Estimate of Engineering Characteristics of Runoff under Conditions of Limited Data on Hydrometeorological Observations, Northeastern Russia

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Abstract

In cases where a shortage of observational data is combined with considerable environment change, the methods for estimating runoff characteristics using the statistical approach of extrapolating observational data may yield incorrect results. The deterministic-stochastic (DS) modeling approach is suggested as an alternative that combines a joint application of two models: the "Hydrograph" deterministic hydrological model and the Stochastic Weather Model (SWM). This paper presents the results of DS-modeling applied at small watersheds on the upper reaches of the Kolyma River. The observation data of the Kolyma Water Balance Station were employed in the research.

Keywords: runoff characteristics; deterministic-stochastic modeling; "Hydrograph" deterministic model; Kolyma Water Balance Station; permafrost; Stochastic Weather Model.

Introduction

The Russian Northeast might soon become one Russia's most dynamic regions in terms of economic development. In order to develop rich natural resources, it is necessary to tackle the tasks of geotechnical site investigations and construction. At the same time, the remote and difficult-to-reach Northeast represents the region of Russia that is least represented in the network of hydrometeorological observations.

Many researchers have noted signs of significant environmental changes during the past 20 years. With the shortage or even absence of observational data, the application of methods to estimate runoff characteristics based on the statistical approach of extrapolation of observational data (the Code of Rules...) may become groundless and even hazardous.

The Northeast region is in the permafrost zone, and that location represents the primary factor determining the processes of runoff formation. The change in the state of permafrost ground (for instance, periods and the depth of seasonal thawing) under the influence of climate change may significantly transform the hydrologic regime.

When historical observation data ceased to be representative, the method of deterministic-stochastic (DS) modeling seemed to be the only solution to the problem of obtaining the distribution curves of runoff characteristics for engineering purposes.

It is almost impossible to research the most complicated physical processes determined by the occurrence of permafrost without special observational data. This fact was clearly understood in the USSR, and it was the reason why the remote Kolyma Water Balance Station (KWBS) was constructed in 1948 during the difficult postwar era. All special observations were stopped at the KWBS in 1997 due to the unpopular resolution passed by officials of the Federal Service of Russia for Hydrometeorology and Environmental Monitoring. But despite this, the data of continuous observations at the KWBS collected for more than forty years still represent a unique source of material for the development and testing of hydrological models (Kuchment et al. 2000, Gusev & Nasonova 2006, Semenova 2010, Lebedeva & Semenova *in review*, Lebedeva & Semenova 2012). These data were also utilized in this research.

Deterministic-Stochastic Modeling in Hydrology

The joint application of two models form the basis of DS-modeling: the deterministic hydrological model and the stochastic weather model (SWM).

The deterministic hydrological model describes runoff formation processes at a watershed based on physical principles. The algorithms of the deterministic model represent a mathematical description of the processes of the hydrologic cycle with different degrees of detail and conceptualization.

The stochastic weather model provides meteorological input for the deterministic hydrological model. The stochastic weather model helps to generate the spatio-temporal images of the weather within a river basin.

The DS-modeling has the following operational algorithm:

1) Implementation of the deterministic model in the given basin. It includes assessment of the hydrological model parameters, modeling of runoff hydrographs, and assessment of the effectiveness of the estimates by comparing the estimate and observed runoff values.
2) Evaluation of the parameters of the stochastic weather model based either on daily meteorological observations of precipitation, temperature, and air humidity at the weather stations located in the given basin or on their estimated values.
3) Stochastic modeling of the daily meteorological data for any period of time (e.g., 100–1000 years) with the help of the SWM.
4) Modeling of runoff hydrographs for the given period of time (100–1000 years).

5) Construction of curves showing the distribution of maximum, minimum, and other runoff characteristics for the given period of time (100–1000 years).

Thus the DS modeling output may have an unlimited series of hydrological data that allow the determination of all the necessary characteristics of the annual, maximum, and minimum runoffs.

The Deterministic "Hydrograph" Model

The deterministic "Hydrograph" hydrological model represents a mathematical system with distributed parameters. It describes runoff formation processes in basins with various physical and geographical characteristics. It was developed under the guidance of Professor Yu.B. Vinogradov. The structure and contents of the "Hydrograph" model are thoroughly described in a monograph by Vinogradov (1988) and in a textbook by Vinogradov & Vinogradova (2010).

The "Hydrograph" model describes all the processes of runoff formation that form the above-ground hydrologic cycle. A diagram of the model is presented in Figure 1.

The network meteorological information, which is composed of the daily values of air temperature, air humidity deficit, and precipitation layer, is used as meteorological input to the model.

The main parameters of the model are the physical properties of the landscapes that may be observed in nature and are classified according to the types of soil, vegetation, and other characteristics. They also may be modified in case of changes in the properties of the basin's landscape. This means that the same sets of model parameters may be applied to estimate the runoff for different basins located within the same landscape and climatic zone. Without hydrological observation data, the parameters are evaluated based on information about the physical and geographical conditions of the basin.

To evaluate the parameters within an investigated basin, researchers single out homogeneous geographical zones called runoff elements (runoff formation complexes) according to which model parameters are systematized. Besides, the entire area of the basin is covered with a hexagonal grid the points of which are the representative points of the established unit area. Such characteristics as height, inclination, slope aspect, and the type of the dominant runoff element are determined for each representative point.

In the process of deterministic modeling, the observed meteorological information is interpolated into a representative point, while during the DS-modeling it is generated by the SWM.

Runoff formation processes are modeled for each representative point. The obtained runoff values are further translated into the basin outlet according to the time lag established for each representative point.

The "Hydrograph" model solves the problem of the heat and moisture dynamics in a soil column, which is absolutely necessary when utilizing it in permafrost areas. The soil is divided by depth into a certain number (3–20) of estimated layers (ESLs) that are normally, but not necessarily, identical and equal to 0.1 m. The model parameters are distributed both vertically (soil column) and horizontally (system of representative points).

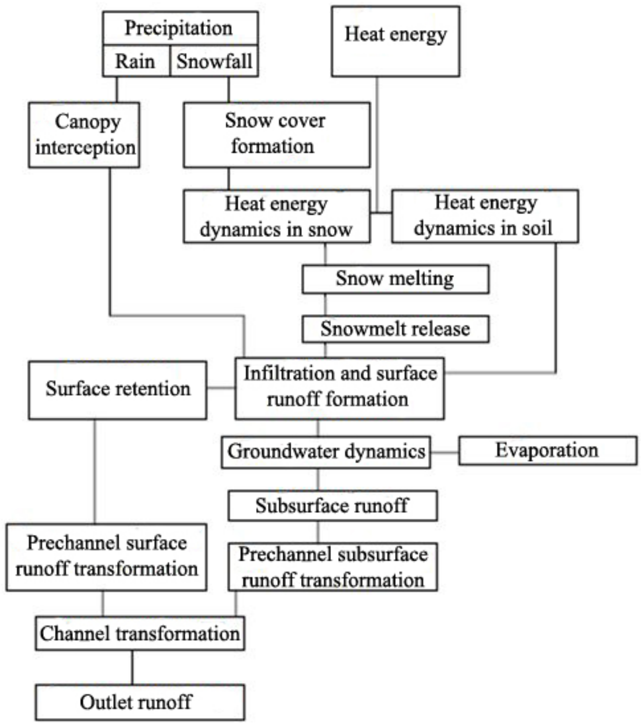

Figure 1. Diagram of the "Hydrograph" model.

The energy and moisture balance is calculated for each ESL within the estimated time interval (i.e., the temperature and moisture of the ESL as well as its thawing and freezing depths). The example estimates of active layer dynamics for the various KWBS landscapes and the comparison of their results with the observed data may be found in the publication by Lebedeva & Semenova (2012).

The "Hydrograph" model considers the heterogeneous distribution of the snow cover on the basin's territory as well as the inclination influence on many hydrometeorological processes.

The model output is the continuous runoff hydrograph in the outlet for a necessary number of years. At the same time, the variable states of soil and of snow cover are estimated.

The results of the "Hydrograph" model application both to runoff hydrograph estimates and to estimates of the variable states of snow cover and soil in the permafrost area of Russia (Semenova & Vinogradova 2009, Semenova 2010, Vinogradov et al. 2011, Lebedeva & Semenova *in review*) and of Canada (Pomeroy et al. 2009) indicate that, on the one hand, this model describes runoff formation processes thoroughly enough, while, on the other hand, it has the robust algorithm and the possibility to assess its parameters based on data about the physical and geographical conditions of a basin.

The Stochastic Weather Model

The stochastic weather model was developed by a group of researchers under the guidance of Professor Yu.B. Vinogradov (Vinogradov 1988, Vinogradov & Vinogradova 2010).

The model makes it possible to generate daily meteorological values at the given regular points of a basin both as reproduction of data that do not differ from the

Table 1. Characteristics of the small watersheds.

No	River - discharge site	Basin area, km²	Mean multi-year water discharge, m³/s	Number of representative points	Distance between representative points, km	Mean elevation, m	Number of weather stations (including those within the basin)
1	Ayan-Yuryakh - Emtegey	9560	62	15	29	1140	2(0)
2	Debin - Beliche	3460	30	9	23	880	4(0)
3	Detrin - the mouyh of the Vakkhanka River	5630	47	15	22	920	6(2)
4	Tenke - at 2.2 km above the mouth of the Nilkoba River	1820	21	10	16	930	3(0)

historically observed ones and with artificially determined parameters (e.g., when estimating the runoff under the conditions of a predicted climate change).

The temporal and spatial correlations of the meteorological values as well as their intra-year flow are taken into account in the course of the estimates.

The parameters of the stochastic weather model are evaluated based on the observed series of daily meteorological information of weather stations and, further, they are interpolated into representative points. It is assumed that reliable assessment of the model's parameters requires not less than 25–30 years of observational data.

The system of the model's parameters is conditionally divided into three large groups: annual and daily parameters as well as the parameters of spatial correlation.

The stochastic weather model makes it possible to estimate the extreme values of the meteorological variables that were not monitored during the observational period.

Research Area

Four small basins were selected in the upper reaches of the Kolyma River for the research objectives. Their geographical locations and major characteristics are presented in Figure 1 and Table 1.

The investigated territory is found within the region of the Kolyma Water Balance Station. A brief description of the physical and geographical conditions of the investigated area may be found in Lebedeva & Semenova (2012).

Results of Deterministic Runoff Modeling

The "Hydrograph" model parameters were assessed and corrected based on the KWBS observational data in three stages (Lebedeva & Semenova 2012).

During the first stage, three major types of landscapes were singled out at the KWBS (stone talus [golets], tundra open woodland, and swamp larch open woodland). These are located with certain dependency on the elevation and the slope aspect. The values of the model parameters for each runoff element determined on the basis of the properties of the dominant soil and vegetation types were made more accurate in the course of the modeling of active layer formation.

The runoff hydrographs for the small watersheds of the KWBS were modeled based on more accurate parameters.

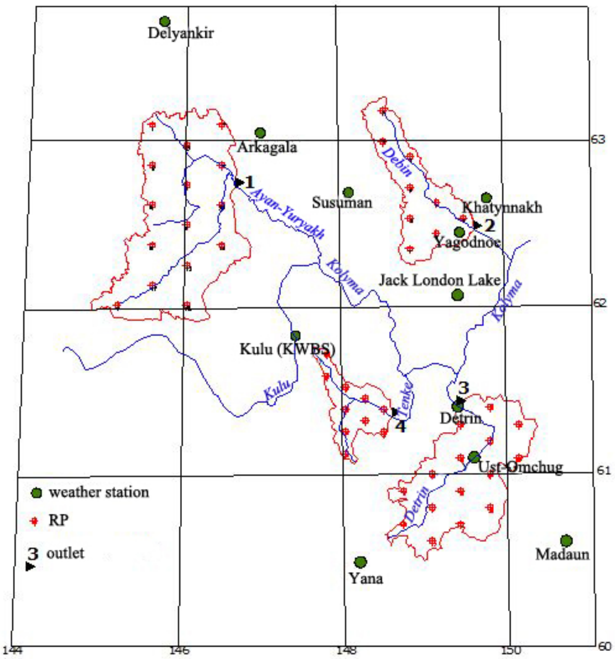

Figure 2. Map of small watersheds in the area of the upper Kolyma with the representative points and weather stations.

The results produced by modeling of both the soil variable states and runoff hydrographs at the KWBS were acknowledged as satisfactory. For this reason, the listed runoff elements were singled out in the larger investigated basins with the same dependency on the elevation and aspect of the locality. The values of the model parameters corresponding to them were accepted.

The runoff hydrographs with the daily estimated interval were modeled for the period of 1977–1984 for four mountain watersheds located within the continuous permafrost zone of the Kolyma River basin. The statistical analysis of the modeling results is presented in Table 2, while the example of the visual comparison of the estimated and observed runoff hydrographs is shown in Figure 3.

The investigated region has a complex orographical structure that exerts a considerable impact on the precipitation distribution. For this reason, the data given by the weather stations located outside the examined basins (Table 1) often turn out to be unrepresentative, despite the

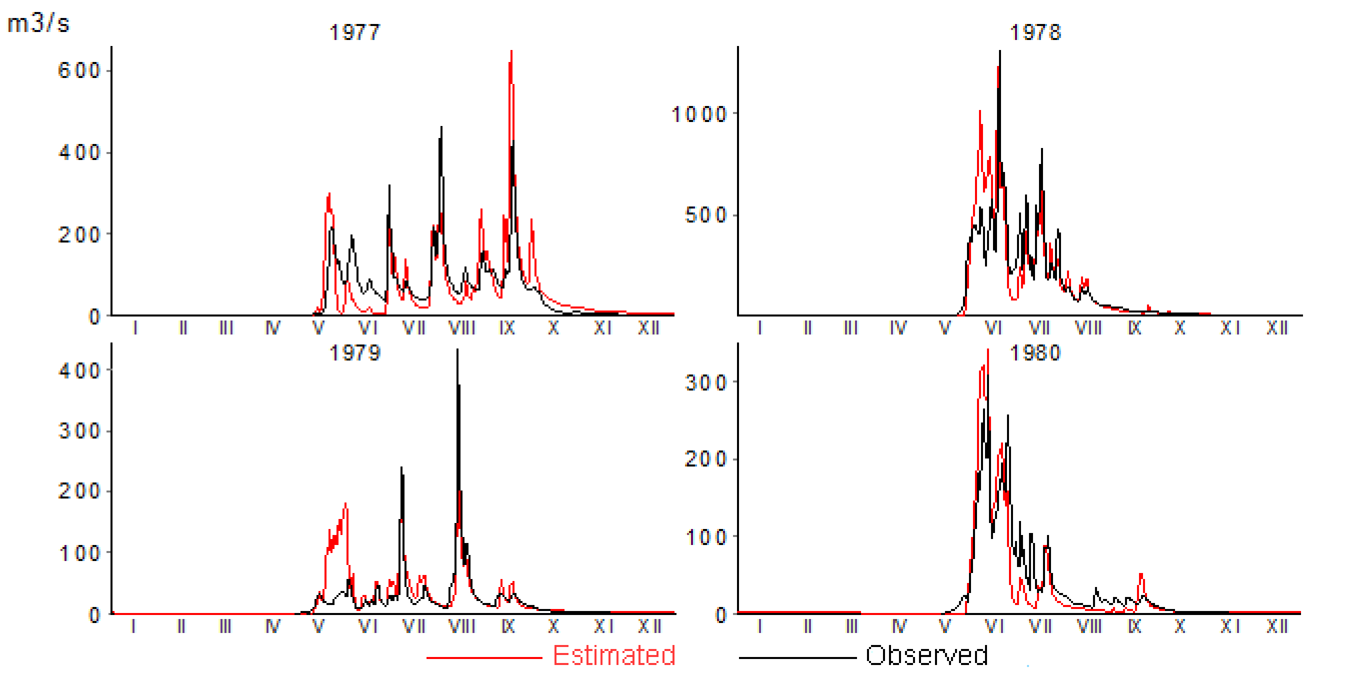

Figure 3. The estimated and observed runoff hydrographs in the upper reaches of the Kolyma basin (1977–1978: the Detrin River, the mouth of the Vakkhanka River; 1979–1980: the Tenke River, 2.2 km from the mouth of the Nilkoba River).

seeming proximity. For instance, there is not a single weather station in the Ayan-Yuryakh River basin (the basin with an area of 9560 km^2). All the estimates were made based on the Kulu and Arkagala weather stations. In addition to the fact that both weather stations are considerably remote from the watershed, they are also separated by ridges and located at leeward slopes. The authors assume that the deviations of the estimated runoff values from the observed ones are mostly explained by the problem of precipitation interpolation in mountain conditions.

As Table 2 shows, after the modeling the estimated maxima of water discharge are slightly higher than the observed ones. This is presumably explained by the overestimated contribution of the surface component to runoff hydrograph formation linked with the underestimated volume of water infiltration into the ground. The estimated and the observed mean runoff layers are in good agreement with each other. In general, the results produced by the deterministic runoff modeling may be regarded as satisfactory, especially where there is a shortage of meteorological data and where only general information on the physical and geographical conditions of the examined areas is present.

Assessment of Runoff Characteristics with Limited Data or Unrepresentativeness

The main task of hydrology in engineering and construction design is to estimate such runoff characteristics as maximum and minimum discharge and volumes of floods with the given probability. The Code of Rules (CR) SP-33-101-2003 (2004) is currently the only instrument officially accepted in Russia that is designed to make such estimates. The Code's methodology employs various extrapolation techniques of the observed series of data to the specified values of runoff probability. It is proposed to use basin-

Table 2. Statistical criteria of runoff modeling results at the watersheds of the upper reaches of the Kolyma River, 1977–1984.

Basin (river - discharge site)	Q1	Q2	V1	V2
Ayan-Yuryakh - Emtegey	878	1054	234	232
Debin - Beliche	386	412	301	309
Detrin - the mouth of the Vakkhanka River	688	740	296	318
Tenke - at 2.2 km above the mouth of the Nilkoba River	248	291	267	311

Q1 and Q2 - the mean observed (1) and the mean estimated (2) maximum water discharge (m^3/s); V1 and V2 - the mean observed (1) and the mean estimated (2) runoff layers (mm).

analogs when no observational data are available or when their number is insufficient.

The quality of the hydrometeorological data provided for the country decreased rapidly over the last 20 years. The historical observational series does not reflect the ongoing changes in the hydrologic regime, which relates more to permafrost areas. Besides, there is no tested method of incorporating environmental change (climate and landscape) predictions into hydrological estimates.

The estimated data series formed the basis for the creation of the distribution curves of maximum water discharge in the investigated basins.

As an illustration, three curves characterizing the distribution of maximum water discharge in the Tenke River basin are shown in Figure 4. This basin has the longest data series (53 years) among all the investigated basins.

Thus Curve 1 reflects the observed values, Curve 2 reflects the estimated values of maximum water discharge for the period of 1977–1984 according to the available

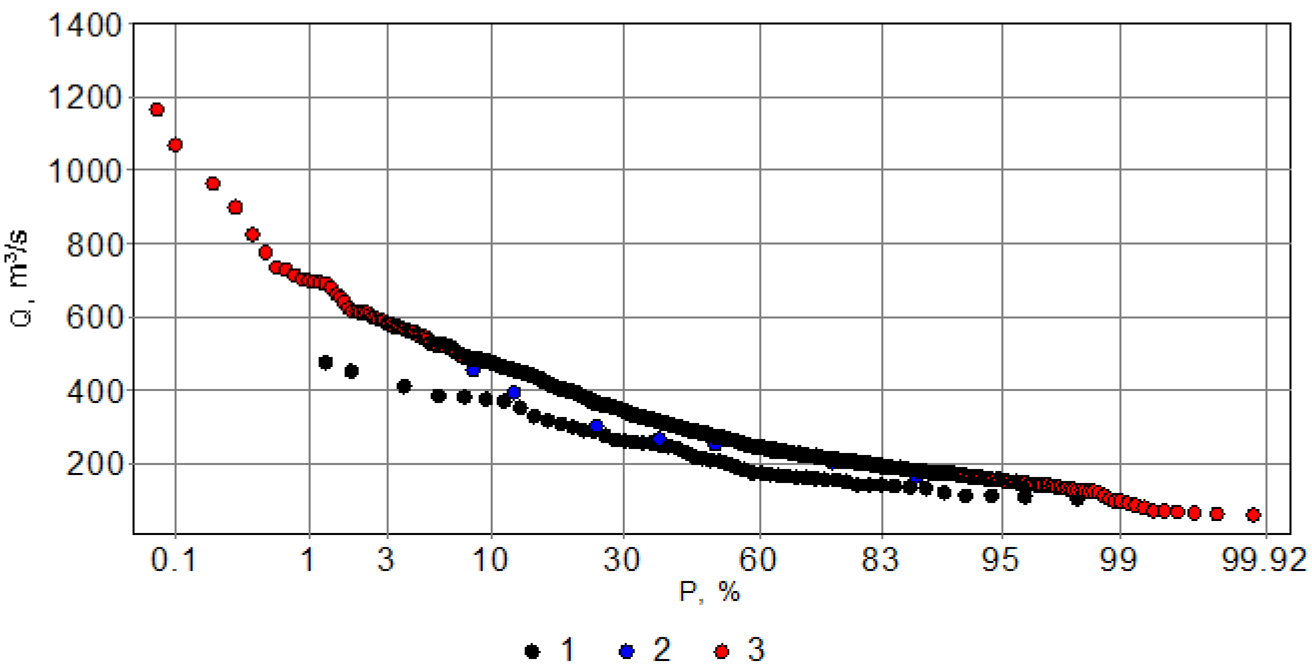

Figure 4. The curves of distribution of the estimated and the observed maximum water discharge (m^3/s) in the Tenke River basin, 2.2 km from the mouth of the Nilkoba River (1, 2, 3 - see text).

historical data of meteorological observations, and Curve 3 characterizes the 1000-year-long series obtained on the basis of DS-modeling. As Figure 4 shows, there is a slight overestimation of the calculated water discharge in comparison with the observed values. However, in general, all three curves correspond to each another.

It should be noted that Figure 4 shows the results of the estimates made on the basis of historical data (i.e., the generated series of meteorological data have the same parameters as the historical observation series). However, a researcher may be faced with a task of evaluation of runoff characteristics under the predicted climate or landscape changes. In the first case, the parameters of the stochastic weather model may be modified according to the predicted climate changes. If landscape changes that may entail a considerable transformation of the hydrologic regime (e.g., forest fires) are expected or probable, the specification of the deterministic "Hydrograph" model parameters makes it possible to consider such cases.

Conclusions

It is necessary to note that Semenova (2009) demonstrated the effectiveness of the application of the DS-modeling method in runoff estimates for small watersheds located in various physical and geographical zones of Russia. The present report demonstrates the DS-modeling results for the basins located in the permafrost zone.

It is shown that the application of the DS-modeling method is possible if there are two models available. The deterministic runoff formation model (such as "Hydrograph") must possess an adequate description of hydrological processes, while its parameters must have a physical meaning. A stochastic weather model (such as the SWM) must, on the one hand, consider the entire complexity of meteorological processes (e.g., the temporal and spatial correlation of meteorological variables) and, on the other hand, be universal in application.

In modern conditions, when the historical series of observation data ceases to be representative due to ongoing environmental changes, DS-modeling becomes the only possible solution to the problem of obtaining curves of runoff characteristics distribution for engineering purposes.

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