivers using physically based models, it is critically important to increase the precipitation measuring network density within the mountain parts of watersheds.

Keywords: hydrological forecasting, floods, rainfall-runoff modeling, the West Caucasus, the Black Sea coast of the Caucasus

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INTRODUCTION

A flood is, undoubtedly, one of the most devastating natural disasters in Russia and in the world, that is why flood forecasting plays a key role in protecting the population and economy from floods. According to the Sendai Framework for Disaster Risk Reduction, adopted at the UN World Conference in 2015, it is necessary to develop monitoring and understanding of various kinds of disaster risks, as well as to improve forecasting and early warning systems in order to increase the preparedness of people and emergency services.

The West Caucasus is one of the most flood-impacted areas of Russia and the only one where floods systematically cause a significant number of deaths. Over the last years, there have been several such accidents. On June 6–7, 2012, as a result of the severe rainfall in the town of Krymsk on the Adagum River, and also at the Black Sea coast in Novorossiysk and Gelendzhik, disastrous floods caused more than 170 deaths. Earlier, a catastrophic flood on October 16, 2010, near Tuapse caused 17 deaths and extensive damage. In 2002, from June 20 to 29, a flood covered 4 regions in the Kuban basin, more than a hundred died. The floods were overviewed and analyzed in [2, 12, 15, 20, 23]. For a number of settlements, flooded areas were highlighted and recommendations on reducing damage were given [1, 4, 24].

Floods on small West-Caucasian rivers during the warm season can be due to both local heavy rainfall (the so-called flash floods) and long-term frontal precipitation. Floods caused by combined snowmelting and rainfall are characteristic of highlands; there are also floods connected with the barrier lakes outbreaks; in the estuary areas, a dangerous rise in water levels can be strengthened by a wind upsurge [1, 15]. However, the strongest and most devastating floods are formed because of extreme precipitation during summer months [1]; therefore, this article considers the possibilities of forecasting such floods.

Under the conditions of non-stationary climate, the probability of extreme precipitation and associated catastrophic floods increases [13, 21, 24]. Basing on ensemble tests of an atmospheric model, the paper [16] demonstrated the role of warming-up of the Black Sea in developing the so-called deep convection. The nonlinear response to an increase in sea surface temperature caused an extreme amount of precipitation, which resulted in the catastrophic flood in Krymsk in 2012.

Despite the topicality of the problem, few investigations have been done so far to simulate the runoff of

Table 1. Characteristics of the test river basins

Characteristic	Tuapse R.–Tuapse C.	Psekups R.–Goryachii Klyuch T.	Pshish R.–Khadyzhensk T.
Main-stream length, km	29	62	75
Catchment area, km^2	351	765	710
Average elevation, m	335	310	510
Maximal elevation, m	1380	990	1839
Average catchment slope, ‰	274	160	200
Annual runoff depth, mm	1230	590	560
Runoff depth in warm season, mm	196	64	89

small West Caucasian rivers. Hydrograph model [13] was used to calculate the extreme characteristics of floods on the rivers of Black Sea Caucasian coast. The modelling of conditions for the extreme flood in Krymsk was carried out in [4]. A model of snowmelt runoff was developed [5] for promptly forecasting the behavior of high-mountain rivers in the Kuban basin; for rain-fed rivers, statistical forecasting methods are used [5, 11]. The modelling of floods becomes more difficult because of the low density of precipitation gauging network, especially in mountainous areas [14]. In addition to the hydrometeorological networks of the Russian Hydrometeorological Service, which have been upgraded over the last years, an automated flood monitoring system has been functioning in Krasnodar Krai since 2013, consisting of more than 190 sensor level gauges [23, 25].

This article presents flash flood simulation with the use of the Flood Cycle Model (FCM), tested during the warm season for some West Caucasian rivers. The FCM has been designed and successfully used for the operational forecasting of rain-induced floods on the southern rivers of the Far Eastern Russia [7]; it was also tested on rivers of Taiwan and Austria [8, 10].

THE SOURCE DATA AND RESEARCH METHODS

To simulate the flash floods of the warm period with the use of the FCM, daily standard observations of precipitation and runoff were used, collected over the period from May 15 to October 16, within which precipitation is almost exceptionally liquid and there is no soil freezing. The tests were conducted for three neighboring river basins in the West Caucasus: for the Tuapse R. on the southern slope of the Greater Caucasus, flowing into the Black Sea, and the rivers Psekups and Pshish, flowing down the smoother northern slope into the Krasnodar Reservoir on the Kuban River (Fig. 1; Table 1). The choice of the rivers was conditioned, first, by the requirements of the model (the size of basins, the predominance of rain feeding); and, second, by the relatively good provision of hydrometeorological data. For every river basin, the data on precipitation in two points were used. One of them was situated near the discharge gauge station (Tuapse, Goryachiy Klyuch, and Khadyzhensk, at the altitudes of 60–109 m abs); and the other, near the watershed (Gorniy at the altitude of 325 m abs, the data were used for all three basins).

The observations on the rivers Psekups and Pshish appeared heterogeneous, in the form of changing relationships between the seasonal runoff and precipitation, which have been observed since the late 1990s–the early 2000s (Fig. 2). The choice of the periods for calibrating model parameters and verifying the results was conditioned by the specificity of observation data—the length of series, interruptions in the series, the homogeneity of the relationship between the seasonal precipitation and runoff.

The climate of the territory is mild, warm, and humid; at the Black sea coast, it is transitory from temperate to subtropical. The annual precipitation is 1350 mm in Tuapse and 1570 mm in Gorniy; in Goryachiy Klyuch and Khadyzhensk, it is 900 mm. Snowfalls are observed periodically from November to March; however, in most cases, snow remains for not more than 10 days and melts quickly, resulting in floods of the snowmelt-fed and snowmelt and rain-fed type [15, 20]. Steady snow cover forms only in the Pshish R. basin at the altitudes higher than 1000–1500 m. The regime of the chosen rivers shows the prevalence of rain floods. Most of them happen during the cold season; however, the highest can form in the warm period. The share of rain feeding exceeds 80%, while the share of snow feeding is significant only for the Phish, where it is about 10%.

The vegetation is generally represented by oak, oak–hornbeam forests on brown podzolized soils and, on the northern slope in the foothills, on grey podzolized soils. At the watershed of the Pshish and Pshekha, there are fir forests. The forests were actively exploited. Thus, in the Psekups basin, from 1955 to 2005, about 53% of the forest have been cut. New roads and power transmission lines were constructed and the human settlement area increased, because of which about 5% of the river basins territory were impacted [3].

The conception and algorithms of the FCM are presented in a number of papers [6–10]. This is a water

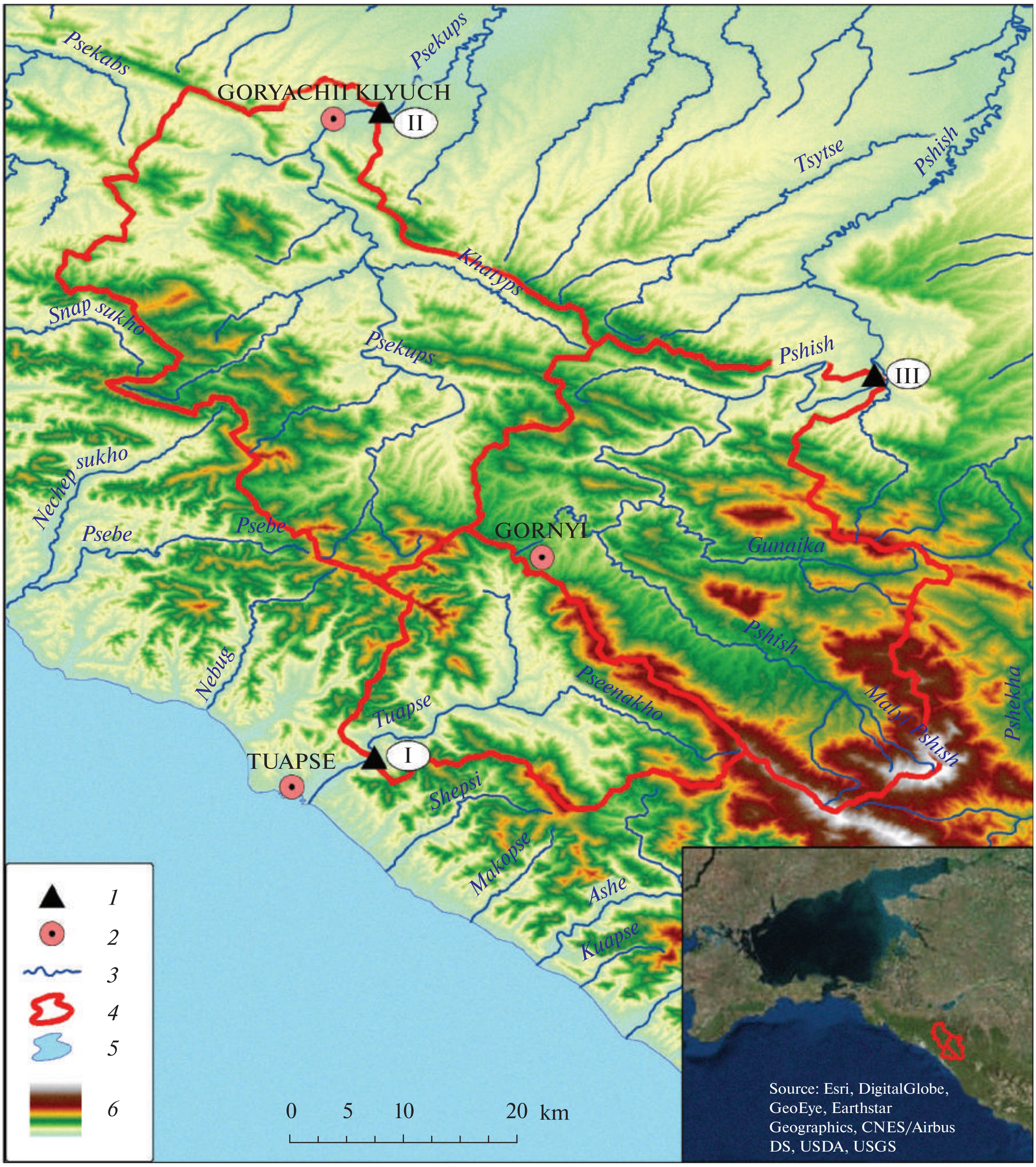

Fig. 1. Layout of the examined river basins. (1) Hydrological gauge stations ((I) Tuapse R. near Tuapse, (II) Psekups R. near Goryachii Klyuch, (III) Pshish R. near Khadyzhensk); (2) meteorological gauge stations; (3) rivers; (4) watershed boundaries; (5) the sea; (6) elevation of terrain.

balance model of a small river basin with lumped parameters, which simulates moisture content dynamics in the watershed near the point of full moisture capacity. The main feature of the FCM is the use of the discharge in the outlet section as a state indicator of the basic components of basin moisture reserves. Four such components are taken into account: channel storage, groundwater storage, and the storage of the upper (vadose) zone which together form the gravitational water content of the basin. The non-gravitational moisture content is considered as a whole, this is generally soil capillary moisture. The algorithm of the model includes elements that reflect the dynamic expansion–regression of the temporary watercourse system within the slope network of surface and subsurface thalwegs and drainage ways [22].

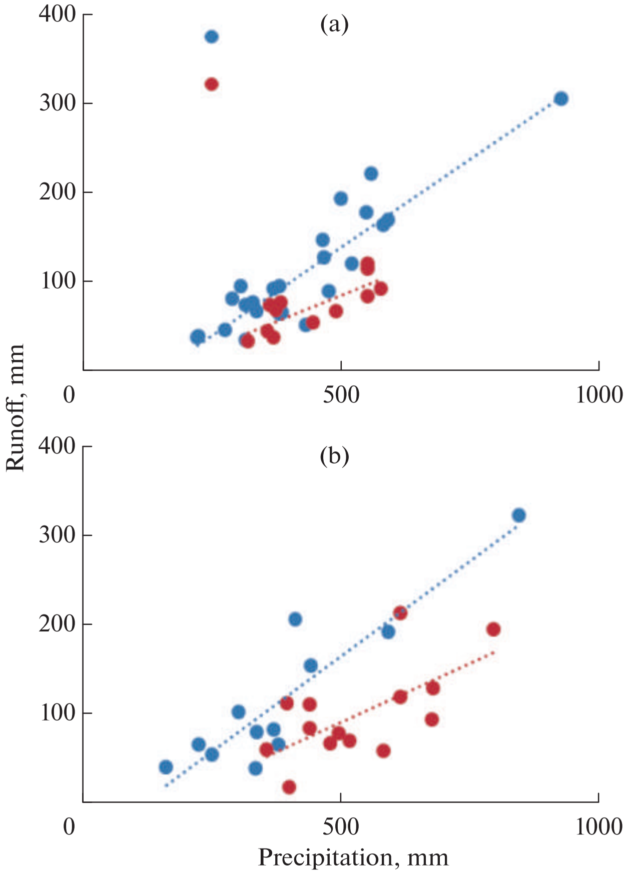

Fig. 2. The relationships between seasonal precipitation and runoff: (a) in the basin of the Psekups R. for 1977–2000 (blue circles) and 2001–2013 (red circles), (b) in the basin of the Pshish R. for 1979–1983, 1992–1998 (blue circles), and 1999–2013 (red circles).

One of the key hypotheses in the FCM concept is the existence of a critical discharge (Q_{cr}), which corresponds to the filling of the basin storage with the moisture contents of all basin storage components simultaneously reaching their characteristic (critical) values, corresponding to their filling. Thus, Q_{cr} is the threshold dividing the two types of basin response. If the discharge is less than Q_{cr}, there is a deficit of the basin moisture content and the coefficient of precipitation drainage is significantly less than 1; on the contrary, if the discharge is greater than Q_{cr}, the drainage coefficient approaches 1.

Along with some less important assumptions, this hypothesis enables determining a number of integral basin parameters, similar to hydrophysical soil parameters, by processing daily data series on precipitation and runoff in the warm season. These are the total (TMC) and the field (FMC) moisture capacities, gravitational critical moisture capacity (GCMC—an equivalent of the maximal water yield of soil), which, together with the critical discharge, are included into the set of basic FCM parameters. It was found that the efficiency of applying the FCM is governed by the combination of spatial-temporal scales, and basin sizes from 10 to 1000 sq. km are considered optimal, with the calculation time step from 4 to 24 hours. Model flow diagram is shown in Fig. 3.

The first step of the model algorithm is to divide the precipitation between the gravitational and non-gravitational components of the basin reservoir (to determine the runoff generation depth or effective precipitation). The proportion of precipitation k_x spent to runoff generation is

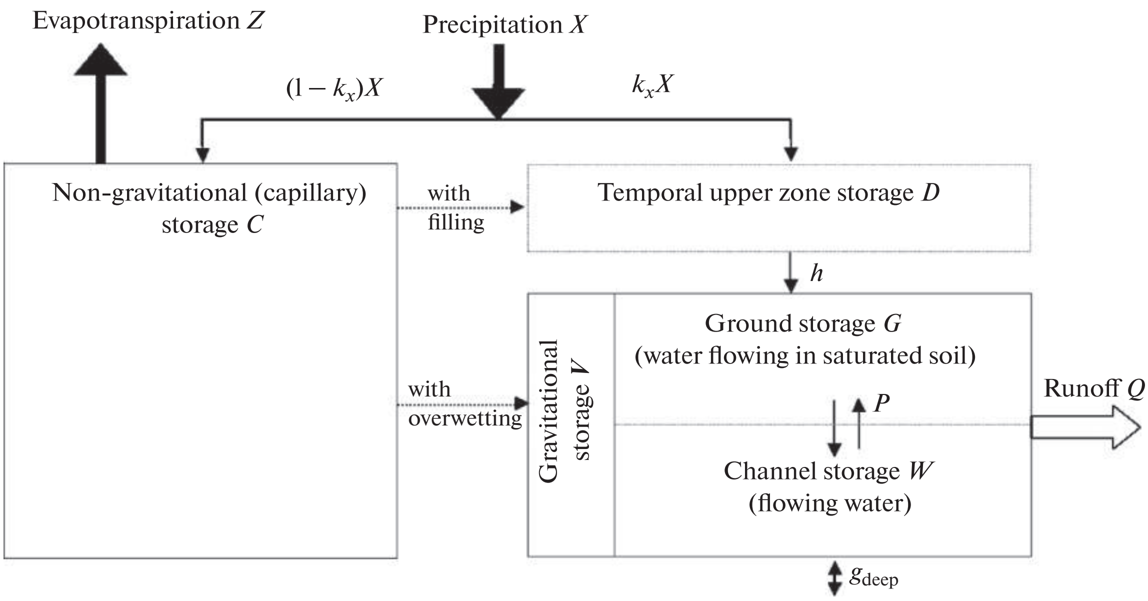

Fig. 3. Flow chart diagram of the FCM model.

$$k_x = \frac{\mathrm{GCMC}^m}{m \cdot a \cdot (\mathrm{GCMC} - V)^{(m-1)} \cdot \mathrm{FMC} + \mathrm{GCMC}^m}, \quad (1)$$

where the variable V, defined as $V = f(Q)$, denotes the value of the gravitational water storage; m and a are parameters.

The portion of precipitation that forms runoff first enters into the linear storage of perched groundwater, which simulates the transformation of precipitation when crossing the upper boundary of the basin. The most important element of the basin model is the gravitational storage and the channel storage contained in it. Their water balance can be described by the system of equations:

$$\begin{cases} \dfrac{dW}{dt} = -k_1 W + p(t) \\ \dfrac{dV}{dt} = -k_2 V^3 + h(t) \end{cases}, \quad (2)$$

where $Q = k_1 W = k_2 V^3$ and $k_2 = \dfrac{k_1^3}{27 Q_{\mathrm{cr}}^2}$.

Here W denotes the channel storage; k_1 and k_2 are constant coefficients (k_1 is defined as a function of R_{chan}, i.e., the depletion coefficient of channel storage), $p(t)$ is the inflow from groundwater into channel storage (the groundwater storage $G = V - W$), $h(t)$ is a function of the external inflow into the gravitational storage. Solving (2), eliminating t and taking Q for an independent variable, we get the phase portrait of the system:

$$W = \frac{Q}{k_1}; \quad V = \left(\frac{Q}{k_2}\right)^{1/3}; \quad G = \left(\frac{Q}{k_2}\right)^{1/3} - \frac{Q}{k_1};$$
$$p = Q - \frac{3k_2^{1/3}}{k_1 Q^{5/3}}; \quad h = Q - \frac{k_1}{3}\left(\frac{Q}{k_2}\right)^{1/3}. \quad (3)$$

These equations compose the core of the runoff hydrograph calculation algorithm.

Since the FCM is oriented towards the integral description of catchment dynamics near the point of full moisture capacity, it describes the procedures of subsurface moisture exchange, evaporation, etc., as "roughly" as possible. The balance of the non-gravitational (soil) moisture capacity consists in receiving some precipitation and providing the evaporation, the daily value of which is assumed to be constant in the calculation interval. Water exchange with deep underground horizons in the existing version of the model is represented by the constant g_{deep}.

As it can be seen in [10], the FCM is essentially non-linear, which manifests itself in the existence of three qualitatively different regimes of runoff generation—subsurface, surface, and the so-called "outburst" one. As a result, it can be noticed that the maximal ordinate and the form of the hydrograph strongly depend on the current state of the basin at similar values of the input signal, i.e., the precipitation. This property makes the model quite flexible, retaining the simplicity of the algorithm and the physical sense of the main parameters. Consequently, the model is rather promising for the operational short-term and very short-term forecasting of flash floods.

MODEL ADAPTATION AND THE ESTIMATION OF ITS PARAMETERS

The key FCM parameters were first assessed on the long-term series of daily precipitation and discharge according to the method described in [8]. The depletion coefficients of channel storage are calculated as the least among the reliably estimated discharges ratios of two consecutive days $R_{\mathrm{chan}} = \min(Q_{t+1}/Q_t)$. As a result of analyzing the histograms of maximal rain flood discharges, the values of critical discharge Q_{cr} and the corresponding runoff layers M_{cr} were estimated. On the basis of calculating the water balance of high floods and constructing the so-called "pseudo-phase diagram", the initial estimates of the total moisture capacity (TMC) and field moisture capacity (FMC) of the basins were determined.

The model was calibrated and verified against homogeneous data series, taking into account the length of the series and the quality of observations. For the Tuapse River, the data series was divided into two approximately equal segments (Table 2). For the Psekups River, the model was calibrated and verified against the data collected before the relationship between the seasonal runoff and precipitation lost its homogeneity (until 2002); and for the Pshish, against the data after it became heterogeneous (after 1999). For the Psekups River, the model parameters found during calibration were checked against the period after 2002.

First, calibration runs were made with the simulation version of the model, intended to obtain the best simulation of the warm-season runoff hydrographs based on actual precipitation. The depletion coefficients of the "upper" storage R_{upg} and the parameter of the deep water exchange g_{deep} were determined. Simultaneously, during calibration, the values of the above parameters (R_{chan}, M_{cr}, and FMC) were checked (specified), and also optimal weighting factors were chosen for measured precipitation from different meteorological stations, in order to better assess the average precipitation in the river basin. The comparison of the estimated and observed hydrographs was based on the Nash–Sutcliffe correlation coefficient (R_{NS}) [17]. The values of the quality criterion R_{NS} lie in the range 0.57–0.72, thus the quality of modelling can be characterized as satisfactory for all the three rivers (Table 2). The verification of the simulation against an independent period demonstrated similar quality assessment, which reflects the reliability and stability of the found parameters.

Table 2. Model parameters and modeling quality assessment for river basins

River–gauge station	M_{cr}, mm/day	R_{chan}	TMC, mm	FMC, mm	g_{deep}, mm/day	Calibration		Verification	
						years	R_{NS}	years	R_{NS}
Tuapse–Tuapse	12.1	0.101	$\frac{210}{130}$	$\frac{166}{86}$	$\frac{0.2}{0}$	1978–1987	$\frac{0.715}{0.630}$	1988–1991, 1994–1996, 2009–2010	$\frac{0.582}{0.525}$
Psekups–Goryachii Klyuch	12.0	0.086	$\frac{190}{200}$	$\frac{147}{157}$	$\frac{-0.3}{-0.2}$	1977–1990	$\frac{0.569}{0.566}$	1991–2002	$\frac{0.694}{0.696}$
Pshish–Khadyzhensk	10.8	0.108	$\frac{160}{170}$	$\frac{120}{130}$	$\frac{-0.1}{0.1}$	1999–2005	$\frac{0.621}{0.592}$	2006–2013	$\frac{0.625}{0.594}$

* When written as a fraction, the numerator and denominator correspond to the values obtained on the calculated and prognostic versions of the algorithm, respectively.

At the next stage, calibration runs were made for the prognostic version of the FCM, which was intended for the maximally full simulation of the operational short-term runoff forecast. For every forecast date, tuning of the model “according to the prehistory” was carried out, i.e. calibration based on the actual runoff and precipitation data during the previous period in different variants of tests from 7 to 13 days. Such tuning requires selecting optimal current values of the mean daily evaporation and non-gravitational moisture content of the basin. The optimal duration of the tuning period for all the three drainage basins was 13 days.

Then, with the help of the model tuned to the current conditions, a forecast imitation is realized, i.e., runoff calculation for the next 1, 2, and 3 days, using actual precipitation on these dates, recalculated into the so-called precipitation categories. The categories indicated for forecasting meteorological characteristics [18] were applied. Every value of the measured precipitation was categorized and replaced by the characteristic value indicated for the given category. Thus, when testing the prognostic algorithm, the use of absolutely successful 3-day precipitation forecast was imitated, and the results of testing can be used to assess the best expected quality of hydrological forecasting.

The quality of the prognostic scheme was estimated by means of the standard forecast quality assessment S/σ_Δ, recommended by the Russian Hydrometeorological Service [19] (Table 3). The results of testing the prognostic version of the model provided a new assessment of the optimal values of its main parameters. The difference in parameters of the estimated and prognostic versions of the FCM testing was significant only for the Tuapse River (see Table 2). Such a feature is evidently characteristic of the Black Sea coastal river basins with a particular contrast of the underlying surface conditions. As a result, the data from some meteorological stations become non-representative, and the response of the drainage basin to precipitation, spatially heterogeneous. For the rivers Psekups and Pshish, the parameters selected in the calculation regime are stable and suitable for the prognostic scheme.

At the final stage, in order to get a more detailed forecast, the model hydrographs [7] were statistically corrected with the help of the following multiple linear regression equation

$$Q_{\mathrm{for},i+\tau} = aQ_{\mathrm{mod},i+\tau} + bQ_{\mathrm{mod},i}, + cQ_{\mathrm{obs},i} + d, \quad (4)$$

where Q_{for}, Q_{mod}, Q_{obs} are the forecast, modelled, and observed discharges, respectively; a, b, c and d are regression coefficients; i and τ are the current moment and the forecast-time interval (in days). The regression equation coefficients were evaluated basing on the results of the prognostic experiment with calibration selection.

The correction improved the quality of modelling according to the prognostic scheme to “good” for the Tuapse River and “satisfactory” for the rivers of Psekups and Pshish (see Table 3; Fig. 4). The quality check of the prognostic model regime during an independent period in the process of verification demonstrated some reduction in quality comparing to the calibration period—the forecast for the Tuapse River became “satisfactory”. For the Pshish River, the satisfactory quality of modelling according to the prognostic scheme was achieved for the 2 and 3 day-range forecast.

DISCUSSION OF RESULTS

The results of modelling demonstrate that the FCM adequately describes the processes of runoff formation in West Caucasian river basins, as evidenced by the high value of the Nash–Sutcliffe criterion (R_{NS} > 0.5). Supplementary evidence is the realistic form of flood hydrographs received by modelling, as well as the realistic values of model parameters, which do not differ significantly and regularly from those received for the small rivers of the southern Far East.

Unlike the Far Eastern rivers, sharper rises and falls, as well as a faster propagation of flood waves are

Table 3. Estimates of the modeling quality of the forecast version of FCM model

Estimation period and stage of	The value S/σ_Δ with the lead time 1–3 days								
	Calibration			Verification 1			Verificati on 2		
	1	2	3	1	2	3	1	2	3
Tuapse R. near Tuapse									
Period	1977–1987			1988–1991, 1994–1996, 2009–2010			–		
Before correction	0.69	0.60	0.78	0.72	0.71	0.71	–	–	–
After correction	0.64	0.55	0.78	0.73	0.72	0.72	–	–	–
Psekups R. near Goryachiy Klyuch									
Period	1977–1990			1991–2002			2003–2013		
Before correction	0.83	0.72	0.81	0.87	0.84	0.79	0.81	0.80	0.83
After correction	0.78	0.68	0.70	0.78	0.73	0.68	0.57	0.53	0.49
Pshish R. near Khadyzhensk									
Period	1999–2005			2006–2010, 2012–2013			–		
Before correction	0.92	0.92	0.91	0.94	0.71	0.78	–	–	–
After correction	0.78	0.71	0.69	0.88	0.76	0.78	–	–	–

characteristic of the Caucasian rivers. Rapid recessions, associated with the small capacity of the initial elements of channel network, are reflected in the small values of the channel storage depletion coefficient R_{chan} (0.086–0.108). To compare, this indicator is in the range 0.143–0.538 [7] for small rivers in the Ussuri basin and for the rivers of Primorye, flowing into the Sea of Japan. The critical discharge modules M_{cr} (10.8–12.1 mm/day) are close to the upper limit of the interval of this characteristic for the rivers of Primorye, where it varies from 6.42 to 15.4 mm/day. The full moisture capacity (FMC) as a characteristic of river basin capacity varies within the range of 170–210 mm in the estimation version of the model, i.e., close to or lower than the average FMC of Primorye river basins.

These differences are clearly due to the higher slopes and the lower "perfection" of small river basins within the mountain system much more active geologically and younger than the medium-altitude mountain systems of the Far East. Characteristically, the inner calculation step of the model had to be reduced for the stability of the algorithm (while solving the equations (3)) from the 12 hours, which are usual for the Far Eastern rivers, to 1.5 hours.

Applying statistical correction to the results of modelling revealed the ambiguity of its effect on the modelling quality estimates according to the prognostic scheme. With the general trend toward better quality, we can notice that, during the verification periods for the rivers Tuapse and Pshish, the results before and after correction almost do not differ. In the case with the Tuapse, correction produced a very slight effect during the calibration period as well—S/σ_Δ decreased by not more than 0.05. The detailed analysis showed that correction helped to improve the simulation of the average floods regularly. However, when modelling the extreme floods of August 1, 1991 (157 mm/day maximum), and of October 16, 2010 (143 mm/day maximum), correction led to a decrease in runoff estimates, thus reducing the general quality assessment.

For the Psekups, correction in the test period had a positive effect on the quality of the simulated hydrograph both during the main (1991–2002) and additional testing period (2003–2013). Two verification periods were used for this basin, since in 2002–2003, it was noticed that there was an evident break in the homogeneity of observation series, expressed in the lower value of the seasonal runoff coefficient. Nevertheless, nearly the same low estimates of S/σ_Δ were obtained for the calibration and the two verification periods—on the verge of satisfactory quality. However, after the correction during an additional period since 2003, the quality of modelling improved considerably, an indirect indication to the better quality of observations.

Overall, the results indicate that the water-balance lumped-parameter model FCM can adequately simulate rain-induced floods on the West Caucasian rivers, including extreme floods. Developing forecasting methods using the FCM and taking into consideration the experience in its application to the rivers in the southern Far East is promising. The suggested prognostic scheme is simple in the development and adjustment, has a small number of parameters to calibrate, can produce acceptable results in situations with little operational information, and shows tolerance to gaps in the information input flows.

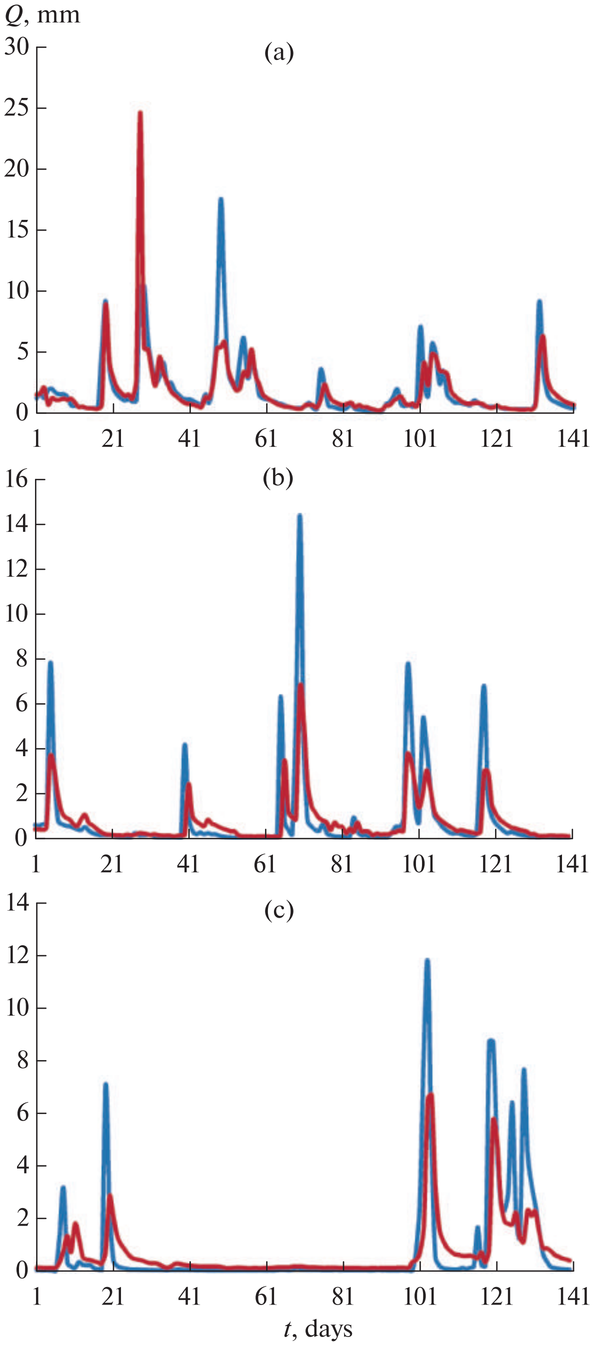

Fig. 4. Measured (1) and forecasted (2) hydrographs with a lead time of 1 day, calculated on the basis of the FCM model. (a) Tuapse R. near Tuapse, 1988; (b) Psekups R. near Goryachy Klyuch, 1991; (c) Pshish R. near Khadyzhensk, 2013.

CONCLUSIONS

The results presented in this article should be considered preliminary. They reveal both the advantages of using the conceptual water-balance Flood Cycle Model (FCM) and the accompanying difficulties. Its application, along with other water-balance models, is appropriate for predicting flood flows in the Caucasian rivers; however, it requires solving some methodological problems and, in particular, developing an observation network in the mountain parts of drainage basins. The existing network of meteorological stations, mainly located where mountain rivers flow out onto the Kuban Plain or in the coastal area of the Black Sea, is not able to reflect the runoff-forming precipitation correctly.

In this study, the Flood Cycle Model (FCM) was successfully adapted to the West Caucasian rivers with rain floods prevailing in their regime. The model can satisfactorily describe rain-related runoff generation in the drainage basins of the Tuapse, Psekups, and Pshish rivers during the warm season. Estimation of the main model parameters by the calibration method produces values that are within permissible intervals and agree with the landscape-climatic basin characteristics. The adjustment of the prognostic version of the model showed reliable calculation results, the majority of which meet the quality criteria of hydrological forecasting established in the Russian Hydrometeorological Service.

The current development of the automated observation network determines the research prospects. The joint use of information from automated hydrological complexes and rain gauges would allow adjusting runoff formation models with different time steps and thus create a forecasting system with the time interval of 12–72 hours. Such a system would help significantly increase the reliability of warnings about dangerous flash floods and, in the long run, reduce the loss of lives and damage caused by them.

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