SPACE CHARACTERS OF RUNOFF FORMATION

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Contents

Summary

The paper describes space specific features of runoff formation and methods for their descriptions. River runoff is a space characteristic because it is formed on the whole watershed. Runoff formation is contributed by two basic groups of factors, i.e. meteorological factors (precipitation, evaporation, etc.) and the factors of the underlying surface. The factors of the first group produce river runoff; the factors of the second group affect its motion over the watershed to the study outlet. Each group of factors, runoff included, are characterized by two main space specific features, i.e. zonality and azonality. The zonality is related with a regular change in the factors and in runoff in latitudinal and altitudinal directions; azonality is related with the effect of the local factors. Principal classifications of river runoff formation in space are discussed (classifications of Voejkov, Zaikov and Lvovich). Different methods for a description of space specific features of runoff and runoff factors are considered, which involve two principal methods for a space presentation of these factors as a continuous field and a discrete homogeneous region and a selection of basic types of models, i.e. deterministic, deterministic-stochastic and stochastic models. Methods are given for making deterministic space models with the help of interpolation, and for making deterministic-stochastic models with the help of space correlation functions and linear space-time regression dependences. Principal ways of plotting regional dependences in homogeneous regions are shown, i.e. generalization of model parameters obtained for each watershed, and plotting territory-common dependences upon the factors of the underlying surface. New updated types of information are considered for the assessment of space specific features of runoff formation, i.e. airborn and satellite surveys and electronic maps. In conclusion, a description of the GIS is given for a hydrological mapping as the most perspective methodology for a generalization of various types of information in a geographic space.

1. Introduction

River runoff is formed in watersheds, which can be conventionally subdivided into small, mid-sized and large. Two basic groups of factors, i.e. meteorological factors and those of the underlying surface of the watershed, explain runoff formation. Meteorological factors (precipitation, air temperature, air humidity deficit, etc.) are external conditions and characterise a possibility of runoff origin, its potential volume and dynamics. Factors of the underlying surface (hydrographic network, slopes, soils, plants, karst, different types of anthropogenic activity, etc.) serve as a function of external conditions transformation and explain the migration and redistribution of precipitation and snow melting in the watershed.

Two types of a geographical zonality (latitudinal and altitudinal) are distinguished for meteorological factors and for most factors of the underlying surface. The latitudinal zonality is revealed in a regular change of runoff formation factors from north to south. For example, air temperature in the north is lower than that in the south; evaporation tends to be higher southward; soil types and vegetation also tend to change in the latitudinal direction.

Altitudinal zonality or altitudinal belts is expressed in the change of practically all the factors of runoff formation, including precipitation, air temperature, etc., according to the altitudinal zones of mountain areas. Zonality is revealed both in the streamflow distribution during a year and in the generalized long-term characteristics and parameters (mean annual runoff, its variability, etc.). Azonality is the second basic feature mainly typical of the factors of the underlying surface; it is displayed in deviations from the specific features of the zonal distribution of the hydrological characteristics.

Ratio between zonal and azonal factors mainly depends on the drainage area and its location. The less the drainage area, the greater the effect of the azonal factors. In accordance with the zonality and azonality features, watersheds are subdivided into azonal, zonal and interzonal. Interzonal watersheds are characterized by a manifestation of several geographic zones and are related to very large watersheds. The values of the critical drainage areas subdividing these three categories depend on the study hydrological characteristic, time interval of its generalization, and location of the watershed. If the hydrological characteristic is expressed as a specific runoff (normalization per drainage area), the most visual subdivision into azonal, zonal and interzonal watersheds may be presented by a reduction dependence of specific discharge upon drainage area.

2. Principal Classifications of River Runoff Formation and Their Space Presentation

There are several classifications of rivers in hydrology: according to water availability in rivers, according to streamflow distribution during a year, according to the sources of river recharge, river lengths, stability of channels, water temperatures, ice regime, chemical composition, etc. All hydrological classifications are aimed at a systematization of all the variety of conditions of runoff formation into several categories and to determine the regions appropriate for these categories in the country, continent, or in the world. The classification of runoff formation factors is displayed most visually in water availability variations during a year.

Classification of the most rivers made by A.I.Voejkov on the basis of the nature of water availability variations during a year depending on climate conditions is one of the earliest ones. The following river types are distinguished in this classification:

- rivers recharged by snow melting in the plains and low mountains (to 1000 m);
- rivers recharged by snow melting in mountains;
- rivers recharged by rains and having snowmelt floods in summer time;
- rivers with snowmelt floods in spring and early in summer with much liquid precipitation during snowmelt flood;
- rivers recharged by rains without any difference in the flood regime in different seasons of the year;
- rivers recharged by rains with a great difference between a wet winter season and dry summer season;
- absence of rivers and permanent streams because of a dry climate;
- rivers recharged by rains of short durations;
- absence of rivers because of the area coverage by snow and glaciers.

Classification of B.D.Zaikov is based on a systematization of streamflow regime during a year and it was developed only for the territory of the former Soviet Union (FSU). It involves three main groups of rivers, i.e. rivers with spring snowmelt floods, rivers with snowmelt floods during the warm season and rivers with rainfall floods.

One more runoff classification has been developed by M.I.Lvovich, it is based on the sources of recharge and conditions of runoff formation during a year. According to the sources of recharge (snowmelt, rainfall, glacial and subsurface), the rivers are subdivided into the rivers with mixed recharge (if the portion of each source is less than 50%), with predominance of some particular type of the source (if its contribution exceeds 50%) and a complete recharge of the specified type (if its contribution exceeds 80%).

3. Methods for Description of Space Runoff Specific Features and Factors

3.1. Basic Methods for Runoff Characteristics and Factors Presentation in the Geographic Space

The considered features of zonality and azonality as well as runoff classifications according to the specific features of runoff formation characterize two basic methods of runoff presentation in the geographic space, i.e. as a continuous field and as a discrete homogeneous region. This presentation is valid only in case of a sufficient generalization of runoff in time much longer than the lag time in the river channel.

Two fundamentally different methods of runoff description seem to be contradictory at the first sight; in fact, they reflect different features of the fields for a restricted space. It is evident, that if the territory is big enough or if watersheds are large, the features of the geographical zonality are revealed and a monotonous change in the hydrological characteristic or runoff parameters occurs. Moreover, any deviation from a monotonous structure of the field presented (e.g. isolines) is very small if compared with the gradient of the change. The second method of presentation as a homogeneous region is valid when some space laws are missing and the field is random. In this case it may be expressed by several parameters, which would be characteristic of the study territory. A homogeneous region where a hydrological characteristic is practically unchangeable and may be presented as a mean value can be considered as a special case. Here random deviations from space mean value are insignificant and they depend on the errors of the basic data and on the effect of insignificant local factors. In the rest cases the field description requires not only mean value but the use of other parameters, such as variability or the whole space distribution function.

Space features presentation as a field is characteristic of the conditions of zonal factors predominance in runoff formation; if azonal factors prevail the space features may be presented as a homogeneous region. In fact, both factors occur simultaneously, but the ratios of these factors may be different.

3.2. Basic Types of Models for a Description of Space Fields of Runoff Characteristics and Factors

To choose any mathematical facility for a description of the space features of runoff and runoff factors it is necessary to estimate to what particular model (out of three) classes the space field may be referred to, i.e. deterministic, deterministic-stochastic and stochastic. In general, the hydrological information is that at a point; it refers to observation points and on the basis of point data it is necessary to get the space situation. A reliability of determining the type of the field structure depends on its complexity, size of the territory, number of observation points and data errors.

It is evident that at the initial stage it is necessary to determine if there is any general change in the space of the study hydrological characteristic or the data are statistically homogeneous. To this end, statistical criteria of homogeneity estimation and classification methods are often applied in hydrology. Depending on the fact homogeneity of what characteristic is to be estimated the appropriate criterion is used. For example, the Student's criterion is used to estimate homogeneity of mean values of two samplings; Fisher criterion is used to estimate homogeneity of variances, etc. When classification methods are used, regions or classes are usually selected on the basis of some feature (e.g., the longest Euclidean distance between two adjacent space points); then homogeneity of classes is estimated from sampling parameters (mean values, variance, etc.). Parametric criteria for the estimation of homogeneity have been developed mainly for noncorrelated samplings from a symmetric normal distribution. Runoff characteristic, however, and runoff producing factors are correlated in space (because hydrometeorological events are space interrelated) and in time, and they have an asymmetric distribution law. If intraseries interrelation is neglected, the homogeneity hypothesis would be rejected more often than it happens in reality; if intraserial correlation is neglected the homogeneity hypothesis would be accepted too often; meanwhile data should differ. Therefore, well-known statistical criteria of homogeneity estimation (criteria of Student, Fisher, Smirnov-Grabbs, Dixon, Kolmogorov-Smirnov, etc.) have been generalized with the account of specific features of the hydrological information.

If the assessment by criteria shows that space statistical data do not differ and the existing difference is related only with the errors explained by a restricted volume of data and with the errors of measurements the field is homogeneous and its described by one mean value. In other cases the following kinds of models are applied to describe the space field.

A). Deterministic model, if the hydrological characteristic or its factors at any space point may be estimated from isolines with the error compatible with the error of measurements or random sampling error (if data plotted on the map are obtained from a generalization in time). The deterministic dependence may be illustrated by a map of isolines of runoff, air temperature in homogeneous mountain regions where there are reliable dependences of these characteristics upon locality elevation and isolines plotted with the account of elevation make it possible to consider the value quite reliably.

B). Deterministic-stochastic model is applied if the error obtained during the description with the use of isolines exceeds the error of measurements or random sampling error. Isolines for the territory with a significant effect of azonal factors (e.g., karst, man's impact, etc.) may be considered as this model. These factors lead to high errors if only isolines corresponding to the geographic zonality are used. Therefore, isolines are used to describe the zonal component (deterministic part of the model), meanwhile the effect of random azonal factors is described, e.g., in the form of parameters of the space distribution function (stochastic part of the model).

C). In some cases it is impossible to plot isolines because the field structure is very complicated and mosaic. But the established difference in the mapped values is significant. A stochastic model is used to describe this field structure; this model is a space distribution function. It may be illustrated by the distribution function of soil moisture content, maximum water equivalent of snow pack, which have a complicated and mosaic structure in space.

3.3. Methods for Deterministic Space Models Preparation

Deterministic field structure is usually presented in space as isolines, i.e. lines connecting points with equal values. Hydrometeorological observation points are distributed in space irregularly and distances between these points may be long enough. Therefore, isolines are plotted by means of interpolation or irregular data to the nodes of a regular grid with a step sufficient to get isolines of the required discreteness. In general, the following interpolation methods are applied: polynomial interpolation, linear cubic, bi-cubic, point interpolation, windows, different types of spline interpolation, etc.

3.3.1. Polynomial Interpolation

The general equation for polynomials is:

$$\hat{f}(x) = \sum_{i-0}^{v} c_i x^i \quad (1)$$

where c_i are the polynomial coefficients and v is the degree of order.

The degree or order of the polynomial is determined by exponent ***i***, thus a first polynomial is simply:

$$f(x) = c_0 + c_1 x \quad (2)$$

$$\hat{f}(x, y) = \sum_{i=0}^{v} \sum_{j=0}^{\mu} c_{ij} x^i y^j \quad (3)$$

The bi-variate expressions generally take the following form:

first order: $f(x,y) = c_0 + c_1 x + c_2 y$, second order: $f(x,y) = c_0 + c_1 x + c_2 y + c_3 x^2 + c_4 xy + c_5 y^2$ and so on.

A first order polynomial is an inclined plane, a second order is a surface with one slope reversal, a third order with two reversals, etc. There are two different fitting by the polynomial: exact fit and least squares fit or smoothing. In the first case many equations must be solved if the degree of the polynomial is high. The coefficients are obtained by solving the linear system. This is not practical and therefore the data set is partitioned in pieces so that lower order curves can be fitted to fewer points. In the second case a polynomial may be fitted is not exact, but some computation problems of the first approach are solved by this way.

3.3.2. Linear Interpolation

The linear interpolation is a piecewise first order polynomial, whereby the knots coincide with the reference points. The interpolation formula for the interval $[x_l, x_{l+1}]$ is:

$$\hat{f}(x) = f_l - \frac{f_{l+1} - f_l}{x_{l+1} - x_l} x_l + \frac{f_{l+1} - f_l}{x_{l+1} - x_l} x \qquad (4)$$

This interpolation is perhaps the most widely used, because of its simplicity. The way two-dimensional linear interpolation is performed depends on whether the points are in a regular grid or not. For irregular networks, triangles are used, known as TIN (Triangulated Irregular Network) and the Delaunay distance criterion is added. The linear grid interpolation is known as the bi-linear method. The most popular method of the interpolation in hydrometeorology as the nearest neighbour or Thiessen polygons method too. This method is also known as Voronoi tessellation, Dirichlet cells or proximal mapping. It is commonly used for determination areal rainfall but also for other applications. The rationale of the method is that, by absence of the other information, the best estimate is the observed value at the nearest proximal distance or the nearest Euclidean neighbour, as described by:

$$d_{min} = \sqrt{(x_0 - x_j)^2 + (y_0 - y_j)^2} \qquad (5)$$

where d_{min} is the minimum distance between any point (x_0,y_0) and observation station $(j=k,1,\ldots,P)$.

Within the resulting polygon, the weight w_j=1 a zero order polynomial. The Thiessen weights (W_t), for the calculation of any areal characteristic (rainfall, for example) in a catchment are:

$$Wt_j = At_j / Ac\,, \qquad (6)$$

where *Ac* is the catchment area and *At* is the Thiessen polygon area within the catchment perimeter of each station *j*, *k*, etc.

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Biographical Sketches

Anatoly V. Rozhdestvensky

Professor, Doctor of Technical Sciences, was born in 1933. Finished Russian State Hydrometeorological University in 1958. Defended of Ph.D thesis in 1967 and thesis on degree of Doctor of Technical Sciences in 1977. Published more than 90 scientific works, including 9 books, 11 recommendations, guidebooks and textbooks. The basic directions of scientific researches in the field of hydrological computations and application of methods of mathematical statistics, theory of stochastic functions and probable processes in a hydrology. The large attention is given to an estimation of accuracy and reliability of hydrological computation. Many developed methods have been introduced into the practice of water projects design. Took part the large participation in the international cooperation - was the member and chairman of several working groups of UNESCO therefore some international documents generalizing experience of many countries of the World in the field of hydrological computations for water projects design were issued by UNESCO. Took part in many international conferences, symposiums, seminars and other scientific events.

Vladimir A. Lobanov

Doctor of Technical Sciences, was born in 1956. Field of specialisation: theory and new methods of hydrological computations for water projects in changing conditions, stochastic time-space modelling of hydrological and climatologic long-term time series, forecasting, development of statistical methods for hydrology, extreme hydrological events, including floods and droughts, regional models and other aspects of applied hydrometeorology. Finished Russian State Hydrometeorological University in 1978. In period 1978-1980 worked as research worker in Hydrological Data Centre of State Institute of Hydrometeorological Information – World Data Centre, Obninsk city. Carried out software for hydrological data bases. In 1980-1983 was a Ph.D. student in State Hydrological Institute, St. Petersburg. Contributed towards development of methodology and methods for application of statistical criteria and regression analysis. Defended of Ph.D. thesis “Statistical criteria and regression in hydrological computations”. From 1983 worked in different departments of State Hydrological Institute: hydrometry, runoff computations, remote sensing and GIS as a senior scientist and leading scientist. Coordinated and carried out a number of the projects, including international ones, related with development of new methods for river hydrometry, hydrological computations, forecasting, processing of remote sensing data. In the period 1993-1996 was at the post Ph.D. courses and defended the thesis "Hydrological computations in non-homogeneous – non-stationary conditions" on degree of Doctor of Technical Sciences. Published about 100 scientific works, including monographs, recommendations, reports. Took part in many international scientific conferences, symposiums, congresses.