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THE PREDICTION OF DAILY OUTFLOW FOR AN UNGAGED MOUNTAINOUS BASIN

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To evaluate the daily outflow from a 212-km^2 basin in a mountainous part of the downstream Amur river, which has no rain gages, a modeling approach is needed. The average basin rainfall during a rainfall period (RP) and antecedent river discharge are used as model inputs. Estimating average basin rainfall is described by Fedorovski (this issue) and involves transfer of rainfall data from two permanent stations located more than 50 km away from the basin. The transformation of rainfall into streamflow is based on the Generalized Flood Pattern Method (GFPM). During method development, selected floods are averaged for rainfall durations of 1-6 days and ordinates of unit floods (UFs). It was established that eleven types (patterns) of generalized UFs exist depending on the rainfall duration and location of daily rain maximum in the RP. The flood hydrograph is calculated by multiplying the ordinates of the selected UF by total flood volume, which is derived from the empirical relationship between total rainfall and flood volume. The daily outflow is the sum of the flood hydrograph, flow from the previous flood, and base flow.

INTRODUCTION

The prediction of daily hydrographs for ungaged basins is important in environmental hydrology, especially in developing countries. Environmental engineers frequently use predictions as an aid in the solution of water pollution control problems, estimating seasonal flood risk, and water storage design (Cloke and Cordary, 1993; Atan and Metcalfe, 1994; Brookshire and Whittington, 1994; Krzysztofowicz, 1994; Ejaz and Paralta, 1995). In the mountainous part of the downstream Amur river, the standard rain rage network is sparse and most stations are located in river valleys. There are two permanent stations located approximately 50 km away from the basin of interest. In this region, practical use of many available models in both lumped and distributed configurations has been limited because of a lack of dense rain gage networks or radar coverage (Michaud and Sorooshian, 1994; Spear et al., 1994).

This study was motivated by the challenge of predicting daily hydrographs from basins with little or no historical data and no rain gages. The following two research tasks must be completed before this challenge can be solved.

1. Techniques must be developed for rainfall interpolation in mountains.
2. Techniques must be developed to transform the amounts of storm rainfall into daily streamflow.

The rainfall interpolation scheme for estimating average basin rainfall was first presented by Kozhevnikova et al. (1984). Fedorovski (1998, this issue) shows the further development of the scheme. Rainfall totals during specific rainfall periods (from some hours to some days) were predicted with a root mean square error of 8.5 mm and a correlation coefficient of 0.94.

There are two approaches to use these data for daily runoff modeling.

1. To develop techniques to disaggregate the amounts of significant storm rainfalls into shorter period rainfall amounts.
2. To transform the rainfall totals into flood volumes and then to redistribute them into daily streamflow.

The techniques for disaggregating daily rainfall amounts into an intermittent rainfall process were proposed at the beginning of the 1960s. Woolhiser and Osborn (1985) have reviewed these works noting that the models developed require a large number of parameters, making them difficult to use in practice.

The transformation of total rainfall into volume of runoff is a commonly known procedure and can be carried out even when few data are available. We present the transformation of rainfall into streamflow based on the Generalized Flood Pattern Method (GFPM) proposed by Mezencev (1979). The method is somewhat similar to the family of Unit Hydrograph (UH) methods but differs in the main concepts.

For runoff generation, the GFPM uses rainfall amounts recorded during a specific rain period (from 1 to 5 and more days) and some patterns of observed floods corresponding to the observed rainfall. The GFPM provides (1) a more simple way to develop the flood patterns from an analysis of rainfall and streamflow records of complex floods (not only of isolated storms with near unit duration as for the UH method), (2) elimination of errors due to linear synthesis of observed floods from the unit duration UH, and (3) the use of the amounts of storm rainfall, which can be interpolated between points of observation in mountainous regions more accurately than other period rainfall amounts.

A simple lumped model based on the GFPM was applied to the mountainous Left Silinka (L.S.) basin and the results were judged to be reliable; however, all tests were made for the warm period when precipitation occurred only as a rainfall. Part of the precipitation over the basin may occur as snow, and additional investigations of the transformation of melting snow into runoff are required. The characteristics of the model give it a great deal of flexibility. It may be used either as an event simulation model or as a sequential model and oriented for practical environmental engineering application on midsized basins with shortage of rainfall data.

STUDY AREA AND DATA COLLECTION

The L.S. basin above Solnetchny drains an area of 212 km^2. Topographically, the basin is located on the southeastern macroslope of the Mao - Chan mountain range. Basin elevation varies from around 350-400 m near the river gage to over 1300-1400 m in the western part of the basin (Figure 1). The mean elevation of the basin is about 780 m.

The geology of the basin consists of Jurassic sandstone, aleurolite, argillite (about 60 percent of the basin area), Upper Cretaceous andesite (about 24 percent), and Pleistocene basalt (about

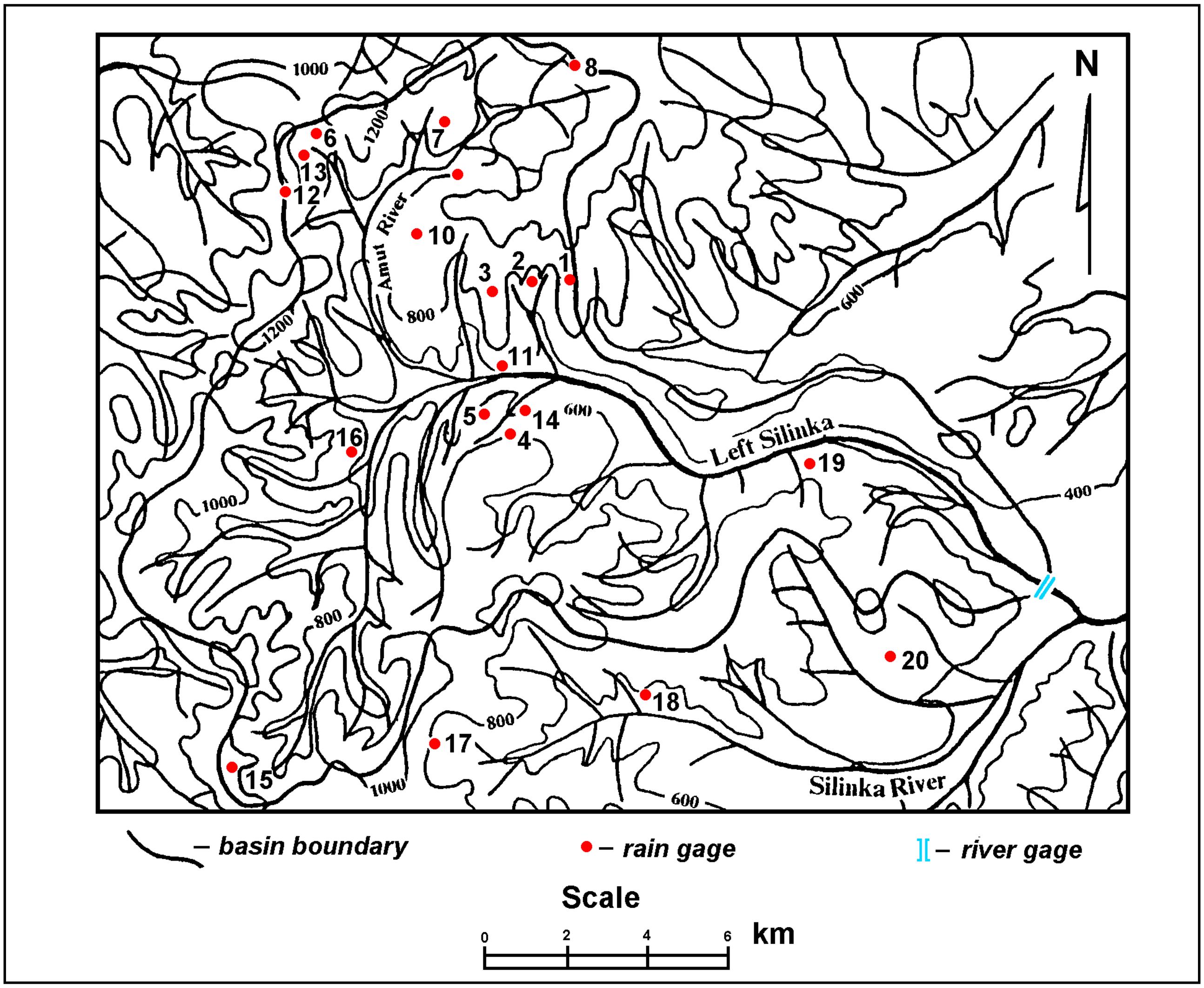

Figure 1. Maps showing the relief and observation network of the Left Silinka basin.

16 percent). On the steep slopes (up to 20-25°) there are gray - brown podzolic soils of 20-30 cm depth with low clay content. The plateau basalt located in the middle of the basin is covered by a sandy clay loam soil of 40-50 cm depth. The rocky slopes of more than 25-30° have no significant soil covering. Secondary forests cover most of the basin.

Mean annual precipitation and evapotranspiration are approximately 1120 and 433 mm respectively (Fedorovski, 1985). About 200-250 mm of the annual precipitation falls from September to May as a snow. Based on standard observations by the Hydrometeorogological Service Far East during the period 1966-1980, mean annual runoff is estimated to be 544 mm.

MODELING APPROACH

Generalized Unit Floods Method

In this work, the transformation of rainfall excess into streamflow is based on the Generalized Flood Pattern Method (GFPM) which is somewhat similar to the family of Unit Hydrograph (UH) methods but differs in the main concepts. The UH method is based on selection and averaging of floods from the unit duration rainfall (ordinary 2 - 6 hours, rarely 12 or 24 hours). To obtain a hydrograph from observed rainfall, the special techniques of linear synthesis of the UH are used (Viessman et al., 1979). All methods mentioned require short-period rainfall data. In the case of the L. S. basin, we obtained the amounts of rainfall only for the rainfall period (RP) and the use of the classical UH method is limited.

Mezencev (1979) showed that patterns of floods from rainfalls of any duration could be used for runoff routing from basins 200-500 km^2 in size . This approach, modified by Kozhevnikova et al., 1984, formed the basis of the model runoff routing.

The GFPM is based on the analysis of floods from precipitation during RPs which can last up to 6 days. The total flood volume is obtained from the daily streamflow records by subtraction of flow from previous floods and base flow via recession curves. Selected floods are averaged for rainfall durations of 1, 2...6 days and ordinates of the unit flood (UF) result in a unit flood depth of 1 mm.

For calculation, we used 76 floods obtained from the data of daily streamflow for the period of 1965-1979. The rainfall totals (P) that produced these floods range from 18.8 to 223 mm and duration of rainfall (t_{RP}) ranges from 1 to 6 days. Coefficients of runoff (the ratio of flood depth (Q) to P) varies from 0.21 to 0.93 with an average of 0.45.

In Figure 2, 11 types (patterns) of UF are shown. The UFs are grouped into four categories depending on the RP duration: 1-2, 3, 4, and more than 5 days. In each group, the type of UF is characterized by the location of the precipitation daily maximum (LMP) from the beginning of the RP in days. Next the UF was identified: the UF of the first type of the second group has identifier 2_1, the second type of the second group 2_2, and so on. The pattern of the UF for 1-day precipitation corresponds to the 2_1 type.

The influence of the variance of daily precipitation on the shape of the UF was found early by Mezencev (1979) and Kozhevnikova et al. (1984). In our case, this variance is considered by LMP. For instance, the value of the maximum ordinate ($U(t_{RP})_{max}$) of the UF whose identifier is 2_1 approximately exceeds ($U(t_{RP})_{max}$) of the UF by two times whose identifier is 2_2 (Figure 2a). For many days precipitation, the LMP frequently equals one or two. For practical purposes, the $U(t_{RP})_{max}$ of floods produced by such precipitation do not differ. The time of occurrence of $U(t_{RP})_{max}$ in days is also determined by LMP (see Figure 2a-2c). For a rainfall duration of more than five days, the time

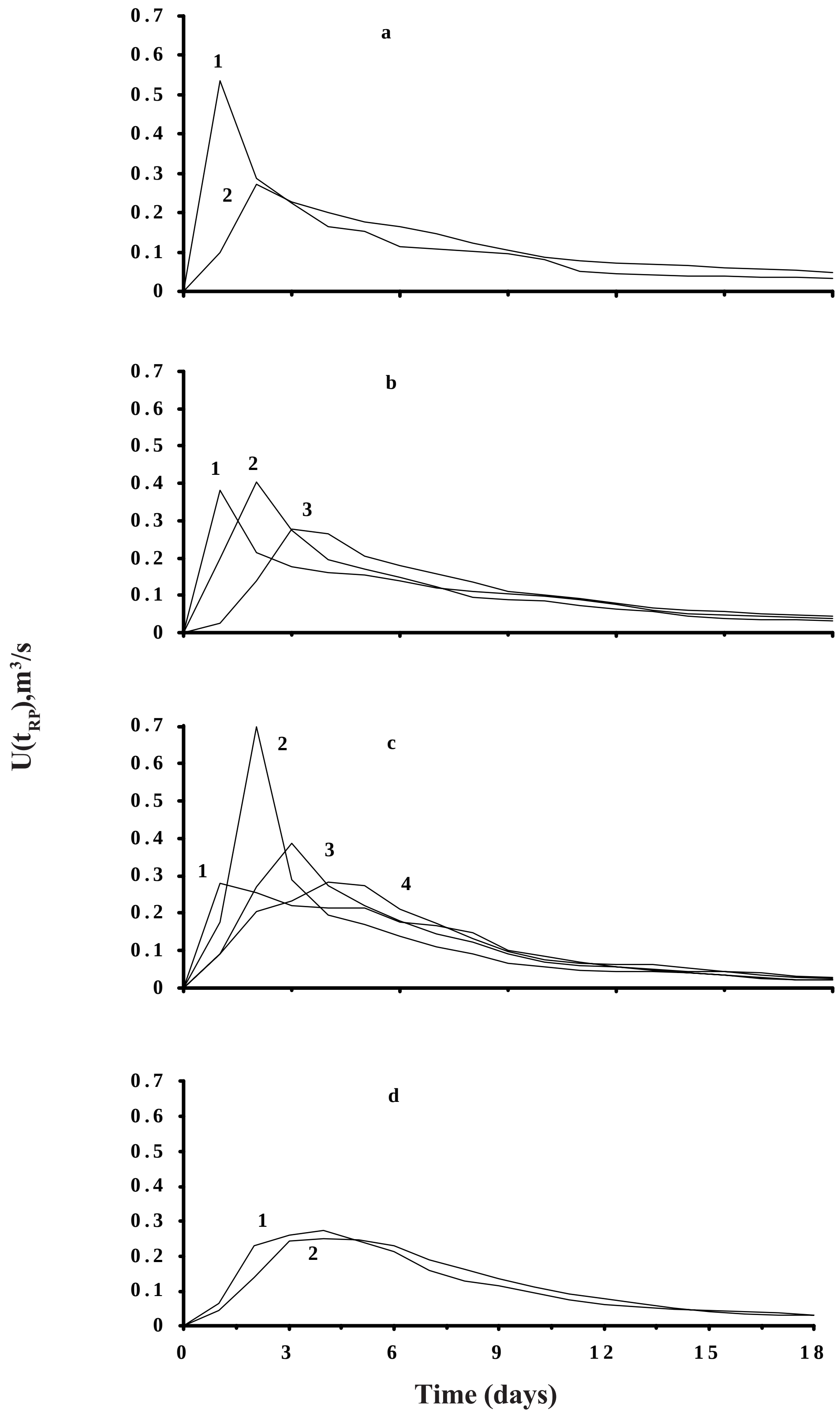

Figure 2. Ordinates of unit floods for L. S. river at Solnetchny for 1-2 (a), 3 (b), 4 (c) and more than 5 (d) days rainfall period duration. The numbers 1 to 4 mark the day number from the beginning of rainfall with the amount of maximum precipitation.

of occurrence of the maximum ordinate is not determined clearly and is equal to 4 for UF 5_1 and 4-5 for UF 5_2.

The UF duration (T) varies from 36 to 39 days respectively for the second and third groups. For the fourth and fifth groups, T also changes from type to type. The UF durations for UF 4_1, 4_2, and 4_3, 4_4 are equal to 41, 42, and 43 days and for UF 5_1, 5_2, 43 and 45 days respectively.

For runoff routing, except for patterns of UF, the total flood volumes should be predicted. The total flood volumes Q, mm (excluding flow from previous rainfall and base flow) were derived from an empirical relationship using total rainfall depths P and antecedent river flood discharge as input (Figure 3).

Figure 4 shows the predicted versus observed flood volumes. The predicted flood volumes Q_{cal} compared very well with the observed flood volumes $Q_{obs.}$ The correlation coefficient between Q_{cal} and Q_{obs} is 0.91 and the root mean square error (RMSE) is 10.6 mm.

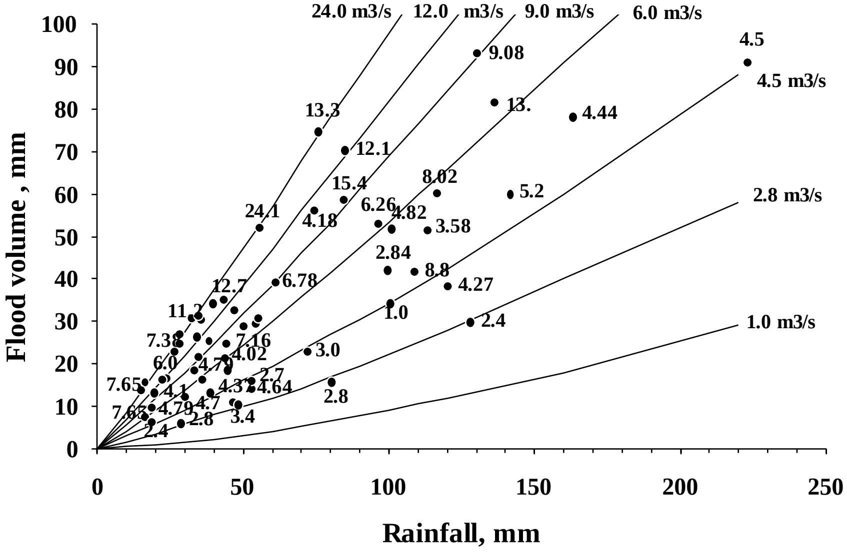

Figure 3. The flood volumes versus rainfall totals for various antecedent discharges

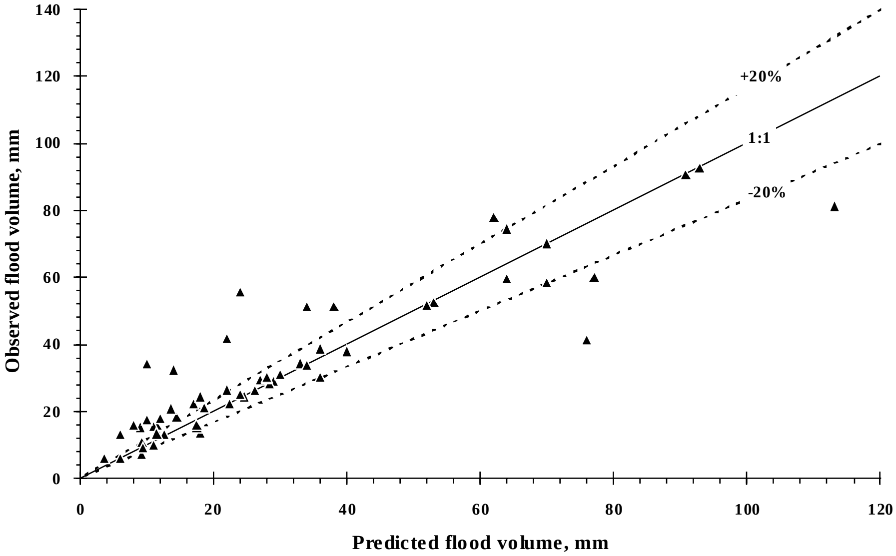

Figure 4. Predicted versus observed flood volumes.

MODEL APPLICATION

The application of the model is based on the following procedures.

1. Estimating rainfall which consists of the steps: (1) determination of the rainfall period and LMP for rainfall data of the V. Gorina station, (2) determination of rainfall totals for the Komsomolsk and V. Gorina stations, (3) using relationships between the temporary and permanent stations, the precipitation for representative rain gages P7, P8, P9 and P11 is determined, and (4) estimating the average basin rainfall is performed using weight coefficients for every rain gage. Note that Fedorovski (this issue) considered these steps.

2. Runoff routing which consists of the steps: (1) the antecedent daily river discharge derivation, (2) total flood volume determination using average basin rainfall and the relationships in Figure 3, (3) selection of the UF pattern based on the values of t_{RP} and LMP (Figure 2), (4) computing a flood hydrograph by multiplying the ordinates of the selected UF by the total flood volume, (5) total outflow is the sum of the flood hydrograph, flow from the previous flood, and base flow.

The above steps are repeated for every RP in daily rainfall observations at V. Gorina station.

MODEL PERFORMANCE

Application of the model for the L.S. basin was performed using 4 years of input data during the period of April 1, 1977 to October 31, 1980 (dependent data set) and an additional 2 years of input data (the period April 1 to October 31 for 1973 and 1976), which were not used for development of the model (independent data set). The daily discharges of L.S. river at Solnetchny and daily rainfall for Komsomolsk and V. Gorina stations were available.

The model captures the volume of stream runoff for the dependent and independent data sets with an approximate error of 11.6 and 14.3% respectively (Table 1). Figure 5 presents a sample comparison of the simulated and observed daily discharge for two warm periods (from April 1 to October 31) of 1976 and 1979. The simulation results follow the observed data and the RMSE for daily discharges for the dependent and independent data sets were 3.9 and 3.7 m^3/s respectively. The correlation coefficients between the observed and simulated data were 0.68 and 0.78 (Table 1).

Table 1. Results of Model Performance

	Dependent Data	**Independent Data**	**All Data**
		Volume of Runoff	
Error, percent	11.6	14.3	10.3
		Daily Data	
RMSE, m^3/s	3.90	3.70	3.75
Correlation coefficient	0.68	0.78	0.74
		Monthly Data	
RMSE, m^3/s	1.70	0.86	1.46
Correlation coefficient	0.92	0.88	0.90
		Monthly Maximum	
RMSE, m^3/s	7.42	2.87	7.16
Correlation coefficient	0.83	0.90	0.85

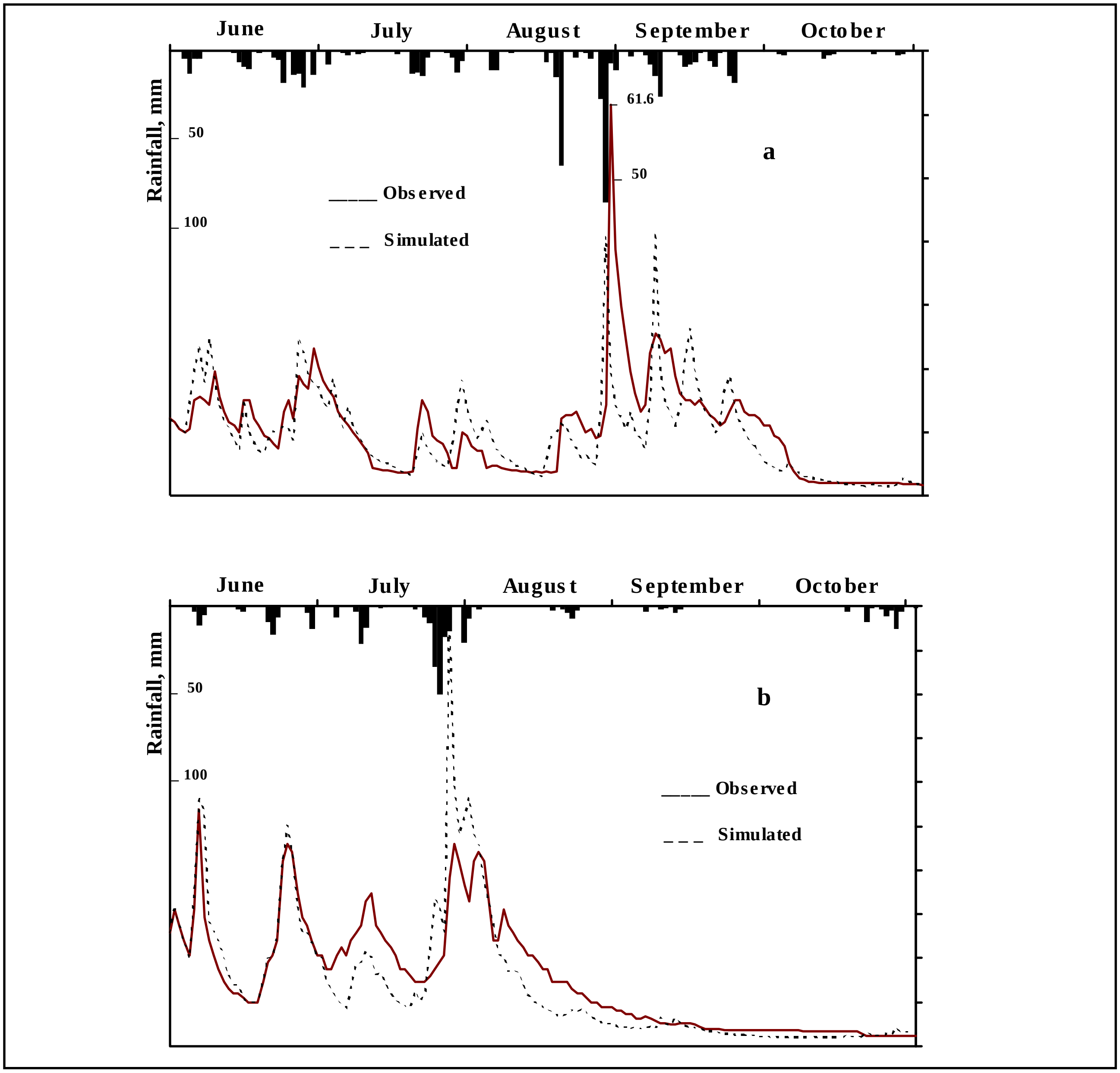

Figure 5. Comparison of simulated versus measured daily outflow in m^3/s for dependent data - 1979 (a), and independent data - 1976 (b).

In order to examine the model performance, the monthly average discharge was computed and compared with the monthly average discharge (Figure 6). The correlation coefficients between the monthly average simulated and observed discharges for the dependent and independent data sets were 0.92 and 0.88. The RMSE for the monthly average discharge were 1.70 and 0.86 m^3/s respectively for dependent and independent data sets. The simulated monthly maximum compared very well with the observed monthly maximum; the RMSE was calculated to be 7.42 and 2.87 m^3/s with a correlation coefficient of 0.83 and 0.90, respectively for the dependent and independent data sets (see Table 1).

RESULTS

The performance results of the model indicate that the model hydrological capabilities are as follows: (1) the model can capture the volume of stream runoff with an overall error of 10.3%,

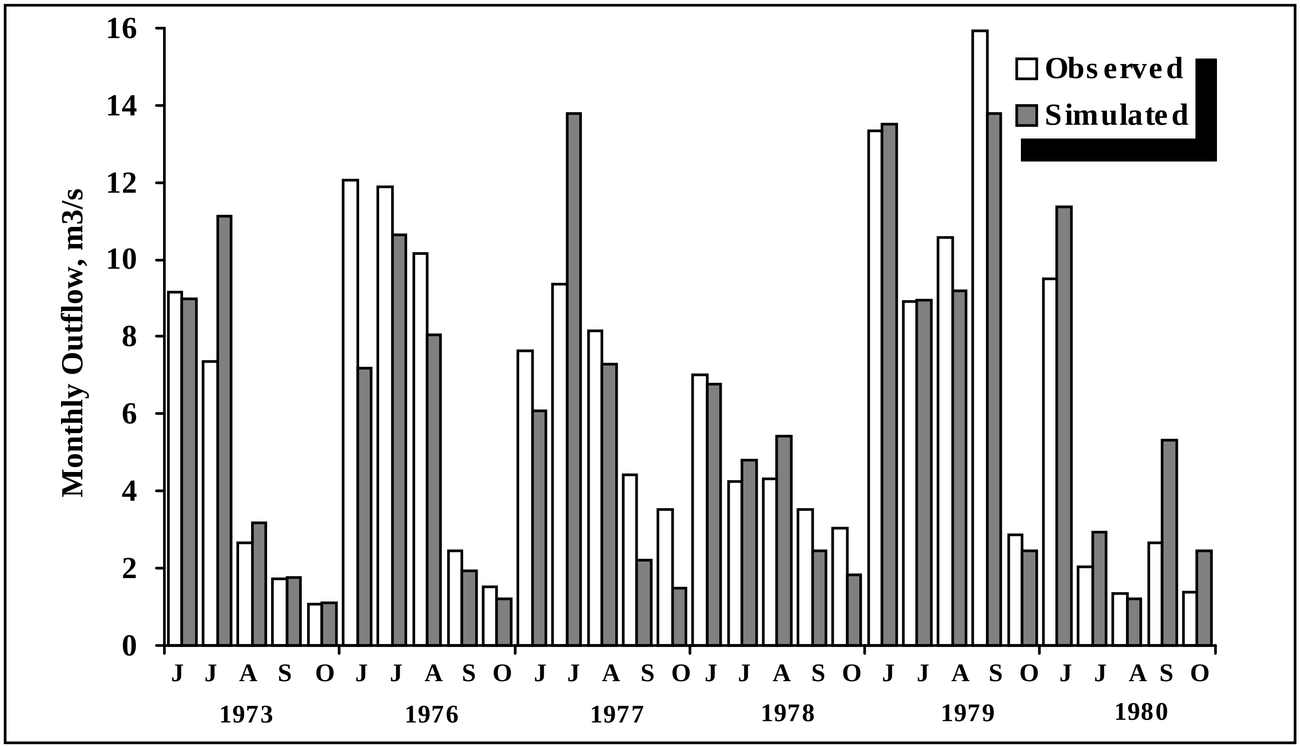

Figure 6. Comparison of monthly average simulated versus measured outflow in m^3/s for 1973-1979.

(2) the RMSE for daily discharges for all tested years equals to 3.75 m^3/s with a correlation coefficient of 0.74, (3) the RMSE for monthly mean discharges for all tested years equals 1.46 with a correlation coefficient of 0.90, and (4) the RMSE for monthly maximum discharges for all tested years was calculated to be 7.16 m^3/s with a correlation coefficient of 0.85. The model is capable of capturing the daily and monthly variability of the hydrological processes of the L.S. basin.

It should be noted that the difference between the simulated and measured discharge is added from the errors of the rainfall interpolation scheme, the prediction of the flood volume, and runoff routing. For the period of July to October, the main difference between the simulated and measured discharge is caused by the meteorological factor (Fedorovski, this issue). Sometimes the rainfall field does not cover the basin completely, and an interpolation scheme over or underestimates the average basin rainfall.

CONCLUSIONS

The need for prediction of streamflow in ungaged mountainous basins led to additional rainfall observations for a basin on the downstream Amur river. Given that rainfall data for a short period are available, a modeling approach was used to extend streamflow records in time. In order to transfer rainfall data from nearby rain gages to the basin of interest, an interpolation scheme was developed.

The transformation of rainfall excess into streamflow is based on the Generalized Flood Pattern Method (GFPM). The GFPM is based on the analysis of floods which are produced by rainfall during periods of 1-6 days. The total flood volume is derived from the daily runoff records by subtraction of flow from previous floods and base flow via recession curves. Selected floods are averaged for rainfall durations of 1, 2...6 days and ordinates of unit floods with unit flood depths of 1 mm. The UFs are grouped into four categories and 11 types (patterns).

For runoff routing, except for patterns of UF, the total flood volume is predicted. The total flood volume is derived from the empirical relationship between total rainfall depths, flood volumes and antecedent flood river discharge. The calculated flood volume compared very well with the observed flood volume with an RMSE of 10.6 mm and a correlation coefficient of 0.91.

The performance of the model shows that the model is capable of reproducing the daily and monthly variability of the hydrological processes of the L.S. basin. The difference between the simulated and measured discharge is caused by meteorological factors and will the target of further improvement of the model.

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