Journal of Engineering and Applied Sciences 9 (7): 268-272, 2014
ISSN: 1816-949X

Evaluation of Spatial Uniformity of Hydrological Characteristics

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Abstract: In this study, the method of estimating the spatial uniformity of hydrological characteristics and the subsequent zoning of the studied territory by means of GIS applications are described. A new algorithm is proposed for estimating the uniformity of spatially distributed data depending on the differentiation of spatial-correlation functions of the studied characteristics. Mathematical calculation algorithm was implemented using object-oriented C++ programming language. Prospects of researches in the creation of information model of the territory, reflecting the spatial structure, the status and relationships between its separate elements with the purpose of optimization of nature management and making decisions about the management of natural objects are outlined.

Key words: Spatial uniformity, hydrological characteristics, mathematical algorithm, statistical analysis, hydrological zoning, GIS technology

INTRODUCTION

The process of modeling of a spatial structure of various natural systems is complex and requires joint consideration of a great number of very diverse factors. For example in hydrology, the study of spatial structure of river run-off has both scientific and practical importance in solving problems related to the evaluation of spatial interpolation of run-offs and the sound management and conservation of natural resources (Pivovarova, 2012). According to leading experts, the water crisis seen in many countries in recent decades is related not only with climate change but also with unsustainable economic activities within catchment area (UNESCO, 2011). Hydrological zoning allows identification of areas which are uniform in terms of physical-geographical and hydrological conditions within which correct generalization is possible of the basic characteristics of water regime and their extrapolation to the hydrologic samples obtained on relatively sparse and not always sufficient river flow observation network. The hydrological analogy method is particularly relevant for the practice of engineering calculations to restore historical series of observations having periods where measurements of hydrological characteristics were not performed for various reasons. However in practice, it is difficult to find a basin-analogy and in such cases the data are simply taken from one of the closest stream-gauging stations and often without sufficient justification. To avoid such situations, clear spatial uniformity criteria are needed for the spatially distributed data, as well as software for summarization, visualization and analysis of characteristics studied.

Analysis of Russian and foreign publications, covering the problems of zoning (regionalization) clearly shows that to date there is no single methodology to identify uniform areas with confidence. The most widely used methods of regression (Tasker, 1982a) and cluster analysis (Acreman and Sinclair, 1986; Tasker, 1982b) in many cases exhibit a high degree of uncertainty. Using these methods and based on the same data, different researchers may arrive to different zoning schemes or at least mismatched boundaries of zones (Gubareva, 2012). This study proposes, the use of statistical analysis (Alekseev, 1971; Nathan and McMahon, 1990) for evaluating the uniformity of hydrological characteristics that according to the researchers allows to come to the formation of a universal approach to zoning of natural sites. However, resaerchers cannot completely exclude some degree of subjectivity in the selection boundaries of areas because the use of different data sets, taking into account or vice versa, lack of attention to the influence of anthropogenic and azonal factors can lead to different variants (schemes) of zoning. To minimize possible inaccuracies in the evaluation of data uniformity researchers need a mathematical algorithm and data processing software to implement it.

MATERIALS AND METHODS

The 1st stage of this study was spatial generalization and preparation of hydrological data for further statistical processing. For this purpose, it was decided to use Geographic Information Systems (GIS) which are suitable best of all to solve this kind of problems. For example, the functionality of the Spatial Analyst Module of ARCVIEW GIS software package, allows one to interpolate surfaces or build isolines based on the values in individual points using interpolation methods provided by ArcView GIS, determine the average values with sufficient accuracy and interpolate hydrological characteristics which are necessary for further mathematical calculations, over large areas (Mitchell, 1999). Technical means of Global Mapper GIS allow one to build a digital elevation model based on satellite data and refine a hydrographic scheme of the basin to account for the influence of azonal factors while interpolating flow characteristics.

The 2nd and main stage of the study included calculation and building of Spatial Correlation Function (SCF). The monitoring data of the annual water run-off of the Oka River obtained at 36 stations distanced from each other by not >850 km were used as the initial characteristics; the period of joint observations is 25 years. The reliability of obtained correlation coefficients was estimated by Fisher (1924)'s ratio test. The primary goal of the study was the evaluation of uniformity spatially distributed data and hydrological zoning of selected territory. The analysis of uniformity of SCF was carried out on the basis of assessment of the significance of difference between the actual correlation coefficient of the estimated coefficient in the total population (Alekseev, 1971). Schematically, the method of calculation is as follows (Fig. 1):

Based on the initial empirical pairwise correlation coefficients r_{ij} and the empirical correlation function values $\tilde{r}(\alpha_{ij})$ auxiliary values are determined according to Fischer Method:

$$z_{jk} = \frac{1}{2}\ln\frac{1+r_{jk}}{1-r_{jk}}$$

$$\tilde{z}_{jk} = \tilde{z}(\alpha_{jk}) = \frac{1}{2}\ln\frac{1+\tilde{r}(\alpha_{jk})}{1-\tilde{r}(\alpha_{jk})} + \frac{\tilde{r}(\alpha_{jk})}{2(N_{jk}-1)}$$

Then deviations are calculated as difference $z_{jk} - \tilde{z}(\alpha_{jk})$ for all $c_l^2 = l(l-1)/2$ pairwise distances α_{jk} between monitoring points. Standard deviations σ_{zjk} of auxiliary values z_{jk} from their conditional mean values $\tilde{z}(\alpha_{jk})$ are determined using the formula:

$$\sigma_{zjk} = \frac{1}{\sqrt{N_{jk}-1}}$$

Taking into account the normality of distribution of the normalized deviations from the mean, the confidence limits:

$$\tilde{z}(\alpha_{jk}) - t_{\sigma jk} < z_{jk} < \tilde{z}(\alpha_{jk}) + t_{\sigma zjk}$$

should cover P (1) = 0.683 = 68.3% for t = 1 or P (2) = 0.954 = 95.4% for t = 2 of all $c_l^2 = l(l-1)/2$.

Therefore, a necessary and practically sufficient condition for homogeneity of the correlation function within the area in question is that the following inequation is true:

$$\left| z_{jk} - \tilde{z}(\alpha_{jk}) \geq \sigma_{zjk} \right| \text{ or } \geq 2\sigma_{zjk}$$

Approximately in 31.7 or 4.6% of cases of the total number of $c_l^2 = l(l-1)/2$ of empirical values z_{jk}. In other words, if t = 1 or t = 2 than the total number of empirical excesses is:

$$K_e(1) = K_e\left[z_{jk} - \tilde{z}_{jk}\right] > \sigma_{zjk}$$

$$K_e(1) = K_e\left[z_{jk} - \tilde{z}_{jk}\right] > 2\sigma_{zjk}$$

should be approximately, equal to the number of excesses theoretically possible for a normal distribution, namely:

$$K_e(1) \approx 0.317C_l^2 = 0.317\frac{l(l-1)}{2}$$

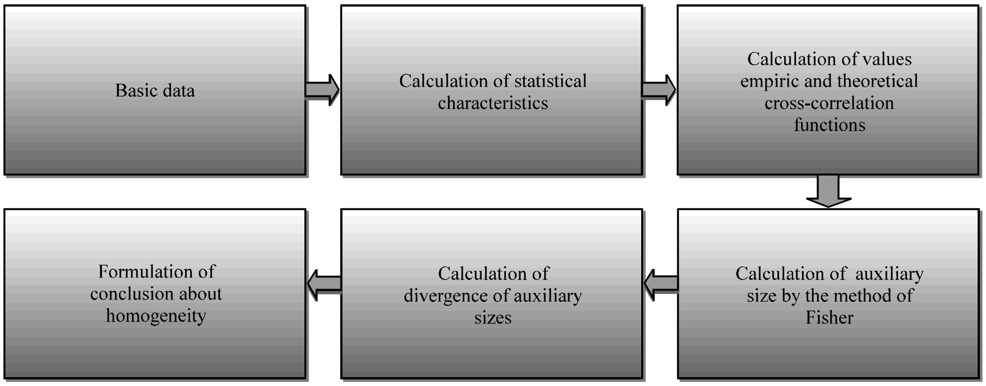

Fig. 1: Algorithm of calculations

$$K_e(2) \approx 0.317C_1^2 = 0.046\frac{1(1-1)}{2}$$

REULTS AND DISCUSSION

Researchers have investigated all possible $C_{11}^2 = 36 \times 35 / 2 = 190$ paired data for stations (j, k) uniformly distributed over the whole catchment area of the Oka River. The correlation function is approximated by a linear dependence with the correlation radius of 850 km. The correlation coefficients vary in the range from 0.30-0.96 and decreases with increasing of distance. The spatial correlation function is recognized as inhomogeneous one, the total empirical number of excesses (by σ_{jk}) is 72 while according to the normal distribution it should be 60.2, therefore the whole zone was divided into 2 subzones based on the certainty of classification of subzone, as belonging to particular hydrological zone. The basin was divided into 2 zones: Oka-woodland and steppe. The example calculations are shown in Table 1.

For the woodland zone, the formula for the empirical correlation function is as follows:

$$\text{For } a < 950 \text{ km}; \; \tilde{r}(a) = 0.8582 - 0.0009a$$

$$\text{For } a \geq 950 \text{ km}; \; \tilde{r}(a) = 0$$

The formula for theoretical correlation function for the woodland zone:

$$\text{For } a < 950 \text{ km}; \; r(a) = \frac{\tilde{r}(a)}{0.95} = 1 - 0.001a$$

$$\text{For } a \geq 950 \text{ km}; \; \tilde{r}(a) = 0$$

The total empirical number of excesses is greater than the allowable number of excesses for the normal distribution for σ_{jk} both and $2\sigma_{jk}$. The apparent reason for non-uniformity of this zone is the influence of azonal factors on the watercourse regime; one of the most important among such factors is karst formation. The following rivers can be mentioned as an example: Zhizdra, Ugra, Pahra, Zusha, Tsna. The formula for the empirical correlation function of the steppe zone:

$$\text{For } a < 790 \text{ km}; \; \tilde{r}(a) = 0.8582 - 0.0009a$$

$$\text{For } a \geq 790 \text{ km}; \; \tilde{r}(a) = 0$$

The formula for theoretical correlation function:

$$\text{For } a < 850 \text{ km}; \; r(a) = \frac{\tilde{r}(a)}{0.95} = 1 - 0.0012a$$

$$\text{For } a \geq 850 \text{ km}; \; \tilde{r}(a) = 0$$

The total empirical number of excesses is less than what is theoretically allowed. Consequently, it was concluded that the Oka-steppe zone is uniform.

Thus, to achieve the objective and carry out zoning of the selected area following the principle of homogeneity of SCF, researchers shall further divide the Oka-woodland zone into additional subzones and formulate a final conclusion about the uniformity depending on differentiation of the spatial correlation functions of the run-off. However due to the cumbersome mathematical calculations and time-consuming processing of raw data, it was decided to automate the process of computation; the computer program was developed using C++ programming language. The program generates conclusion about the uniformity of a hydrological area (the output) based on spatially distributed data (the input).

In the computing algorithm itself, the block for graphic finding of parameters of equations for empirical and theoretical correlation functions is replaced by constructing approximating dependencies and further finding of approximation parameters by minimizing the total quadratic error (least square method). Results of

Table 1: Estimation of homogeneity of cross-correlation function of the investigated descriptions (a fragment over of calculations is brought on 10 pairs from 190)

Distance between river stations	Pairs	Coefficient of pair wise correlation	Value of empiric cross-correlation function	Value of theoretical cross-correlation function	z_{jk}	$\tilde{z}_{jk}$	Rejection (Δ)	Mean square error (δ)	Doubled mean square error (2δ)	Case when a rejection exceeds a MSE ($\Delta>\delta$)	Case when a rejectionexceeds a doubled MSE ($\Delta>2\delta$)
61,78	273-272	0.96	0.80	0.94	1.91	1.11	0.80	0.21	0.76	1	1
81,75	273-280	0.92	0.78	0.93	1.58	1.06	0.52	0.21	0.76	1	1
184,87	273-270	0.88	0.69	0.83	1.37	0.85	0.51	0.21	0.76	1	1
332,60	273-201	0.62	0.56	0.70	0.73	0.63	0.10	0.21	0.76		
429,42	273-198	0.56	0.47	0.61	0.63	0.51	0.12	0.21	0.76		
381,08	273-162	0.51	0.52	0.66	0.56	0.57	-0.01	0.21	0.76		
266,01	273-165	0.60	0.62	0.76	0.70	0.72	-0.03	0.21	0.76		
226,27	273-168	0.62	0.65	0.80	0.72	0.78	-0.06	0.21	0.76		
116,08	273-241	0.87	0.75	0.90	1.33	0.98	0.35	0.21	0.76	1	
162,92	273-171	0.67	0.71	0.85	0.81	0.89	-0.08	0.21	0.76		

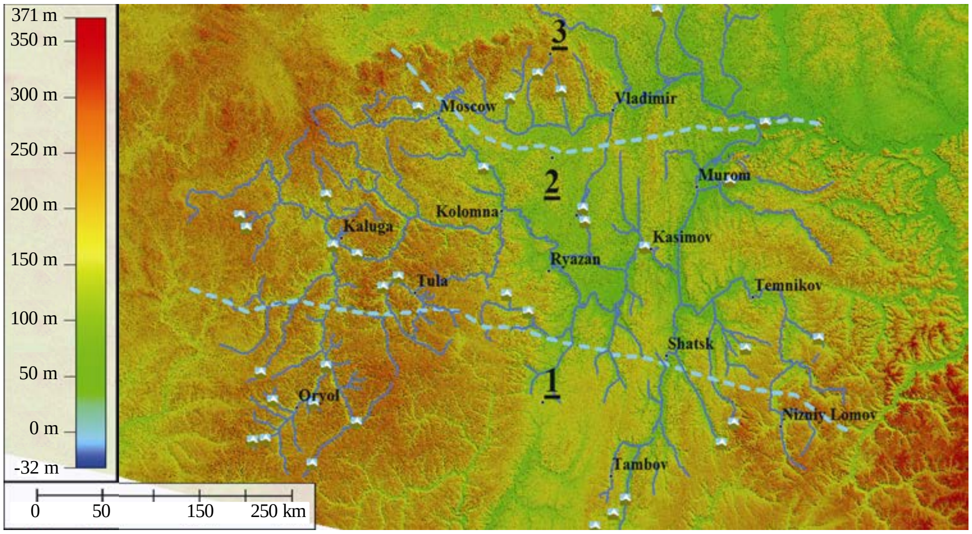

Fig. 2: Hydrological regions

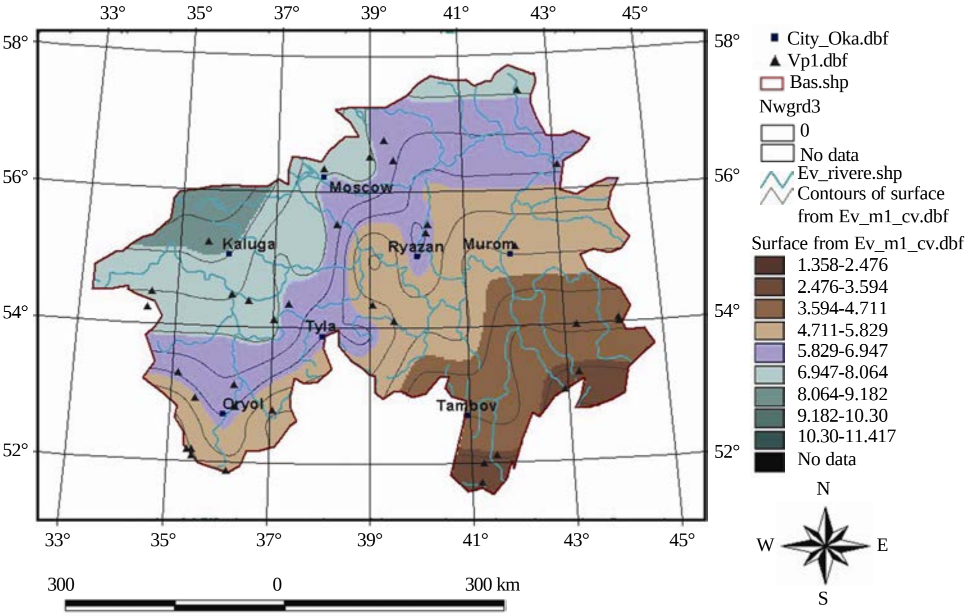

Fig. 3: Electronic maps for rate of annual flow

Table 2: Hydrological characteristics of the selected regions

Hydrological zone	Basin area (km^2)	Rate of annual flow	Gradient flow	Coefficient of variation
Oka-steppe	78400	4.08	0.008	0.35
Oka-woodland	124100	4.66	0.008	0.27
Klyazma River basin	42500	5.56	0.0075	0.24

the study support the conclusion that taking into account the nature of the run-off formation and the commonality of hydrological and climatic characteristics, the Oka River basin can be divided into 3 uniform zones: Oka-steppe, Oka-woodland, Oka-woodland-Klyazma River basin (Fig. 2).

The digital relief model of said territory was prepared using the data from Shuttle Radar Topographic Mission (SRTM) provided by NASA (http://www2.jpl.nasa.gov/srtm/). The resolution is 50-90 m; this allows demonstrating the specifics of underlying surface and the geological structure of region under study.

By means of ARCVIEW GIS statistical analysis for GRID-themes of characteristics under study, researchers obtained the averaged values of the main hydrological characteristics for selected areas (Table 2), built electronic maps for rate of annual flow (Fig. 3) and determined coefficient of variation.

Thus in the course of the study the following problems have been solved:

- The new algorithm for the evaluation of uniformity of spatially distributed data was proposed
- The application for windows was developed making it possible to conclude, quickly and with the least probability of error, about the uniformity of a natural object (site) based on spatial differentiation of the correlation functions of characteristics under consideration
- Hydrological zoning of the territory was carried out
- GIS technology potential for optimal spatial interpolation of hydrological characteristics was studied

CONCLUSION

It should be noted that tools and methods used in this study fully comply with the UN recommendations for a strategic approach to monitoring and assessment of rivers, lakes and groundwaters: The conversion of data into information involves analysis and interpretation. In particular, simulation models and GIS support the integrated management of data. Given that different concepts for databases may be used, at least compatible interfaces should be developed (Nathan and McMahon, 1990). Development of methodology for assessing the uniformity of spatially distributed data using up-to-date means for processing and analysis of information is particularly relevant in the light of global climate change, an increase in the frequency of natural disasters and as a consequence, an increase in the need for timely information about disturbances in the formation and functioning of natural systems. Therefore at the next stage of the research project, the development of a software module is planned which will be connected to GIS systems and will allow the user on the basis of raw data not only make conclusion about spatial uniformity of an area in terms of set characteristics but immediately see the area on an electronic map. The proposed method will also be adapted for ecohydrological problems, for the purpose of identification of polluted areas of water bodies and their classification in terms of the degree of the disturbance and environmental safety.

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