

Functional-analytical capabilities of GIS technology in the study of water use risks

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Abstract. Regional security aspects of economic activities are of great importance for legal regulation in environmental management. This has become a critical issue due to climate change, especially in regions where severe climate conditions have a great impact on almost all types of natural resource uses. A detailed analysis of climate and hydrological situation in Tomsk Oblast considering water use risks was carried out. Based on developed author's techniques an informational and analytical database was created using ArcGIS software platform, which combines statistical (quantitative) and spatial characteristics of natural hazards and socio-economic factors. This system was employed to perform areal zoning according to the degree of water use risks involved.

Introduction.

The problem of studies of water use risks is closely connected with the problem of comprehensive knowledge about the processes which occur in natural and socio-economic environments. There is a need for precise and geo-correlated information about the ecological situation of geosystems located in a particular region. Therefore, in order to provide an integrated assessment of water use conditions, which, to a great extent, are the result of intensified human activities within the floodplains of river channels, we should incorporate results of separate studies considering either climatic, hydrological or socio-environmental conditions in the area [1].

Water use is a key factor which determines the society functioning and development of its economic potential. Tomsk Oblast possesses significant surface water resources which by far exceed the needs of industry, agriculture, housing and communal services. Surface water resources in Tomsk Oblast are concentrated in 131 000 water bodies, including 8 100 rivers which are 95 thousand km long in total. River network density ranges from 0.39 to 0.29 km/km² [2]. Tomsk Oblast is characterized by extensive methods of water use and there are local areas of increased intensity of water use due to the peculiarities of their economic structure.

Water resources in Tomsk Oblast are used for oil and gas production, manufacturing, agriculture activities, water supply of cities and towns, timber floating, fisheries. In a number of areas within the region, rivers are practically the only means of transportation. Population of the region is concentrated within the valleys of the rivers Ob, Tom, Vasyugan, Chulym and Ket [2].

However, climate conditions of Tomsk Oblast do not only shape and regulate the river system dynamics, but also determine the direction, intensity and risks in the use of its water bodies – rivers. The commercial use of water is made under the influence of multiple adverse climatic factors: low winter temperatures, considerable weather variability, sharp fluctuations of daily and annual



temperatures, unfavourable hydrological situation in the area, strong and persistent winds, and large swampy areas. Based on many environmental indicators, the region can be referred to as an area extremely uncomfortable for living. A high number of natural hazards is observed here (from 180 to 240 cases of natural risks per year), increasing by almost 6% annually [3,4]. When making analysis and forecasts of these hazards, there is a need for precise and geo-correlated information about events and processes, based on which a detailed assessment of the area can be made. This task can be successfully accomplished using modern GIS (Geographic Information System) technologies. Development of GIS technologies demonstrates benefits of the integrated use of varied data to receive new information about geographic features. Systematic and comprehensive approach is the most important characteristic of GIS [5]. These capabilities make GIS technology the most effective method for spatial-temporal assessment of existing climatic hazards for the purpose of water resource management [6].

Materials and methods

The data from the most representative meteorological and gauging stations over the last 40 years were used as GIS modeling base for spatial distribution of climatic and hydrological conditions and water use risks in Tomsk Oblast. ArcGIS software was used as a tool for processing, analyzing and reporting data [7]. The advantage of this GIS-based software package is that it can create an extensive information base, combining digital, cartographic characteristics of natural hazards and their dynamic state. Basic functions of ArcGIS software within the framework of the created geographic information system contribute to comprehensive analysis of natural hazards by adding statistical information from standalone separate tables to the tables of spatial object classes within the system. This, in turn, provides an opportunity to combine diverse parameters and produce multi-component maps for individual tasks of environmental management, thus visualizing the received results.

In the present study, development of a spatial dynamic model of hazardous natural processes based on GIS technology has involved several stages. The first stage was the formation of a geodatabase, which consists of standalone tables, vector and raster data, geographic feature behavior rules. Spatial data were divided into two blocks representing feature datasets. One feature dataset includes a topographic base. Another dataset contains thematic data, including information about location of weather and gauging stations presented as point features.

To obtain correct results, all spatial data were arranged into a single coordinate system with regard to projections, distortions and generalization rate.

Standalone tables were formed on the basis of statistical data comprising climatic and hydrological parameters. From the entire set of natural factors, only those were selected that could be hazardous to water use processes.

Data on natural risks which were included into the standalone tables were divided into 3 groups: climatic, hydrological and socio-economic.

When calculating the integrated climatic hazard index, $NC = \frac{\sum_{i=1}^7 n_i \times 100}{7}$ seven climatic factors

were considered among which there are those producing the most negative impact on the natural resource management activities in the studied area:

1. number of windy days (wind speed of 15 m/s or more);
2. snowmelt runoff /melt water formation (average daily intensity of snowmelt in mm);
3. temperature fluctuations (maximum temperature difference at the soil surface in April - a period of extreme instability of temperature);
4. number of days with excess rainfall (per year);
5. exposure to storms (maximum number of storms per year);
6. risk of drought (maximum number of days per year with humidity below 30%);

7. low winter temperatures (maximum number of days per year with the temperature of -35°C and below).

Hydrological stress index was calculated as $NG = \frac{\sum_{i=1}^5 k_i}{5}$, where k_i – a coefficient corresponding

to the value of five major hydrological factors characteristic of Tomsk Oblast:

1. low water level (number of days per year with a low water level);
2. ice phenomena (complex index considering ice-drift and ice-cover duration and early icing;
3. high water level (number of days per year with a maximum level of high water);
4. difference between low and high water levels;
5. intensity of ice phenomena and meltwater accumulation;
6. sediment runoff rates.

Basic information included socio-economic indicators characterizing the condition of water resources management and possible damages from the natural hazards. Social and environmental stress index NR within a separate river channel borderlines was calculated by the following formula

$NR = \frac{\sum_{i=1}^3 g_i}{3}$, where g_1 – population density score (within riverbed area); g_2 – bridge crossing

frequency score; g_3 – score indicating the number of environmentally hazardous oil-gas pipeline and river channel intersections.

The quantitative values listed above were used as input data and were correlated to the location of the selected weather stations, gauging posts and water bodies, with the help of Join – a specialized tool ArcGIS. Each indicator was included into the database with reference to observation year. The database structure and functions provide the possibility to add and modify information.

The next stage involved the spatial analysis of data, including areal zoning, creating a series of thematic maps and visualization. To perform regional variability assessment of separate hazard parameter, its values were interpolated using an additional ArcGIS Spatial Analyst Module.

Results and discussion

Based on the conducted analysis, the areal zoning has been performed according to the degree of water use risk. In addition, the areas with the greatest frequency of dangerous climatic phenomena as well as areas with different variability degrees of meteo-climatic parameters were plotted in a series of thematic maps.

1.1. Major trends of climate change in Tomsk Oblast

According to the received estimates, over the past 10 years the temperature has been rising at an average rate of 0.34°C per year in the entire Tomsk Oblast area. For the vast plain areas, actually obtained values of average temperature increase ranged from 0.68 to 0.92°C over the studied period. Most intense warming occurred in the northern and south-eastern parts of Tomsk Oblast, the least intensive warming – in the western parts. Of particular interest is submeridianally oriented area, located along the main waterway of the oblast – the Ob River and its major tributaries – rivers Tom, Parabel, Vasyugan and Tym. This zone is characterized by relatively high values of the average temperature increase (up to 0.85°C) (figure 1).

The rainfall variability analysis has shown that the increase in precipitation is the main trend throughout the region. Moreover, the growth rates of average annual rainfall exceed by 2.5 times the rainfall reduction rates, although both values are small and do not exceed 2.8 mm in the absolute value over the study period (figure 2).

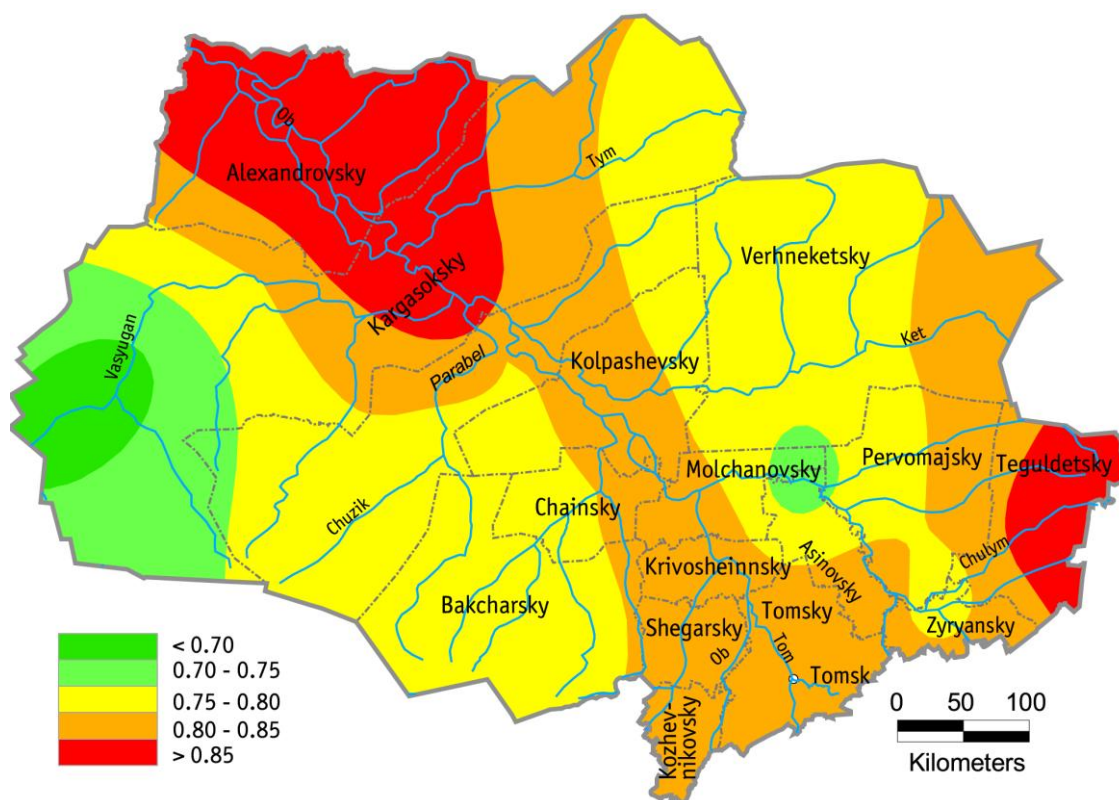


Figure 1. The average annual temperature changes in the years 1976-2006.

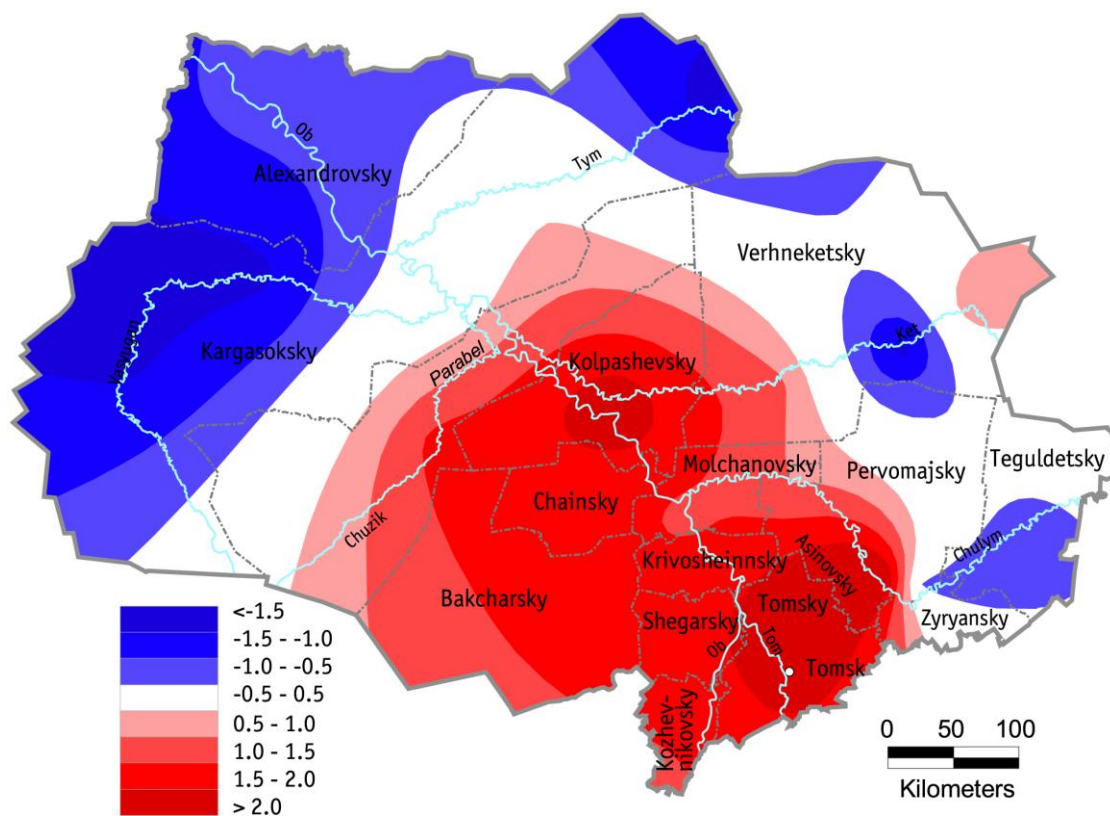


Figure 2. The average annual precipitation changes in the years 1976-2006.

The precipitation growth trend is observed in the central and southern areas. Furthermore, it should be noted that most of these areas are subjected to increasingly strong local effects of dangerous exogenous processes including coastal and gully erosion as well as landslides.

Another important result of the rainfall variability analysis is the distinguished reduction of rainfall in the western and northern parts, as well as significant reduction in precipitation levels in some eastern parts of Tomsk Oblast. With the increase of average annual temperatures, especially during the coldest part of winter, reduced rainfall can cause degradation of relict permafrost and contribute to thermokarst phenomena.

These findings were used to perform the spatial assessment of the studied climatic factor risks. The wind regime in Tomsk Oblast is characterized by significant spatial homogeneity of strong gusty winds (figure 3).

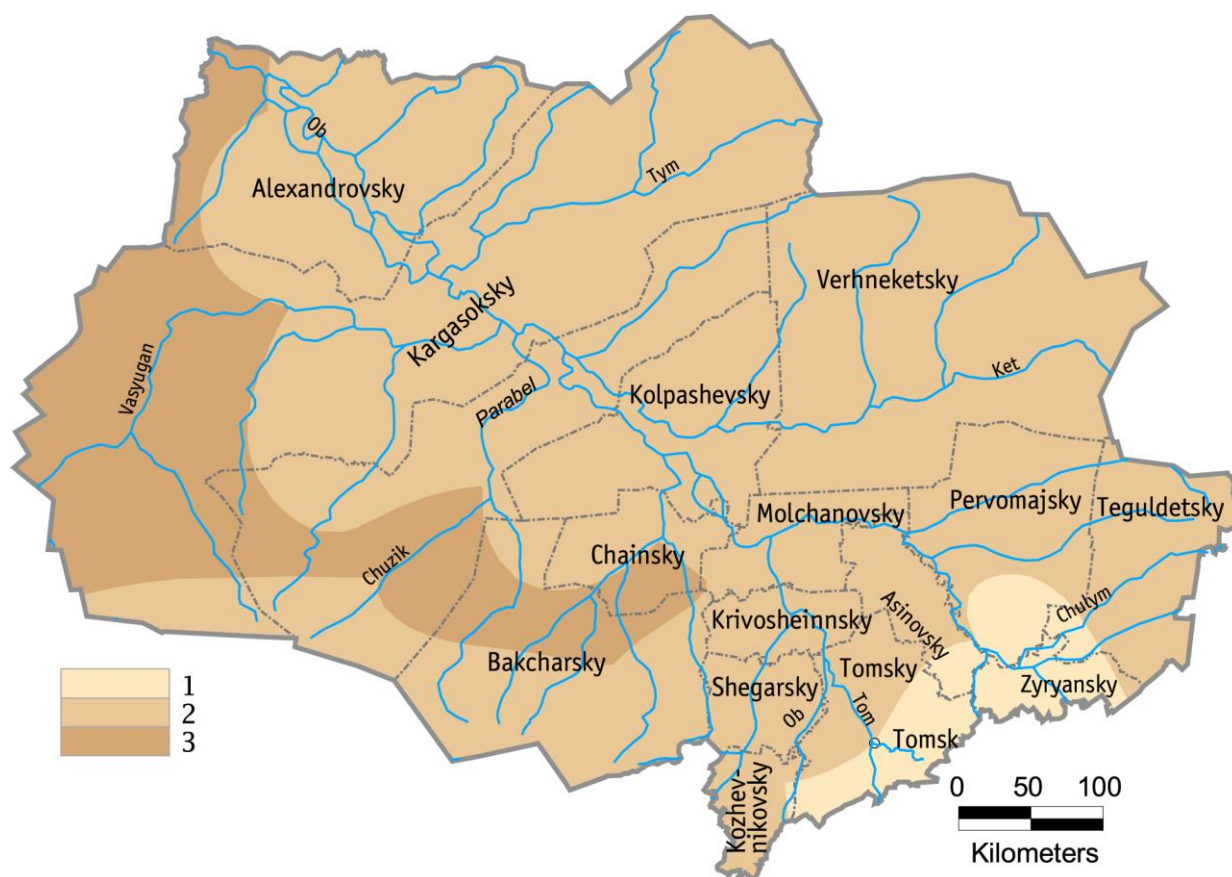


Figure 3. Evaluation of wind regime risk level: 1 - weak; 2-average; 3-high.

Since threshold wind velocity resulting in soil erosion ranges from 5 to 12 m/s in Tomsk Oblast, the increased wind erosion hazard rate is characteristic of almost entire Tomsk Oblast area.

1.2. Hydrologic vulnerability of Tomsk Oblast

These trends are changing the heat and moisture ratio, which determines the dynamics of climatic processes, including the mode of drainage system operation in the studied area [8]. Based on the calculations of hydrological stress, the territory was ranked by the degree of hydrological hazards. Thus, it was found out that the major risk factors for the Ob River are the intensity of snowmelt water accumulation (in southern areas) and sediment runoff rate fluctuations. The growth of these factors leads to increased soil erosion and riverbed deformation.

1.3. Water use risk assessment

Analysis of climatic and hydrological characteristics of the area provides assessment of water use risks, occurring as a result of human activities within the river floodplain complexes. Based on comprehensive analysis of climate, hydrological and socio-economic stress parameters, the integrated water use risk assessment was conducted. Water use risk calculations carried out within Tomsk Oblast introduce a wide assessment range (figure 4). The map shows the water stressed areas ranked according to risk level: high and heightened risk water stress zones constitute over 66.5% of total area, medium risk zones account for 9,89 %; low and reduced risk water stress zones comprise 23,61 % of Tomsk oblast area.

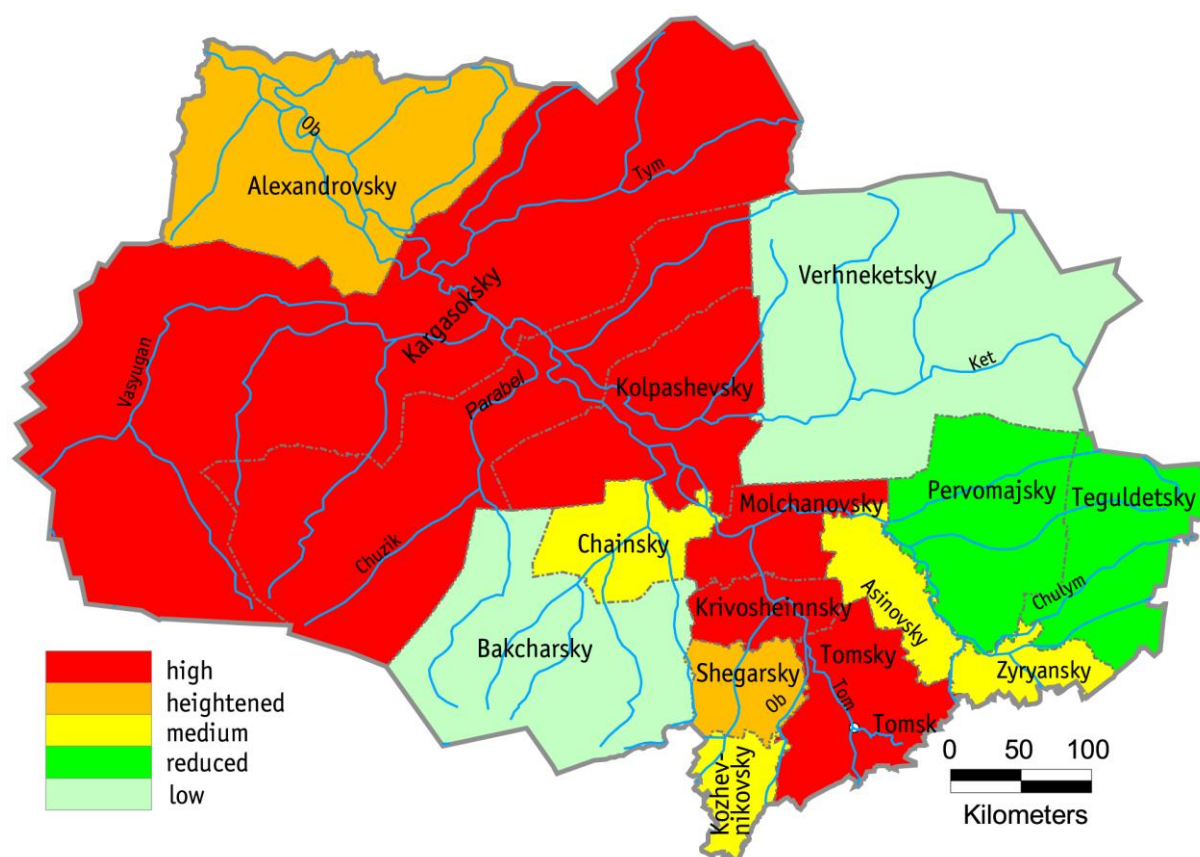


Figure 4. Water use risks in Tomsk oblast

Thus, considering high risk area prevalence, the water use hazards can be referred to as mass phenomena in Tomsk Oblast. The areas adjacent to the Ob River are of particular concern. Despite the obvious appeal of these areas, economic development of the region results in risk increase during high water periods. Population pressure in the south of the region (Tomsky, Krivosheinnsky, Molchanovsky raions), oil and gas pipeline transportation development in oil-bearing parts of the region (Alexandrovsky, Kargasovsky, Parabelsky raions), enhanced by high hydrological stress and active river channel formation processes account for high levels of water use hazards in these areas. In this respect, the eastern parts of the oblast (Verhneketsky, Pervomajsky, Teguldetsky raions), where social infrastructure and pipelines transportation are least developed, are less stressed. Relatively low values of climatic, hydrological, socio-environmental stress indexes in Bakcharsky Raion determine relatively low natural hazard potential of the area.

Conclusion

The conducted studies have revealed a set of features which characterize natural and anthropogenic interconnections and meteorological conditions in the studied area. The collected factual material was used as the basis for the analysis of climatic, hydrological and socio-economic impacts on the spatial distribution and degree of water use risks. Interactions of climatic and socio-economic processes define both the nature and the amount of water use risks. Territorial differentiation of these risks is determined by hydrological and socio-economic characteristics, rather than by meteorological and climatic conditions of the area. The degree of risk is proportional to the territory inhabitation level and the level of its economic development. The proposed approach to water use risk assessment can be used to perform the areal zoning according to different climatic, hydrological parameters and social factors, based on local conditions.

A large number of location-based and temporally distributed data on the climatic, hydrological and socio-economic conditions of water use determines the need for their integration into a single data storage and processing system, which can serve as an analytical tool for making decisions. Due to GIS capabilities, which allow accumulating a wealth of information, it is possible to conduct rapid, real-time analysis and visualize distribution of dangerous natural processes and water resources management risks.

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