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Research Article

OPTIMIZATION METHODS FOR HYDROECOLOGICAL MONITORING SYSTEMS

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ABSTRACT

The paper describes current approaches to the rational distribution of monitoring stations. A short review and the organization of the system of hydro-geological observations in different countries are presented. On the basis of real data we propose a solution to the problem of how to calculate the average area per one hydrological station, which is the main indicator of the efficiency and performance of the monitoring system in general. We conclude that a comprehensive approach to the monitoring system organization is important, because only hydrometric and hydrochemical activities coordinated in time provide possibilities needed to analyse the underline causes of the observed pollutants content dynamics in water bodies in the long term.

Keywords. Monitoring, hydrological stations, optimization, GIS, ecology, correlation, regression relationships.

INTRODUCTION

Under modern conditions, functions of the hydrological networks and the intended purposes of information obtained using them became more diversified. Along with traditional types of such information (support for water resources assessment, hydrological forecasts, water management planning), hydrological observations become increasingly important as part of the environmental monitoring and in the sphere of prevention of emergency situations. The use of fixed hydrological stations is of particular relevance in solving environmental problems for several reasons. First – the spatial distribution of local water sampling points is not always appropriate; second – the analysis for pollutants in such points is never accompanied by the monitoring of hydrological parameters: water level, water flow in the mainstream, phase of the hydrological regime, etc. All this makes it impossible to analyse the underlying reasons of the dynamics of pollutants content in water bodies during the period of observation. This situation can be improved by conducting coordinated in time hydrometric and hydrochemical activities at fixed hydrological monitoring points [Kalinin at.el. 2011]. The optimal number of hydrological stations is also needed in the light of global climate change accompanied by increasing frequency of natural disasters. There are 120 types of natural phenomena leading to loss of human lives and causing significant economic damage. Dangerous hydrological phenomena are one of the most significant ones. According to the Munich insurance company [Osipov at.el. 1995], the contribution of floods alone is 32% of the total number of natural disasters. Besides the growth of material and human losses due to adverse impacts of water, the shortage of water resources is also increasing; such resources are needed for food and energy production, providing drinking water of required quality and for the conservation of vulnerable ecosystems. According to leading global experts [UNESCO 2011], the "water crisis" observed in recent decades in many countries is caused not only by climate change, but also by inefficient economic activities at water basins. The main source of information about dangerous hydrological phenomena is the national hydrological monitoring network. The development of monitoring network in Russia, as well as in other countries, not always took place onward and upward due to the increasing flow of information consumption (as someone may think it should be). In 1990s, after disintegration of the Soviet Union and due to underfunding of hydrometeorological agency, the number of river runoff monitoring points in Russia has dropped by almost 30% [Frolov 2014]. In the US, more than 2200 water level gauges were shut down during the period from 1980 to 2005, although the total number of operating gauges remained fairly constant at around 7000 [NSIP 2007]. In this case, the problem is not merely that stations are lost, it is important that for some of lost stations records are available for as long as 30 years and more. These stations are especially needed for accurate analysis of the frequency of floods and low flows, as well as for the assessment of hydrological characteristics and trends under conditions of changing climate [Harry 2008]. Another example of downsizing the monitoring network that have a detrimental impact on the study of climate trends includes the Pan-Arctic region, where the number of hydrological stations has recently declined to the level of early 1960s. In Ontario (Canada), 67 % of river water level gauges were shut down in the period from 1986 to 1999 [Shiklomanov at al. 2002]. In EU countries, there were no significant reductions in the monitoring network. The density of stations distribution is high there; this is justified given the wide variety of physical conditions, anthropogenic factor, population density and land use, as well as the types of river and hydrographical conditions. There are about 19 000 hydrological stations on average; the average density is one station per 270 km^2. All monitoring stations are part of the European Environmental Agency (EEA). EEA focuses on water quality; however, the monitoring network also maintains a full range of surface and ground water monitoring data [EEA 2016].

MATERIALS AND METHODS

No general criteria are currently available for distribution of hydrological stations across given area and for calculation of the required number of them. We can distinguish two main approaches: according to one of them, monitoring stations must be placed in a way to make it possible to perform spatial interpolation of hydrological regime data in areas not covered by observations [Glushkov 1933, Karasev 1968]. The second approach is based on the use of regression relationships and regional information in order to provide possible combination of data obtained at different hydrological stations [Benson and Matalas 1967, Burn and Goulter 1991]. General recommendations from WMO are also available; the recommended minimum number of monitoring points is as follows: 1 station per 1000–2500 km^2 for plains, 1 station per 300–1000 km^2 for mountainous areas and 1 station per 5000–20 000 km^2 for arid and polar regions [WMO 1996]. These recommendations are almost never followed. In polar, desert and coastal areas the network density is close to the recommended figures; however in mountain and inland areas the real density is 3–5 fold lower than WMO recommends (Kundzewicz 1997). Therefore, the development of criteria to determine the necessary number of monitoring stations is relevant from the scientific point of view, as well as of great practical importance from the point of view of decision-making in the field of environmental management and economic feasibility.

In this paper, we propose an approach to the theory of optimization monitoring network based on the use of geographic information systems as a tool for processing, mapping and analysis of spatially distributed data. We decided to use the optimization criteria proposed by professor Karasev as mathematical algorithm, which are characterized by practical reasonableness and do not require complex field surveys. In this case, the problem of calculation of the number of network points is to determine the optimal catchment area, covered by the station. For this purpose, the criterion is used which allows monitoring of the normal runoff change along the gradient axis – a gradient criterion. The upper limit of the estimated basin area is the correlation criterion. In addition to the above criteria, condition must be met that limits the minimum basin size, the runoff from which reflects regional patterns. Thus, the optimal catchment area is determined by the following relationship:

$$F_{repr} < F_{grad} \leq F_{opt} \leq F_{cor} \qquad (1)$$

where: F_{grad} – the gradient criterion, or the minimum area per runoff monitoring station that makes it possible to detect changes in the runoff due to the geographical zoning of climatic factors, determined from the in equation:

$$F_{\text{grad}} \geq \left[8\sigma_0{}^2/(gradY)^2\right]Y_{\text{av}}{}^2 \quad (2)$$

where: σ_0 – is the uncertainty in determining the runoff characteristics using hydrometric data,
grad Y – gradient of the runoff (absolute value),
Y_{av}. – mean absolute value of runoff for the area in question,
$F_{кор}$ – correlation criterion or the maximum catchment area monitored by the hydrological station where positive correlation of the runoff is possible, obtained using the ratio:

$$F_{\text{cor}} \leq \sigma_0{}^4/(a^2 c_v{}^4) \quad (3)$$

where: *a* – is the reciprocal of the spatial correlation radius of hydrological characteristics;
C_v – coefficient of variation of annual runoff.
F_{repr} – representative criterion, or the minimum catchment area per runoff monitoring station with which it is still possible to obtain information reflecting the general zonal patterns rather than local specifics.

Evaluation of the optimal composition of the hydrological regime network for a particular river basin is achieved by dividing the total area of this river basin by the optimal catchment area:

$$N_{\text{opt}} = F / F_{\text{opt}} \quad (4)$$

RESULTS AND DISCUSSION

The territory that we choose for our study was the most economically developed region of the Russian Federation – the Oka River basin. In terms of intensity of industrial production, transport and public utilities, this region concentrates more than 10% of the productive forces of Russia that leads to high anthropogenic pressure on the Oka River and its tributaries. The total area of the river basin is 245 000 km^2; the river flows in the forest and steppe geographical areas. In terms of the nature of the runoff formation and the commonness of hydrological and climatic characteristics, the Oka River basin can be divided into three subareas: “Oka-steppe”, “Oka-forest”, and “Oka-forest – Klyazma basin”. The topographic base of the geo-information project shown in Figure 1 was represented by regional relief data.

The digital data on the underlying surface elevation were imported from the website of Consortium for Spatial Information (CGIAR-CSI) [CGIAR-CSI 2015]. These data are also available on NASA website [NASA 2015]. These data are distributed free of charge by the US Geological Survey and are the result of interferometric radar mapping of the globe (Shuttle radar topographic mission) carried out in February 2000 by the NASA’s space shuttle. SRTM data provided by Consortium for Spatial Information (CGIAR-

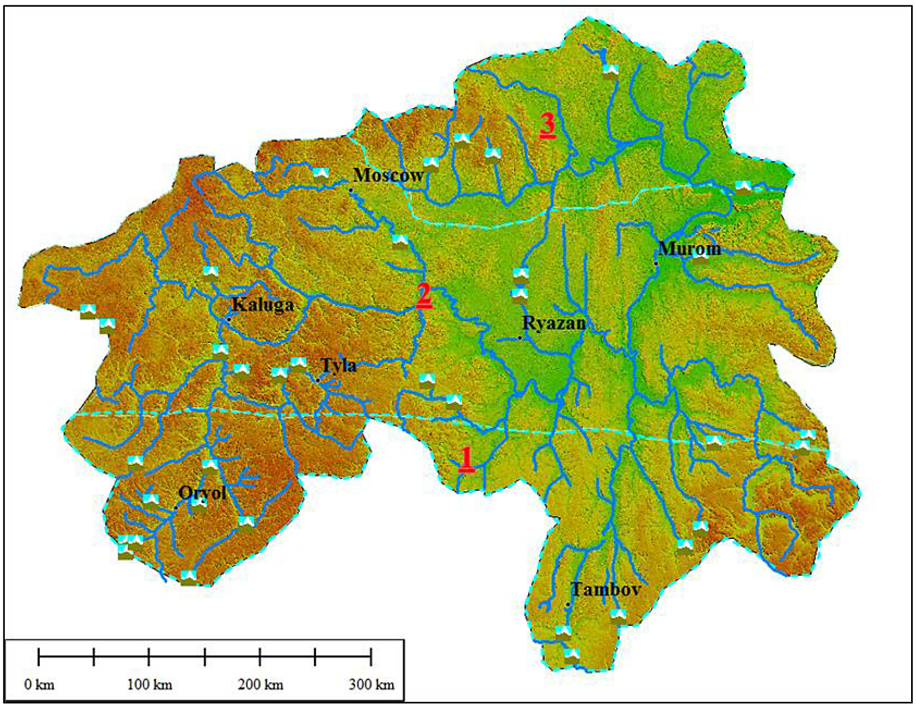

Figure 1. Hydrological regions

CSI) are characterized by high resolution (30–90 meters), are divided into squares of 5×5 degrees, each of which has a name corresponding to the coordinates of its lower left corner, for example: N60E032.hgt – 60 degrees north latitude and 32 degrees east longitude. Files with the extension .hgt can be easily loaded into Global Mapper GIS without any additional preparation. The absolute uncertainty of elevation data for Eurasia is 6.2 meters, the relative uncertainty is 8.7, and all uncertainties are within the confidence interval 90% .The relief of such degree of detail and accuracy is a very good basis for any GIS project [Makhovikov and Pivovarova 2015].

We then compiled maps for the absolute value of runoff and the coefficient of variation based on data from 36 monitoring stations uniformly distributed over the catchment area (basin) and having representative series of observations (Figure 2).

Using the module Spatial Analyst ArcGIS we calculated the average statistical characteristics for the hydrological areas of interest. The final stage included the calculation of network optimization criteria and finding the optimum number of hydrological stations (Table 1). The gradient and correlation criteria are calculated according to the formulas 2 and 3, accordingly. The correlation radius, i.e. the distance at which the function passes through zero, needed to calculate the correlation criterion for optimization was obtained from the diagram of space correlation function of the annual runoff and was assumed to be 690 km for steppe area and 810 km for forest area.

The representative criterion for optimization (F_{repr}) for the Oka River basin, according to data by K.P. Voskresensky [Voskresensky 1962], can be assumed to be equal to 500 km^2 for forest area and 1500 km^2 for steppe area. We proceed as described above. The resulting optimal area per monitoring station (F_{opt}) was determined from the ratio 1. For the area "Oka-steppe" the parameter turned to be equal to 5300 km^2, for "Oka-forest" – 3800 km^2, for "Klyazma River basin" – 6150 km^2. In general, this is consistent with the average monitoring network density in Russia – one hydrological station per 5250 km^2 [Bobrovitskaya at al. 2011]

Table 1. The optimization criteria

Hydrological zone	Basin area (km^2)	Mean absolute value of runoff Y_{av} (lit/sec·km^2)	Gradient of the runoff grad (Y)	Coefficient of variation (C_v)	$F_{grad.}$ (km^2)	$F_{cor.}$ (km^2)	$F_{repr.}$ (km^2)	$F_{opt.}$ (km^2)	$N_{opt.}$
Oka-steppe	78 400	4.08	0.008	0.35	9900	760	1500	5300	15
Oka-forest	124 100	4.66	0.008	0.27	6800	820	500	3800	33
Oka-forest – Klyazma basin	42 500	5.56	0.0075	0.24	11000	1300	500	6150	7
	∑ 245 000								∑ 55

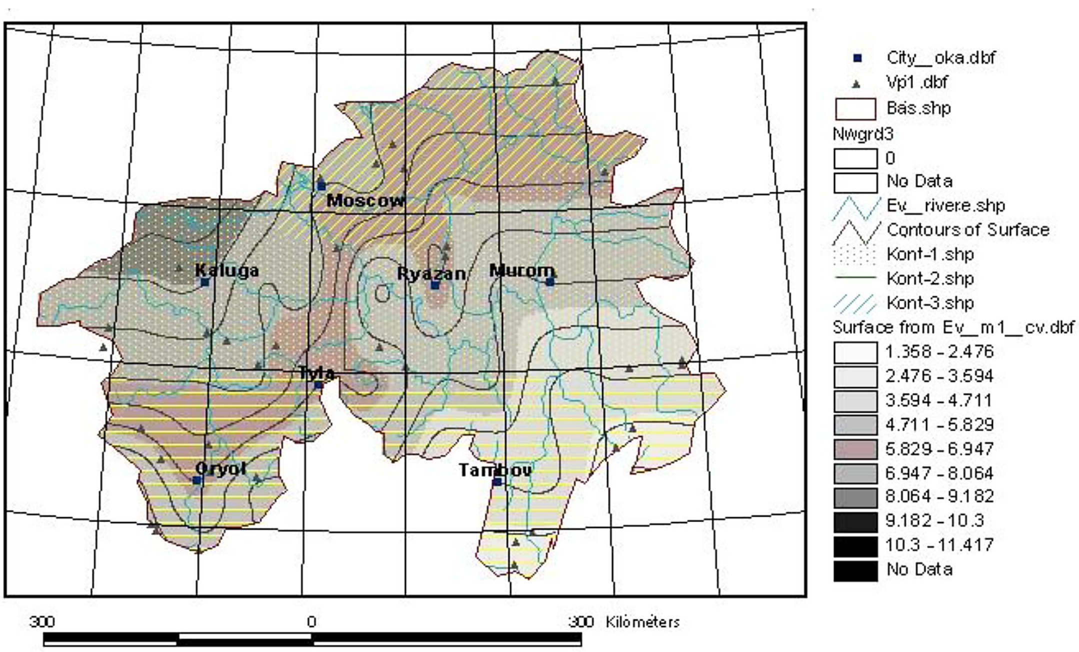

Figure 2. Map of flow module isolines

CONCLUSIONS

In general, the monitoring network can be regarded as optimal if the quantity and quality of the data collected is economically justified and meets the needs of users [Pyrce 2004]. Typical water basins should be integrated into the network to obtain the data and study the climatic, hydrometric and environmental data concurrently. When making decisions to deploy or shut down monitoring points it is important to take into account the anthropogenic load on the ecosystem in economically developed regions and the resulting environmental and hydrological problems.

The results of our study are not intended to provide specific guidelines to decrease or increase the number of points in the hydrological monitoring network; however, we delineated general features of advantages and disadvantages of currently existing approaches to the selection of density of streamflow monitoring stations. In the course of study we developed electronic analogue of maps of basic hydrological characteristics for annual runoff, which can further be used as a basis for computer models to forecast the runoff; we also presented illustrations of GIS technology capabilities, which can provide a solution of the problem. The conclusion was made about the prospects of using a hydrological network for environmental monitoring to assess the damage caused by pollution of water bodies, as well as the long-term tracking of trends.

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