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LAND WATER ISSUES

Runoff Formation Settings: Multifaceted Research in Testbed Catchments in the Headwaters of the Ussuri River

B. I. Gartsman[a,b,c,*], **V. V. Shamov**[b], **T. S. Gubareva**[a,b], **S. Yu. Lupakov**[b], **N. K. Kozhevnikova**[d], **A. N. Bugaets**[b], **A. G. Boldeskul**[b], **T. N. Lutsenko**[b], **N. F. Pshenichnikova**[b], and **L. V. Gonchukov**[b,e]

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Abstract—The results of long-term field studies on small catchments in the upper reaches of the Ussuri River (Primorskii krai, Pacific Russia) are presented. By virtue of modern means of observation, a unique dataset was obtained to record effectively the complicated runoff formation process in small low-mountain river basins. Geochemical and hydrological modeling were used jointly to describe the catchment dynamics, and genetic components of the river flow were assessed to study more thoroughly the runoff processes and to evaluate the runoff modeling accuracy factors.

Keywords: field observations, experimental catchments, hydrological conditions, water balance, modeling

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INTRODUCTION

The formation of runoff is a complex set of near-surface water cycle processes each of which, even within small land areas, is characterized by an extreme spatial and temporal heterogeneity. Some components of the water balance (atmospheric precipitation, water flow, and evaporation components), their dynamics, and spatial distribution can be measured directly with a varying accuracy. Other components can only be determined indirectly, and this is, ultimately, one of the fundamental problems of land hydrology [1].

To date, the methodological foundations of water balance calculations and runoff estimates have been developed. The near-surface water circulation processes have been understood to some extent based on a set of calculation models: those with lumped and distributed parameters, relatively simple and very complex models. However, in general, hydrologists do not have reliable methods to parameterize the current calculation procedures to describe the water movement in a particular river basin with sufficient accuracy. This problem is hard to solve because of the rather limited necessary data [2]. An equally difficult problem is the correlation of point measurements with the spatial scale of objects under study [1]. It is usually solved in hydrology using geomorphological data and/or landscape similarity principles.

This work is a generalized ten-year experience of interdisciplinary research of runoff formation conditions and processes in the experimental basins of the Ussuri River headwaters, Primorskii krai, Pacific Russia. In small catchments, in the warm season, we organized the monitoring of hydrological, hydrochemical, meteorological, soil, and plant characteristics, taking into account the requirements for the initial data used in a number of runoff formation models and in geochemical mixing models. The stability of the model parameters in the runoff simulations was analyzed; the influence of the amount of data, the observation data errors, and the uncertainty of model structure on estimated runoff dynamics and basic genetic components were assessed.

OBJECTS AND METHODS

The main study objects are Medvezhii (7.6 km^2 in area) and Elovyi (3.5 km^2) catchments located within

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[a] *Water Problems Institute, Russian Academy of Sciences, Moscow, 117971 Russia*
[b] *Pacific Geographical Institute, Far East Branch, Russian Academy of Sciences, Vladivostok, 690041 Russia*
[c] *Institute of Natural and Technical Systems, Sevastopol, 299011 Russia*
[d] *Federal Scientific Center of the East Asia Terrestrial Biodiversity, Far East Branch, Russian Academy of Sciences, Vladivostok, 690022 Russia*
[e] *Far East Regional Hydrometeorological Research Institute, Vladivostok, 690091 Russia*
**e-mail: gartsman@inbox.ru*

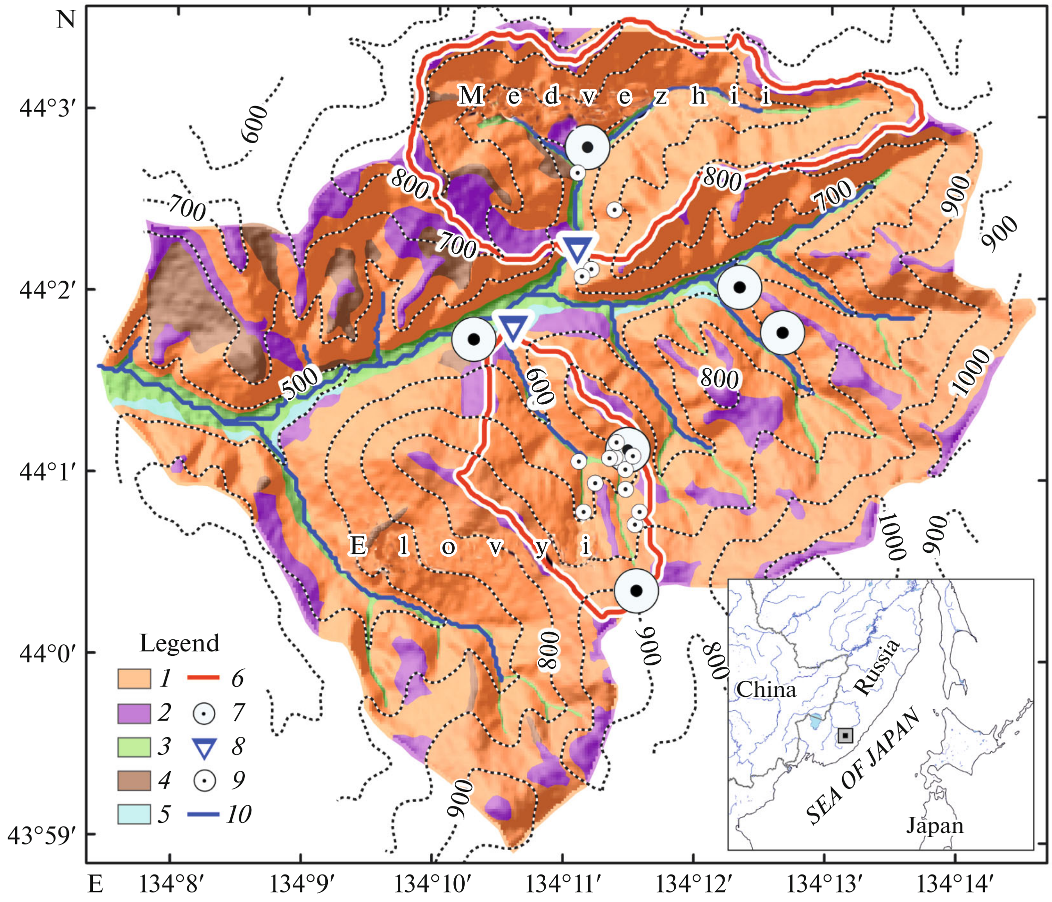

Fig. 1. Map of the Verkhneussuriiskii Biocenological Station. (*1*) Mountain brown taiga illuvial–humus nonpodzolized and podzolized soils; (*2*) forest brown underdeveloped soils; (*3*) residual floodplain and peaty–humus–gley soils, (*4*) mountain forest brown gley soils, (*5*) brown forest soils on alluvial deposits; (*6*) catchment boundary, (*7*) precipitation gauge/weather station, (*8*) stream gauge, (*9*) tensiolysimeter, (*10*) river network.

the Verkhneussuriiskii Biocenological Station of the Federal Scientific Center of the East Asia Terrestrial Biodiversity, Far Eastern Branch of the Russian Academy of Sciences (44°02′ N, 134°11′ E) (Fig. 1). The study area is a typical low-mountain zone in the southern Far East taiga [3, 4]. The average terrain height is 500–700 m, and the maximum height is ~1100 m. The Medvezhii Creek basin is underlain by Jurassic rocks, while Elovyi Creek basin is underlain by Late Cretaceous rocks. The regional climate is monsoon with excessive watering during the warm season, and the daily precipitation can exceed 100 mm. The daily maxima of the runoff depth sometimes reach 30–40 mm (the corresponding specific discharge are 300–500 l/(s km^2)).

A soil map of the study area was created to parameterize physically based hydrological models. The results of earlier soil surveys were used to create the database of soil–hydrophysical characteristics [3, 4]. Hydrological models with a simplified description of the hydrological cycle (FCM and HBV) and complex spatially distributed models (ECOMAG and SWAT) were used as a methodological basis for modeling the water balance components [4–9]. The EMMA procedure and the principal component analysis were used to adapt the geochemical model of natural water mixing [10].

MONITORING RESULTS

Based on the analysis of hydrometric data with a time resolution of 10–15 min, the water level in the order of watercourses I–III under a lack of precipitation is subject to diurnal cyclic variations with a minimum during the day and a maximum at night; the variation amplitude is about 5–10 mm at an average flow depth of 10–20 cm [11]. These diurnal variations in the water level correlate with the measurement data on the stem sap flow [12]. The tree transpiration rate is controlled by light, air temperature, and air humidity. The stem sap flow inertia in relation to meteorological processes is 1–2 h. The transpiration volume of one adult tree per day is 100 l or more [12], i.e., ~2–3 mm on the catchment scale (Fig. 2). In the moderate- and

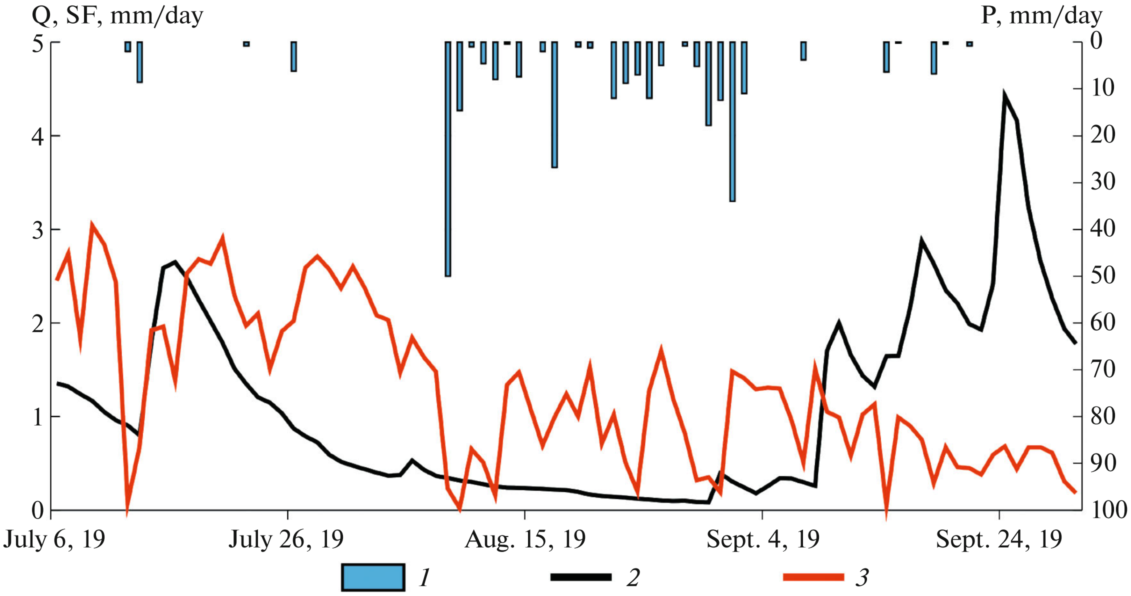

Fig. 2. Dynamics of the measured (*1*) precipitation (P), (*2*) runoff (Q), and (*3*) stem sap flow (SF) in the small catchment [7].

low-watering periods, evapotranspiration is a dominant hydrological process and the total evaporation can be 5–6 times higher than the runoff volume [7, 11].

The drainage catchment network reacts differently to the rainfall depending on the initial watering conditions, as well as the rain rate and it's duration [11]. During the low water period, more than 90% of the river runoff is generated by the upper parts of the basin, while the lower part is almost not involved in the channel runoff formation; the runoff losses due to infiltration into channel sediments are ~20%. Under average initial watering conditions, the first flood peak is formed within 2 h, while the second, smoother, peak is generated by the slope drainage system within 0.5–2 days after the rain started.

Heavy rainfall leads to a rapid increase in water levels. The rapid catchment response to precipitation is due to the predominance of soils with a high (up to 90%) content of coarse clastic material contributing to the slope subsurface draining [14]. Specimens of the Ussuri long-tailed salamander (*Onychodactylus fischeri*) found in slope streams are indicative of stable flooding of drains [14]. The water movement in drains varies from filtration (flow velocity is 0.002–0.200 cm/s) to turbulent flow (10 cm/s and more). The water flow rates in drains vary from hundredths to a few l/s (0.25–6.6 l/s, on average). During outstanding rainfall, the specific discharges in drains reach 700 l/(s km^2).

As follows from the analyzed ionic composition of water [11], at least eight genetic types circulating in the basins can be distinguished: cyclonic and air-mass precipitation; undertree water; slope (soil) water; ground water; river low flow and low and medium floods. Rain water is predominantly acidic (average pH 4.9) and ultrafresh (mineralization is 1–15 mg/L, 5.0 mg/L, on average) [13]. Ion concentrations vary greatly in atmospheric water, and their maximum values occasionally can be 5–10 times higher than the average. The chemical composition of river water is changed substantially after precipitation due to their interaction with the soil and vegetation cover and underlying rocks [14], while the water composition and mineralization in adjacent streams are drastically different.

MODELING RESULTS

According to the hydrological modeling results, adjacent catchments are drastically different in the runoff formation conditions. This difference is observed as variations in the model parameters responsible for the groundwater feeding, the infiltration rate, and evapotranspiration [3, 5, 6, 8]. This conclusion is confirmed by the hydrological and geochemical modeling results compared [4]. The model parameters values are effective only if the calibration period includes all hydrological conditions. In almost all cases, the transfer of parameters between adjacent catchments leads to unsatisfactory results [8]. The main sources of uncertainty that affect the calculation accuracy of the water balance components include errors in potential evapotranspiration calculation [7], simplified estimation of the actual evaporation [5, 6], the hydrological model structure [5], and local features of water exchange in the soil cover not taken into account in the models [4]. In the low-water periods, the absolute error of river runoff values is low (within fractions of mm), while the relative error can reach tens of percent [3, 5, 6, 8].

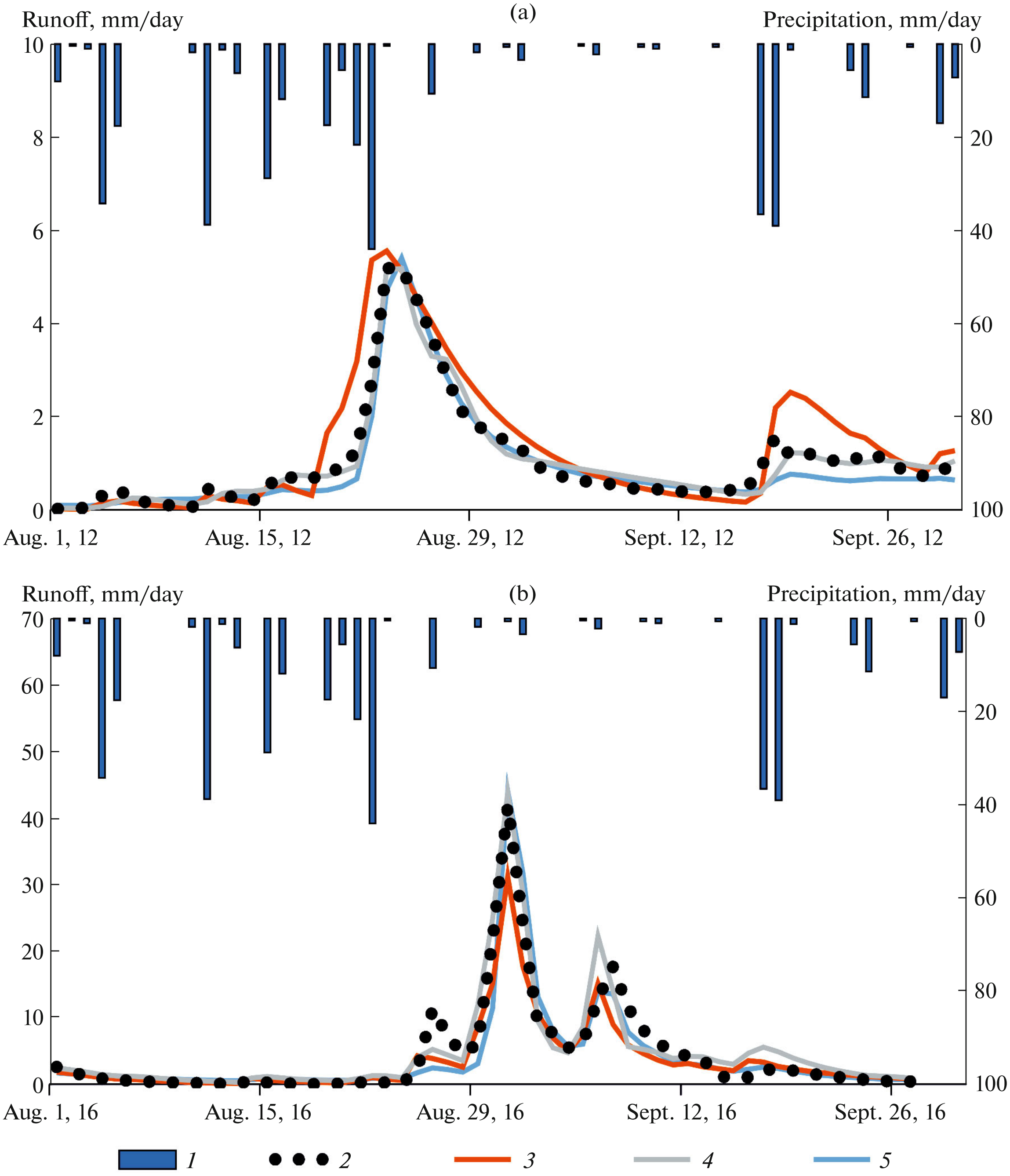

Fig. 3. Examples of runoff trends calculated using (*3*) SWAT, (*4*) HBV, (*5*) FCM models, measured (*1*) precipitation and (*2*) runoff during high-water periods in the (a) Elovyi and (b) Medvezhii creeks.

The difference in the amount of precipitation at the points located at a distance of 30–35 km from each sother can reach 100 mm/day [5]. For this reason, the flood modeling accuracy (Fig. 3) primarily depends on the representativeness of the rain gauge network. The measurement data of rain gauges (from two to six points) located over an area of about 20–30 km^2 made it possible to obtain the high-quality modeling of almost all floods [3–6, 8]. In addition, the modeling efficiency depends on the accuracy of detection of runoff formation moment of occurrence. Such accuracy is related to a correct assessment of the earlier catchment watering [4–6, 9]. The use of the earlier obtained regional dependences for the parameterization of runoff formation model routine makes it possible to calculate more accurately the characteristics of the pre-flooded catchment [5, 9].

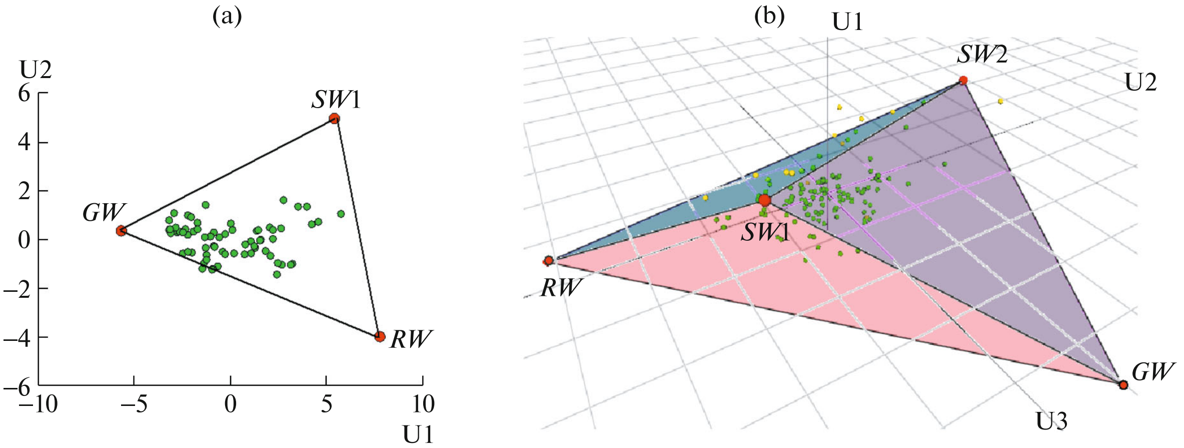

Fig. 4. Mixing diagrams: (a) Medvezhii Creek, (b) Elovyi Creek. (*RW*) Rainwater (surface runoff), (*GW*) groundwater runoff, (*SW*1 and *SW*2) soil runoff components, (U) mixing space, each green dot is a sample of river water.

Based on the genetic components of the river runoff estimated using a tracer mixing model and the EMMA procedure, under the catchment landscape heterogeneity conditions, the dimension of the mixing model increases due to the more complex structure of soil components in the runoff (Fig. 4), which includes two independent river feeding sources such as waters of near-surface organic and slope mineral horizons [10, 17]. In general, the number of soil sources depends on the water content and landscape features of the catchment area [16, 18], while the rain surface and ground runoff sources remain constant under any conditions.

The estimated proportions of river feeding (surface, soil, and ground) sources obtained on the basis of the models used differ considerably [4, 5] depending on the accepted conceptualization of hydrological processes in the models. This difference raises the problem of more accurate determination of the runoff genetic components. Based on the general experience, hydrological models including a more complete physical description of the water movement in the soil are in better agreement with the hydrograph separation results obtained by the geochemical analysis supported by the calculation verification procedures [4].

CONCLUSIONS

As of today, the modeling approach in hydrology is the main tool to study hydrological processes, while special observation data on experimental catchments are the only source of representative information needed to test the hypotheses and to verify the runoff formation models. The combination of conceptually different models and data from special hydrological and geochemical monitoring in the typical small catchments made it possible to study the runoff formation processes at a new detail level, as well as to determine the main factors affecting the modeling accuracy of the runoff and the water balance in general. The results obtained are indicative of the considerable spatial heterogeneity of runoff formation conditions even in the small catchment areas located at a distance of 2–5 km from each other. The prospects for further studies are primarily related to the extension of the experience gained to the river basins of other landscape zones, the inclusion of new instruments and methods for measuring special parameters (including those related to the evapotranspiration processes) into field observations, and the transition to the water balance calculations and models with an hourly time step.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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