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Assessing the Sensitivity of a Model of Runoff Formation in the Ussuri River Basin

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Abstract—A physically based model of runoff formation with daily resolution has been developed for the upper part of the Ussuri basin with an area of 24 400 km^2 based on ECOMAG hydrological modeling platform. Two versions of the hydrological model have been studied: (1) a crude version with the spatial schematization of the drainage area and river network based on DEM 1 × 1 km with the use of soil and landscape maps at a scale of 1 : 2 500 000 and (2) a detailed version with DEM 80 × 80 m and soil and landscape maps of the scale of 1 : 100 000. Each version of the model has been tested for two variants of meteorological inputs: (1) meteorological forcing data (temperature, air humidity, precipitation) at eight weather stations and (2) with the involvement of additional data on precipitation collected at 15 gages in the basin. The model has been calibrated and validated over a 34-year period (1979–2012) with the use of runoff data for the Ussuri R. and its tributaries. The results of numerical experiments for assessing the sensitivity of model hydrological response to the spatial resolution of land surface characteristics and the density of precipitation gaging stations are discussed.

Keywords: runoff formation, model sensitivity, precipitation gaging network, land surface characteristics

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INTRODUCTION

Precipitation plays the dominant role in the formation of the hydrological regime of water bodies. Therefore, the quality of runoff simulation with the use of spatially distributed models largely depends on the correct reproduction of the spatial pattern of heterogeneities of meteorological impacts on the watershed and, primarily, on the resolution of precipitation input field. In the two recent decades, various aspects of hydrological model sensitivity to variations of input precipitation data were studied (e.g., [5, 7, 13, 14]). In particular, it was demonstrated that the quality of hydrological modeling decreases with precipitation network density reduction. Studies have also shown that the sensitivity to precipitation varies widely depending on the models used, the type of precipitation, watershed sizes, and hydrological conditions, and the lengths of time intervals. Therefore, estimates of model sensitivity in a region cannot be immediately extended to other basins. The effect of the spatial resolution of the land surface characteristics (relief, soils, vegetation) on the hydrological responses of a river basin is less known [1]. It was found that the aggregation of surface characteristics to a certain degree has no effect on calculation accuracy [14]; however, this effect becomes visible and adverse after some threshold.

In Russia and many other countries, precipitation is measured at the weather and hydrological stations and gages. Some researchers believe the precipitation data from weather stations to be more reliable than the data of measurements at hydrological gages. Therefore, the precipitation data from such gages are often ignored in hydrological models, as the poor-quality data on precipitation at some gages can deteriorate the simulation results.

In this study, the processes of runoff formation are described with the use of the spatially distributed physically based model ECOMAG (ECOlogical Model for Applied Geophysics) [9, 12]. The model was tested in many river basins in different physiographic zones, and at different spatial scales and proved effective for both calculating runoff hydrographs with daily resolution and simulating the dynamics of hydrological fields (soil moisture content, snow-cover water equivalent, and runoff) in large river basins [10, 11].

This study is focused on the following three aspects:

(1) examining the potentialities of ECOMAG model for simulating the spatial pattern of runoff regime in river basins with specific features of runoff formation under monsoon climate [4];

(2) examining model sensitivity to precipitation network density and the effect of incorporating the data of precipitation measurements at hydrological gages for hydrological calculations in a region;

(3) examining model sensitivity to the resolution of land surface characteristics.

CASE STUDY BASIN

The case study area is the upper part of the Ussuri River Basin upstream of Kirovskii Settl. with an area of 24400 km^2. The length of the river channel from the source is 240 km. The relief of the river basin is diverse (Fig. 1). Mountains are predominant in its southeastern part; and lowlands, in the northwest. The upper reaches of the Ussuri and Arsen'evka rivers lie in the Przheval'skogo Mountains with the highest Oblachnaya Mountain 1854 m in height. The Ussuri and its tributaries mostly flow in intermountain depressions. From the west, the basin is separated from Prikhankaiskaya Plain by the Sinii Ridge.

The spatial distribution of the soil and vegetation types shows latitudinal zoning. The highest elevations are typical of mountain-tundra soils and suffruticous type of vegetation. Mountain brown-taiga soils and mountain-podzol soils with coniferous forests are typical in the eastern and southeastern parts of the basin. Brown-taiga soils with spruce–cedar–larch forests can be seen in the southwestern areas. Mountain–forest brown soils with coniferous–broad-leaved forests and brown forest soils on low bald mountains occupy the largest area in the Ussuri Basin. Brown soil varieties are common in the lowland valley of the Arsen'evka R. Meadow gley soils on river terraces and plains are used in agriculture [2].

The climate of the basin is determined by its position near the Pacific coast and the monsoon character of atmospheric circulation. The average winter and summer temperatures are –18 and +20°C, respectively. The annual precipitation in the mountains is 1000 mm, and that on the plain is 300–400 mm less. The major portion of precipitation is summer rains.

River recharge is mostly rainfall: more than 80% of runoff falls in the spring and summer from April to September; the winter low-water season accounts for as little as 2–5% of the annual runoff.

DATA SOURCES DESCRIPTION

The spatially distributed model of runoff formation in river basins ECOMAG, based on the achievements of the school of physico-mathematical simulation of hydrological processes [6], describes the main processes of the land hydrological cycle in the mixed rain- and snow-fed river basins. The model was adapted to the conditions and the available forcing data on the Ussuri Basin [3]. The model spatial schematization of the river basin and its channel network was carried out based on digital maps of the region with the use of ArcGIS Ecomag extension technology. This is a special application, which performs the analysis of streamlines based on digital elevation model (DEM) in automatic mode to reproduce the structure of river network with different detail and identifies watersheds' (elementary calculation sub-basins') boundaries, which are used as spatial model calculation units. In addition, digital soil and landscape maps are used to specify the properties of soil and landscape types in the model domain.

The data sources for schematizing the drainage basin of the Ussuri R. were two sets of maps with different spatial resolution: (1) a detailed version with DEM 80 × 80 m along with soil and landscape maps at a scale of 1 : 100000, specially developed for this basin [2], and (2) a crude version based on DEM 1 × 1 km along with soil and landscape maps at a scale of 1 : 2500000. Accordingly, two versions of the hydrological model were constructed. In the detailed version of the model, the schematization of the basin based on the first set of maps was used to choose partial drainage areas of 802 model elementary sub-basins, with the mean area about 30 km^2. In addition to the main river, the model river network included 69 1st-order tributaries, emptying into the main river (the main river is assigned the order 0 in accordance with the ascending order classification), 157 2nd-order tributaries, 129 3rd-order, 42 4th-order, and 5 4th-order tributaries. The crude version with the second set of maps contained 255 model elementary sub-basins with the mean area of about 95 km^2; the model river network, in addition to the main river, included 29 1st-order tributaries, emptying into the main river, 66 2nd-order, 36 3rd-order, and 5 4th-order tributaries.

The hydrometeorological observation network of the Ussuri Basin upstream of Kirovskii Settl. shows high density and quality of hydrometric observations, as it is the Ussuri Test Area for study methods. Daily meteorological data from eight meteorological stations (air temperature, air humidity, and precipitation) along with data of precipitation measurements at 15 hydrological gaging stations over 1979–2012 were used to specify the meteorological forcing in the drainage basin (Fig. 1). Daily runoff hydrographs from 14 hydrological gages on the main Ussuri channel and

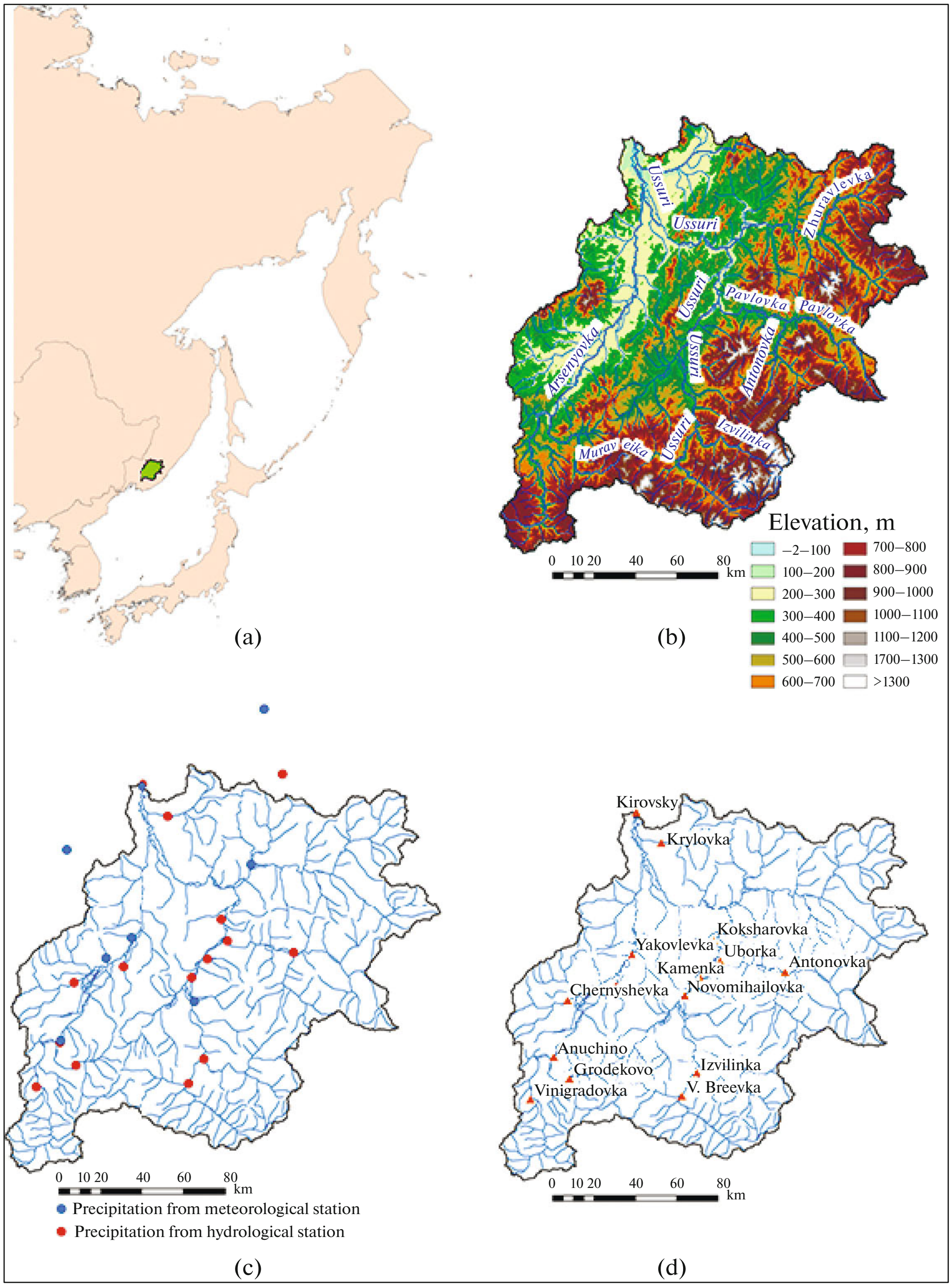

Fig. 1. (a) Location of the Ussuri R. drainage basin, (b) relief, and the layout of (c) precipitation gages and (d) hydrological gages.

on its tributaries over the same period were used to calibrate parameters and validate the model (Fig. 1).

PARAMETER CALIBRATION AND MODEL VALIDATION

The majority of the ECOMAG model parameters were specified based on data from databases of soil characteristics, vegetation, and relief. Several key parameters were chosen by model calibration against the difference between calculated and measured runoff hydrographs. The target function was the Nash–Sutcliffe criterion (NS), often used in hydrological calculations:

$$\mathrm{NS} = \frac{F_0^2 - F^2}{F_0^2}, \tag{1}$$

Table 1. Nash—Sutcliffe criterion values for the calibration and test calculations series with the detailed and crude model versions

Gage	Kiro	Koksh	Yakov	Novo	Ubor	Anto	Anuch	VBre	Izvi	Kryl	Sama	Vino	Mura	Kame	Total	Mean
thous., km^2	24.4	9.34	5.18	5.17	3.35	2.67	2.48	1.8	1.16	1.07	1.03	0.94	0.76	0.14		
Detailed version																
Calibration 1979–1989																
NS	0.79	0.72	0.75	0.76	0.76	0.67	0.76	0.72	0.7	0.18	0.73	0.68	0.74	0.49	0.82	0.68
BIAS, %	–3.8	–8.8	9.5	–1.3	–12.8	–9.1	–6.5	–12.8	–17.6	7.3	–13.8	–10.5	–7.8	–36.1	–5.2	–8.9
Validation 1990–2012																
NS	0.79	0.8	0.73	0.64	0.75	0.64	0.76	0.57	0.42	0.42	0.52	0.63	0.62	–0.1	0.83	0.58
BIAS, %	–1.9	0.4	–3.6	20.6	–5.4	–5.3	6.2	2.6	7.2	7.9	–1.8	8.8	–16.3	–14.2	0.6	0.4
Crude version																
Calibration 1979–1989																
NS	0.75	0.64	0.67	0.65	0.65	0.67	0.60	0.49	0.57	0.14	0.62	0.47	0.65	0.54	0.78	0.56
BIAS, %	–4.5	6.4	–3.2	22.2	–6.2	–0.8	–6.7	–17.1	15.9	21.9	–20.9	–12.2	0.6	–25.1	–1.0	–5.2
Validation 1990–2012																
NS	0.79	0.7	0.69	0.42	0.73	0.70	0.70	0.54	0.37	0.37	0.64	0.58	0.62	0.23	0.82	0.58
BIAS, %	–2.8	14.9	–10.2	45.6	0.6	1.7	7.8	1.3	41.7	–33.7	–9.3	10.7	–8.9	–1.1	5.3	4.2

where $F_0^2 = \sum_i (Q_i - Q_m)^2$, $F^2 = \sum_i (Q_{i,p} - Q_i)^2$, $Q_{i,p}$ is the water discharge on the ith day calculated by the model; Q_i is the actual discharge, Q_m is the mean actual water discharge over the calculation period. The closer NS value is to one, the higher the simulation accuracy.

In hydrological calculations using ECOMAG model, runoff characteristics are simulated at each time step in all river network cells; therefore, the calculated and measured runoff hydrographs within each model run can be compared in all points of the model river network, corresponding to the gages of the hydrometric monitoring network. The NS criterion shows the agreement between the calculated and measured hydrographs for a monitoring point in the river network, e.g., at the outlet section of the drainage basin. To simultaneously take into account the modelling quality in several monitoring points, a target function can be specified in the following forms:

(1) an averaged criterion in the form $\mathrm{NS_{mean}} = \frac{1}{M}\sum_{i=1}^{M} \mathrm{NS}_i$, where M is the number of comparison points;

(2) weighted mean criterion $\mathrm{NS_{total}}$ in the form (1), in which $F_0^2 = \sum_k \sum_i (Q_{i,k} - Q_\mathrm{m})^2$, $F^2 = \sum_k \sum_i (Q_{i,k,p} - Q_{i,k})^2$, $Q_{i,k,p}$ is the calculated streamflow discharge on the ith day at the kth comparison point, $Q_{i,k}$ is the observed streamflow discharge on the ith day at the kth comparison point, $Q_m = \frac{1}{MN}\sum_k \sum_i Q_{i,k}$ is the weighted mean actual discharge over all M comparison points over the calculation period of N days.

In the former case, all gages were assigned equal weights, while in the latter case the gages with higher mean annual discharges were assigned greater weights.

Another criterion, BIAS, characterizes the relative error in the calculation of streamflow discharges:

$$\mathrm{BIAS} = \sum_i (Q_{i,p} - Q_i)/Q_i \times 100\%.$$

Depending on the value of criterion BIAS, the results of runoff hydrograph simulations can be assumed good at $|\mathrm{BIAS}| < 15\%$, satisfactory at $15\% < |\mathrm{BIAS}| < 25\%$, and unacceptable at $|\mathrm{BIAS}| > 25\%$ [8]

The parameters of the detailed and crude versions of the ECOMAG model were calibrated against daily runoff hydrographs at 14 gages with data of 23 precipitation gages (8 at weather stations and 15 at gages) for period 1979–1989 taken into account; the model was validated against the observation data for the period 1990–2012. Table 1 gives the values of criteria NS and BIAS for individual gages for calibration periods for both model versions and the values of criteria $\mathrm{NS_{mean}}$, $\mathrm{NS_{total}}$, and BIAS averaged over all hydrological gages. In addition, Fig. 2 illustrates the runoff hydrographs at the basin outlet at Kirovskii Settl. over the entire calculation period. As can be seen from Table 1, the values of criteria for the calibration and test series are not significantly different, thus suggesting the stability of model parameters.

In the detailed version of the model, the agreement between hydrographs for the calibration period is good for 5 hydrological gages out of 14 (NS > 0.75), unsatisfactory for one gage (NS < 0.35), and satisfactory in other cases. In the test series of calculations, the numbers of gages with good, satisfactory, and unsatisfactory results were 4, 9, and 1, respectively. In the crude version of the model the agreement between hydrographs is good only for one gage out of 14, unsatisfactory for another one, and satisfactory for all others. For the validation period, the numbers of gages with good, satisfactory, and unsatisfactory results were 1, 12, and 1, respectively. For both versions of the model, the values of the averaged criterion NS_{mean} for the calibration and test periods were similar (about 0.7–0.6), as well as those for the weighted mean NS_{total} which were about 0.8. In terms of the absolute value of criterion $(BIAS)_{abs}$ in the detailed version of the model in the calibration period, the error of runoff evaluation was in excess of 15% only at one gage and in excess of 25%, in another one. In the validation period, two gages showed errors in excess of 15%. In the crude version of the model, in the calibration period, errors higher than 15 and 25% were obtained at five and one gages, respectively; while in the validation period, three gages showed calculation errors in excess of 25%.

Thus, we can conclude that the agreement between the measured and simulated hydrographs for both model versions is, in general, satisfactory (in each series, the estimates were unsatisfactory by NS criterion only for one gage out of fourteen; BIAS criterion yielded unsatisfactory estimates for 5 cases out of 56). In addition, we can note that the statistical estimates of simulation results by the detailed version of the model were somewhat better than the analogous estimates for the crude version. These issues will be discussed in more detail in the following section.

ESTIMATION OF MODEL SENSITIVITY

The sensitivity of the model to the density of precipitation network and the detail of land surface characteristics was evaluated by the following numerical experiments. The boundary conditions of the model in the form of daily precipitation fields were specified with the use of

—the data on precipitation at 8 meteorological stations combined with the data of measurements at 15 hydrological gages;

—only precipitation data at 8 meteorological stations.

The calculations with this input data were carried out by the detailed and crude versions of the model. The results of these numerical experiments are given in Table 2.

First, we will analyze the estimates of model sensitivity to precipitation network density. Table 2 shows that the reduction of this density from 23 to 8 gages

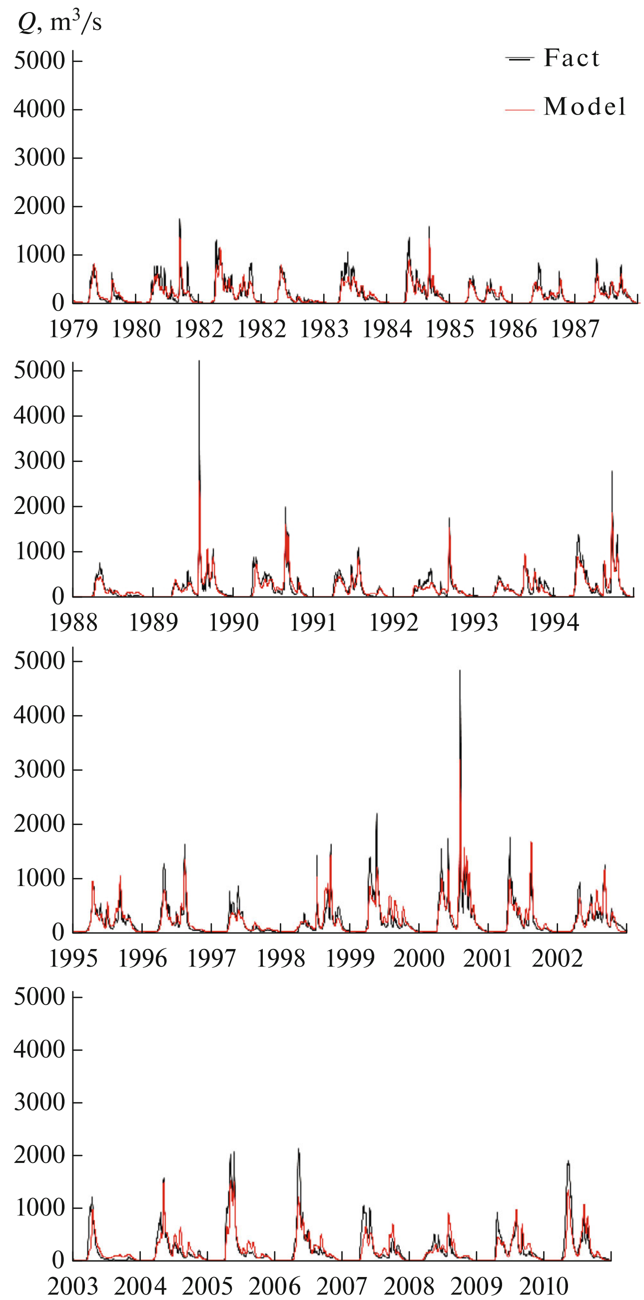

Fig. 2. Actual and calculated runoff hydrographs of the Ussuri R. in Kirovskii Settl.

decreases the calculation accuracy of the detailed version of the model by NS criterion by 0.06 and more for nine out of fourteen gages. Only one gage showed an improvement in the results. The values of all criteria NS_{mean} and NS_{total}, averaged over all gages, decreased by 0.06 and 0.04, respectively. For the crude version of the model, a decrease in the density of precipitation gage network caused a less obvious decline in calculation accuracy: a decrease in the accuracy by NS criterion by 0.06 and more was observed at 8 gages out of

Table 2. Model sensitivity to the density of precipitation gage network (over the entire period 1979–2012) and land surface characteristics detail level

Gage	Kiro	Koksh	Yakov	Novo	Ubor	Anto	Anuch	VBre	Izvi	Kryl	Sama	Vino	Mura	Kame	Total	Mean
thous. km^2	24.4	9.34	5.18	5.17	3.35	2.67	2.48	1.8	1.16	1.07	1.03	0.94	0.76	0.14		
Detailed model																
23 precipitation gages																
NS	0.79	0.76	0.74	0.68	0.75	0.65	0.76	0.62	0.51	0.36	0.57	0.66	0.65	0.18	0.83	0.62
8 precipitation gages																
NS	0.75	0.67	0.72	0.6	0.67	0.53	0.68	0.5	0.42	0.51	0.55	0.58	0.57	0.14	0.79	0.56
Crude model																
23 precipitation gages																
NS	0.79	0.68	0.68	0.50	0.71	0.70	0.66	0.52	0.43	0.24	0.64	0.52	0.63	0.37	0.81	0.58
8 precipitation gages																
NS	0.76	0.64	0.66	0.56	0.65	0.63	0.61	0.51	0.46	0.44	0.61	0.49	0.55	0.35	0.79	0.57

14, while 3 gages showed some improvement in the results. The decrease in the values of criteria NS_{mean} and NS_{total} was less than that in the detailed version of the model by 0.01 and 0.02, respectively. Therefore, the numerical experiments show that an increase in the density of precipitation gage network in most cases improves the calculation accuracy of runoff hydrographs at different hydrographic gages, and this improvement is more pronounced in the model with more detailed land surface characteristics (relief, soil, and vegetation).

The sensitivity of the model to the detail in specifying the characteristics of the land surface was evaluated by comparing the values of NS criterion in Table 2 for two model versions under identical meteorological forcing. When 23 precipitation gages were used, the accuracy by NS criterion in the crude version of the model was higher than that in the detailed version only in 3 hydrological gages out of 14. In other cases, the runoff estimates by the detailed version of the model were more accurate, except for those at the outlet section (Kirovskii gage), where both model versions showed the same accuracy. The values of criteria NS_{mean} and NS_{total} in the detailed version of the model were higher by 0.04 and 0.02, respectively than those in the crude version. In the case where precipitation fields were specified by the data of eight precipitation gages, the advantages of greater detail in land surface characteristics are less significant: the numbers of the cases with the predominance of either model in terms of the criterion were nearly equal. The values of criteria NS_{mean} and NS_{total} in the detailed and crude model versions were also similar.

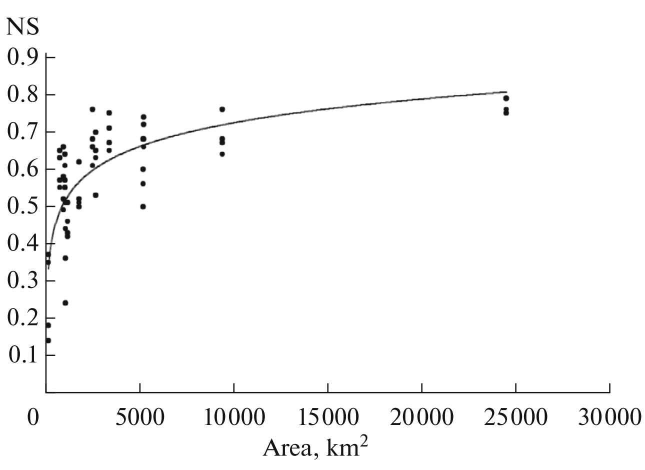

Fig. 3. The relationship between NS criterion and drainage basin area at hydrometric observation sections.

The analysis of the results of numerical experiments showed the following regularity: the values of NS criterion for drainage basins with larger areas were, on average, higher than those for small watersheds (Fig. 3). This can be the consequence of two factors. The first is associated with inaccuracies in the approximation of precipitation fields for small areas with sparse observation network. In large areas, these inaccuracies are smoothed because of the averaging of the precipitation fields. The second factor, most likely, is due to the use of parameters of the weighted-mean NS criterion for calibration in form 2, where the runoff hydrographs with greater mean annual discharges are assigned greater weights.

CONCLUSIONS

The spatially distributed physically based model ECOMAG was adapted to the Ussuri R. Basin. The study was carried out for two versions of the hydrological model. In the detailed version of the model, the spatial schematization of the drainage area and river network was made based on DEM 80 × 80 m and soil and landscape maps at a scale of 1 : 100000. In the crude version of the model, this was made with the use of DEM with a resolution of 1 × 1 km along with soil and landscape maps at a scale of 1 : 2500000. The results of testing of both model versions against daily runoff hydrographs over a long-term period at 14 hydrological gages with precipitation data from 23 precipitation gages (8 at meteorological stations and 15 at hydrological gages) showed, in general, acceptable simulation quality and confirmed the applicability of ECOMAG model to runoff calculations in different sections of river network in river basins in monsoon climate.

The sensitivity of the model to the density of precipitation gage network and the detail in land surface characteristics was evaluated by numerical experiments for both model versions with two precipitation data sets: in the first, the data from 23 precipitation gages were used, while in the second, precipitation data measured at only 8 meteorological stations were used. The results of numerical experiments showed that an increase in the density of precipitation gage network through the incorporation of precipitation data from hydrological gages improves the accuracy of runoff hydrograph calculation at the majority of hydrological gages, and this improvement is greater in the model version with detail land surface characteristics (relief, soils, and vegetation). These facts are also an indirect confirmation of the faithfulness and reliability of data from precipitation gages at hydrological gages in the region. The results of numerical experiments showed that the accuracy of runoff hydrograph calculations at the majority of gages with the use of precipitation data from 23 precipitation gages was higher in the detailed version of the model than it was in the crude model. At the same time, the accuracy of runoff hydrograph calculations at the outlet section was the same in both model versions. At a less accurate approximation of precipitation fields by eight precipitation gages, the advantages of the greater detail in land surface characteristics became less pronounced.

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