

A GEOGRAPHICAL APPROACH TO WATER RESOURCE MAPPING FOR ATLASES

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ABSTRACT. We examine water resource mapping as an important component of the geographical approach in land hydrology and in the water sector which serves to assist considerably in dealing with water problems and water resource management. We suggest that seven groups of water resource maps be distinguished: introductory maps, maps of formation of surface and subsurface water regimes, maps of assessments of water resource potential, maps of water management, maps of anthropogenic impacts on water, maps of hazardous hydrological phenomena and maps of water protection measures. Characteristic properties water resource mapping for atlas products are identified using a case study of territory surrounding Lake Baikal as a site of global significance. We compiled an inventory of water resource themes covered by various atlases of the Baikal region and determined gaps relating to economic aspects of water and to maps on water protection. Limitations of the traditional isoline method in geographical water resource mapping are shown. At hillslope level where atmospheric precipitation transforms to surface runoff further to stream flow, it is recommended that the indication localization method be used, which is based on interdependencies of components of the geosystem. Water runoff mapping at the regional level in the hydrographic network uses the technique of long-channel (epure) mapping based on tools of structural hydrographic and Horton-Strahler classification. A technique of regionalization is described for flood hazards, water protection and recreation zoning of Baikal's shores as well as cartographic modeling of processes in the Selenga river delta.

KEY WORDS: water resource maps, Baikal region, atlases, indication localization, long-channel mapping, delta

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INTRODUCTION

Water resources have a number of special features which distinguish them from other natural resources. They are characterized by a dual natural-social essence: the water as the component of the natural environment and, at the same time, one of the major elements of productive forces, plays a large social-historical, infrastructural and region-forming role. Not only do water resources have mass and energy properties but they also provide a basis for human livelihoods and economic development.

Problems caused by scarcity or surplus of water and by pollution of water bodies are growing at an ever increasing pace worldwide. Today about 1.3 billion people are in dire need of freshwater, and about one-fourth of a billion are experiencing enormous water stress. Pollution has currently affects up to 17,000 km³ of water, or half the maximum estimated volume available for use. So far it is impossible to determine whether a global water crisis is approaching.

Over the last several decades, climate and human-caused have changed of water regime and water quality, showed insufficient hydrological and hydrochemical observations. Assessment of the current hydrological conditions requires the use geographical methods of analogy and zoning, the use of indirect and indicative characteristics, and the widespread introduction of remote methods and GIS technologies. The need to take into account the parameters and functions of specific landscapes of the catchment, the manifestation of local and regional natural relationships is especially relevant in the Eastern regions of Russia, which is determined by the variety of natural conditions, the complexity of economic tasks and the lack of hydrometeorological network.

Water resource mapping is an important geographical tool for assisting with water management. Mapping has been widely used for long periods of time in scientific research and practical applications. «The map as any other model reproducing an object for scientific inquiry is able to substitute it in such a way so that its study provides a possibility of scooping new, intrinsically important information» (Sochava 1978).

The underlying cartographic atlas products are the result from accumulated knowledge of different sectors and disciplines of Earth sciences as well as from various territorial subdivisions of countries and regions. Atlas maps reflect achievements of these sciences stimulating new ideas. In this paper, we examine the characteristic properties of water resource atlas mapping by using the Baikal region as an example.

In this case, four main tasks are solved:

- to propose a new classification of water resource maps according to the mapped characteristics and purpose;
- to consider the experience of water resource mapping of the Baikal region;
- to identify the methodological features of water resource atlas mapping;
- to outline the prospects for water resource mapping in the Baikal region.

RESULTS AND DISCUSSION

Classification of water resource maps

According to its content, we propose to distinguish several groups of maps:

(1) *Hydrographic (introductory)* maps of the hydrographic network, river basins, the river network density and other hydrographic indicators, river sailing directions, valleys, presence of lakes, dams and bogs etc.. This group also includes schematic maps of the network of water resource monitoring: hydrometric sections, gauging stations, sampling locations, etc.

(2) Maps on *formation of surface and subsurface water regimes*. As the largest group it incorporates maps on water balance elements, rates of streamflow, ice phenomena as well as thermal, hydrochemical, hydrobiological and microbiological regime and status, channel processes, usable resource and regimes of subsurface waters, and hydrological and hydrogeological regionalization.

(3) The group on *assessment of water resource potential* includes maps on the availability water and its energy production, water supply, transport and fishing.

(4) The group on the *water sector and its management* includes maps of water infrastructure such as intakes, canals, water transport routes, irrigation and drainage systems etc.

(5) *Consequences of anthropogenic impacts* on water bodies and their catchments are represented in this group. Central to it are maps depicting changes in water status such as pollution, clogging, depletion, salinization and disturbances of natural flow regimes.

(6) The group *hydrological risks* comprises maps on hazards and risks related to floods, debris flows, avalanches, water erosion, bank abrasion, etc.

(7) Finally, the group *«Water protection measures»* includes maps on water protection facilities and zones and recommended water protection measures.

Presentation of water resource themes in atlas products for the Baikal region

The Baikal region includes three territorial units of the Russian Federation: the Irkutsk oblast, the Republic of Buryatia, and the Zabaikalskii krai. The total area of the region is 1.56 million square kilometers, its population is 4.45 millions (3% of the population of the Russian Federation, as of 01.01.2019). The region has all attributes of landscape-ecological and economic-cultural integrity where a significant role is played by water resource relationships. The region is an integral entity primarily because a significant part of its territory lies within the drainage basin of Lake Baikal, a water body of global significance. Baikal is one

of the greatest lakes of on Earth and a UNESCO World Heritage site. The reserves of freshwater in the lake are 23.6 thousand cubic kilometers, or 26% of the world reserves of lake freshwater and 90% of Russia's lake water, and 5.5% of all freshwater of the world. The lake is unique in its flora and fauna, in the diversity and degree of endemism of the species inhabiting it, and in unprecedented self-purification mechanisms. It is the world's oldest lake with an estimated age of 20–25 million years, or several orders of magnitude older, than any other reservoir across the globe.

Baikal's waters are central to the immense hydroelectric and water-supply potential of the region, which largely determines the economic profile of the territory. The region is among the main sources satisfying domestic and export needs of Russia for diverse natural resources. The largest industrial-economic complex has been created in the east of the country. Therefore, it has rightfully served (and continues to do so) as a powerful base for development of Far Eastern and northern regions of Russia and as the testing grounds for prospective implementation of a number of programs of national significance relating to energy, transport, gold and furs; various sectors of the defense complex, and recreation and tourism.

It is appropriate to carry out the planning of socio-economic development of the Baikal region using a powerful cartographic information base represented by atlas products. Many years of efforts of the Irkutsk-based V.B. Sochava Institute of Geography SB RAS managed to achieve Russia's highest level of cartographic presentation and information support (Batuev & Korytny 2018).

Let us consider the way in which water resource maps are presented in the atlases of three classes, basing ourselves on the atlases produced in the ex-Soviet Union and in today's Russia. The first class includes atlases of a global level, i. e. of the world, parts of the world and Russia in general. Small-scale maps provide a means of positioning the indicators of the federal subjects of the Baikal region in Russia and in the world. This applies for comprehensive atlases, such as the (Atlas of natural resources of the world 1998) or the (National atlas of Russia 2004–2008) as well as for specialist water resource atlases: the (Atlas of the world water balance 1974) and the (Atlas of snow-ice resources of the world 1998). We now consider in greater detail three atlases for the territory of Russia that were published in the last decade.

The (Atlas of socio-economic development of Russia 2009) offers a comprehensive multi-purpose model, with its 240 maps making it possible to analyze the qualitative and quantitative changes that occurred in Russia in the late 20th – early 21st centuries in the economy and in social relations. A characteristic of the atlas is the only regional section that includes 50 maps of the Baikal region. And the territory of the region is displayed on most of the other small-scale maps: on a total of 94.7% of all maps in the atlas. But the water resources and their use are neglected in the atlas; not a single water resource map can be found even in the regional section, with the exception of the water transport block on Russia's map of water transport systems.

A next atlas offers a different situation. An encyclopedic compilation of information on the full spectrum of natural, technogenic and socio-biological hazards and risks is provided in the (Atlas of natural and technogenic hazards and risks from emergency situations 2011). The atlas contains 323 maps and is intended for a wide range of users. The Baikal region is presented on 268 maps, or 83% of all maps. Out of them, 28 maps are water resource maps; of course, most of these maps belong in the group «Hazardous hydrological phenomena».

The latest example is provided by the (Ecological atlas of Russia 2017) that reflects spatio-temporal information on the formation conditions for the ecological situation, economic impacts on the natural environment, the ecological status of the environment, and on the measures undertaken for environmental sanitation and optimization of the ecological situation at the beginning of the 21st century. The atlas was developed on the basis of the latest scientific-methodological and technological achievements in the array of modern subject sciences (geography, biology, ecology, informatics, etc.) and in mapping by ensuring continuity with the best examples of national and foreign cartographic products; it contains 262 maps accompanied by texts, satellite images and other illustrative material. The Baikal region is presented on 178 maps (68%), and 36 maps are devoted to the water resource themes in the seven groups but the maps of anthropogenic transformations and hazardous hydrological phenomena are dominant.

The second class is represented by two atlases of lakes. The first of them, the (Atlas of Lake Hovsgol), situated in the Mongolian part of the Baikal drainage basin, was published in 1989. The atlas contains a total of 91 maps. The maps in the first part of the atlas characterize the surface and subsurface, the climate and waters, soils and vegetation, wildlife, the population and the economy of the Hovsgol region; the second part contains information on the characteristics of the lake bed, the morphology and dynamics of its shores, wind-driven wave, water temperature, chemistry of waters and bottom sediments, and the organic world of the lake. It is logical that one-third of the maps are water resource maps, and an absolute predominance corresponds to the group of formation of regimes and in this group, to hydrochemical and hydrobiological maps.

The situation with the (Atlas of Lake Baikal 1993) is somewhat different. It is structured in the same way, i. e. the water area and its surroundings are considered but about 60% of all maps now refer to water resource maps. And most of the maps refer to the second group (formation of regimes of the lake) but the geophysical properties: currents, wave disturbances, the ice and thermal regime, etc. are presented on about half of the maps.

The third class is comprised of the ecological atlases of the Baikal region. The first of them is entitled (Irkutsk region: ecological conditions of development 2004). The purpose of 90 maps in the atlas is to furnish a means of linking the ecological connections and phenomena displayed on the maps to a broad geographical background of a diverse thematic spectrum as well as showing the concrete indicators of particular deviations in the nature management system in order to eliminate them through the measures for its rationalization. Furthermore, about 30% of the maps are water resource maps, and the maps of formation of regimes and anthropogenic impacts carry basic and equal «weight». It is for the first time that the (Ecological atlas of the Lake Baikal basin 2015) reflects the spatial formation patterns of the ecological situation throughout the entire catchment of Baikal and its water area, which provides a means of determining and substantiating the future directions of ecologically balanced and sustainable development of Russia and Mongolia. The atlas was published in the Russian, English and Mongolian language. Out of the 142 maps of the atlas, about 16% refer to water resource themes. Although more than half of them belong in the group of formation of regimes, almost all other groups are presented.

The (Ecological atlas of the Baikal region) that was posted on the online geoportal maintained by the Institute of System Dynamics and Control Theory SB RAS in 2017 is yet another completed cartographic compilation product. It

serves as a base component of the cartographic information system for sustainable development of the Baikal region and is intended primarily for managerial bodies of the subjects of the Russian Federation on the territory of the region. The atlas contains 348 maps, and about a hundred of them refer to the water area of Lake Baikal. Thus the number of water resource maps reached 20%, although the group of formation of regimes is dominant, but all groups of maps are presented.

The final analysis shows that sufficient attention is paid to water resource maps and, especially, to lake maps in particular. However, the groups of maps presented are nonuniform, the least – the maps of the water economy, and the water protection maps. This should be taken into account in future mapping of the Baikal region.

Methodological foundations of geographical water resource mapping

Geographical mapping of water resources uses most of the procedures and methods employed in thematic mapping. However, there are limitations as regards the conventional isoline method. It is based on the assumption that changes are continuous in the space of hydrometeorological elements, which is, to a large extent, typical for the radiation balance, air temperature and evaporation and, to a lesser extent, to atmospheric precipitation, mostly on flat territories, with the type of latitudinal zonality predominating, and with a significant spatio-temporal averaging. However, when streamflow characteristics are represented by isolines, a very important factor is neglected: if atmospheric precipitation occurs at any point of the terrestrial surface, then the channeled runoff is, essentially, a point characteristic which can be regarded as an area characteristic (in the form of moduli or a layer of flow) as a result of generalizations and statistical transformations. Therefore, the drawing of isolines where river channels are absent altogether is quite arbitrary in character and the values of the flow obtained from such a map have rather crude and, often, simply empty values.

Certainly, the main spatial mapping cell in hydrology is the basin (catchment), and we substantiated this in the theoretical development of the basin concept in nature management (Korytny 2001; Korytny 2017). The difference of the main mapping procedures for elements of the hydrographic network and landscapes of the catchment is due to this.

At the hillslope level, i. e. where atmospheric precipitation transforms to the runoff, to the overland runoff first, and then to the channeled runoff, it is recommended that the method of *indicative localization* be used, which is based on interdependences of geosystem components (Gagarinova 2012). For instance, the map «Long-term average flow» in (Ecological atlas of the Baikal region 2017) reflects the formation patterns of the water regime of the territory which are based on the properties of landscapes to transform meteoric moisture (rainfall, fog, snow etc.) into runoff (Fig. 1). The value of the runoff from landscape complexes is determined by solving the inverse problem, i. e. identifying the relationship of the water discharge in the outlet section of the catchment with the runoff from landscape units occupying its area, and calculating on the basis of the equation $Q_j = \sum q_i f_{ij}$, where j is the river basin index; Q_j is the runoff from it, L/s; q_i is the modulus of flow from the i th landscape complex, L/s km², and f_{ij} stands for the areas of the j th basin occupied by the i th landscape, km². The map is constructed on the basis of the long-term average values of river flow and landscape characteristics of the Lake Baikal drainage basin. The lake's catchment encompasses different landscape zones and altitudinal belts, which is responsible

for a high degree of generalization and a large contrast of the values of the flow. The amplitude of fluctuations in the modulus of annual flow varies from more than 10 L/s km² in goletz and mountain-taiga landscapes to virtually 0 L/s km² in deserts areas of Mongolia (the Selenga basin). A similar procedure was used in constructing maps of minimum summer flow and maximum flood flow within the Lake Baikal drainage basin which were included in (Ecological atlas of the Lake Baikal basin 2015).

Other requirements should be taken into account in the event of mapping the streamflow at the regional level in the hydrographic network. First, it is desirable to show the true magnitude of streamflow in river systems in channel water discharges rather than the characteristics averaged over the territory. Second, it is important to cover on a single map the maximum possible spectrum of rivers of a different size (except for the smallest rivers). And, third, in order for the map to have a practical importance, it is necessary for users

to be able to rapidly obtain specific and sufficiently accurate information on the magnitude of streamflow in any given river section.

These requirements are satisfied by the technique of *longchannel mapping*, based on the tools of structural hydrography (Korytny 2001; Ilyicheva 2009). Large-scale topographic maps are used to construct the river network graph for the region, based on the principles of the Horton-Strahler river order classification. A calculation of the structural measures taking into account hierarchy, order, braiding and subordination of all elements of the river system saturates all topological space of the graph of the river system with structural information, and a close linkage of the structural measure to the mean magnitude of streamflow permits the flow to be determined at almost every point of the system. The relationships of the mean magnitude of streamflow, represented as an average long-term water discharge, with the structural measure in the same river section are constant

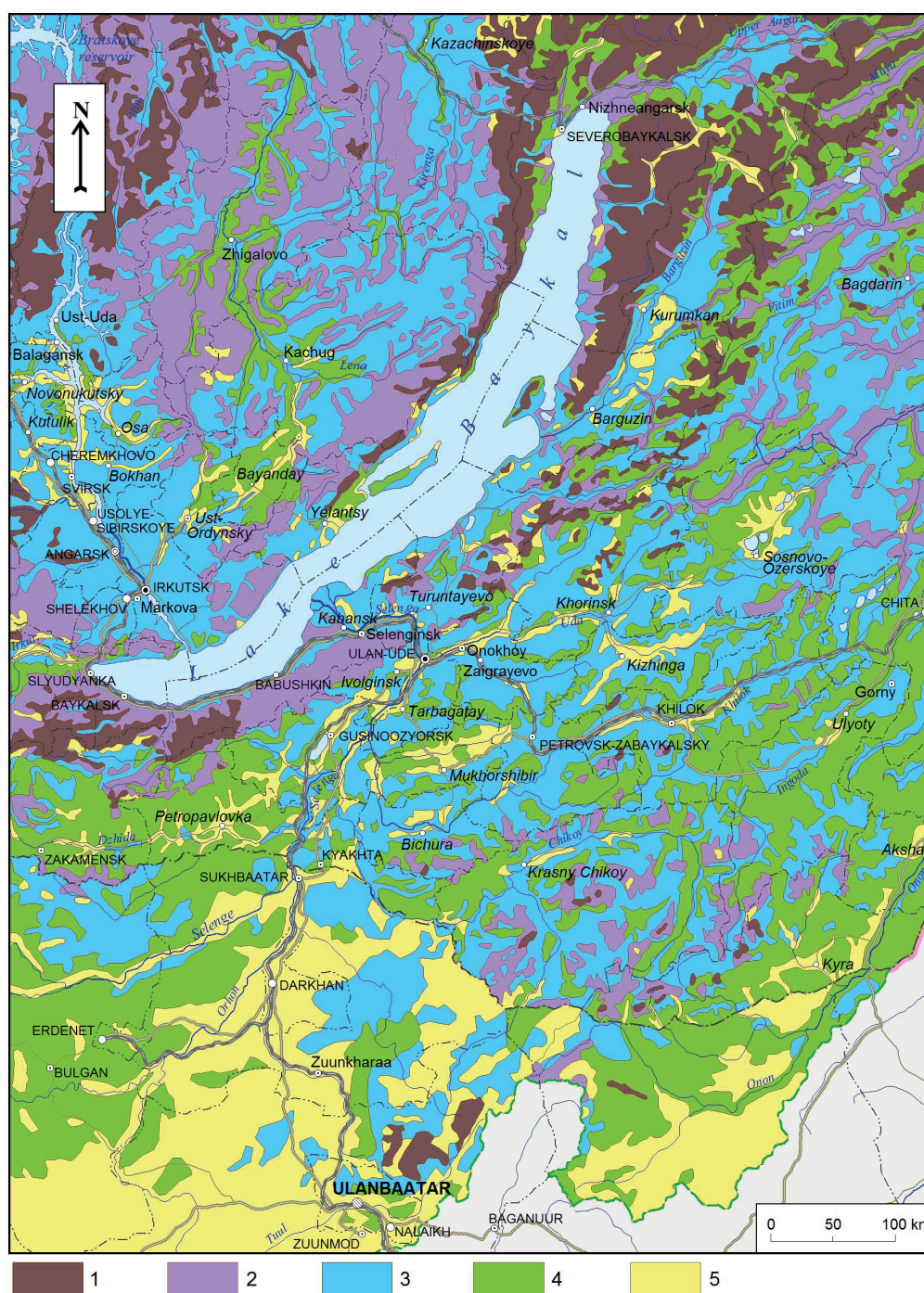


Fig. 1. Average annual runoff in the Baikal region. Modulus of flow, l/s/ km²: 1 – more than 10, 2 – 5–10, 3 – 3–5, 4 – 1–3, 5 – less than 1

for geologically homogeneous territories and constitute a statistical model of the river system as the set of permanent streams displayed on topographic maps, which corresponds to a stable average long-term flow.

The maximum or extremely high water runoff can be assessed using the dynamical model for the river system constructed from SRTM images. The dynamical model is represented by the set of thalwegs more than 75 m in length, whose activity is responsible for an increase of the number of elementary water-erosion components which operate solely in the period of maximum humidification at the passage of extreme water runoff. The calculated maximum water runoff (extremely high flow) shows a complete capacity of the water-erosion network. The calculated values exceed many times the observed values, in some cases by a factor of several tens or hundreds, and the reliability of such values is less than 0.1% (Amosova, Ilyicheva 2018).

This technique was used to prepare maps of water resources in the ecological atlases of the Baikal region. Structural parameters were calculated for each point of confluence of the streams on the basis of the river network graph. Structural modules were determined, which represent the ratio of water discharge to the structural measure at this point. The basic characteristic, water runoff of the river systems, is shown as a longchannel scale band (epure) (Fig. 2). This procedure refers to the group of localized diagrams, a method of mapping phenomena that are of continuous or linear (bank-like) occurrence. In this case, the epures are assigned to the linear element of space, i. e. to the river channel. The epures are drawn on both sides of the river channel proportional to the flow. The width of the epures varies smoothly along the length of the river, at the points of confluence with tributaries, depending of their water runoff.

A similar technique was also used for the other maps. Thus, on L.A. Bezrukov's map that was included in (Ecological atlas of the Baikal region 2017), where the spatial characteristics of the distribution of a stable streamflow were determined through a special zoning of the territory of the Baikal region from the conditions of the organization of large-scale centralized water supply from surface sources, the zone of different water availability are highlighted as bands running parallel to surface sources, i. e. water bodies: rivers, lakes, and reservoirs.

Regionalization also refers to traditional geographical methods. Thus, for generating the flood hazard maps the aforementioned atlas used the approach in which a flood hazard is characterized by the flood genesis and frequency, strength of flood impact, the size of damage and by the possibility of forecasting a hazardous situation. An integral flood hazard is determined by a different combination of these characteristics, and hazard classes are identified (low, moderate, significant, high and very high) (Kichigina 2018). Three classes of hazard (significant, high, and very high) are singled out for periodically flooded settlements. A combination of all characteristics analyzed is used to identify districts with a different integral flood hazard; in this case, the genesis of floods in river sections is designated by symbols (Fig. 3).

Based on the dual (socio-economic and natural) character of the spatial aspect, the flood hazard was determined for municipalities in the rank of administrative districts, with due regard for basin approach. Such an approach provides a means of making targeted practical use of results obtained. A **very high hazard** of flooding is characteristic for the most developed agglomerations of Irkutsk oblast, the Republic of Buryatia and Zabaikalskii krai (district). A *high hazard*

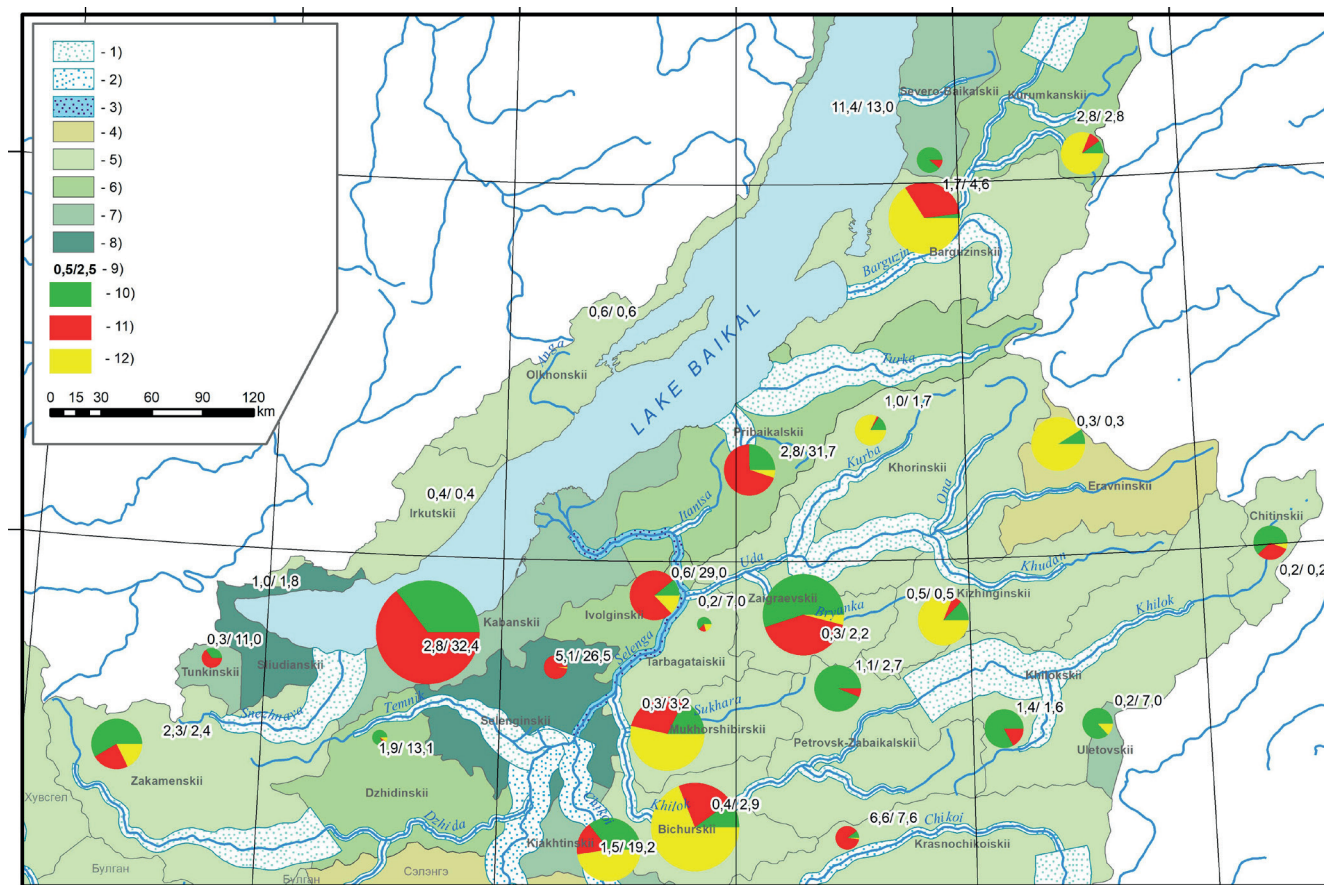


Fig. 2. A fragment of the map of water-carrying capacity and water use in the Baikal region
Water bearing capacity, m³s⁻¹: 1 - 1 mm: 5; 2 - 1 mm: 50; 3 - 1 mm: 500. Water availability, km³/1000 km²: 4 - less than 0.005; 5 - 0.005-0.15; 6 - 0.15-0.25; 7 - 0.25-0.35; 8 - more than 0.35; 9 - local flow/total flow, km³/year.
Water use, %: 10 - Household and drinking; 11 - Industrial; 12 - Agricultural

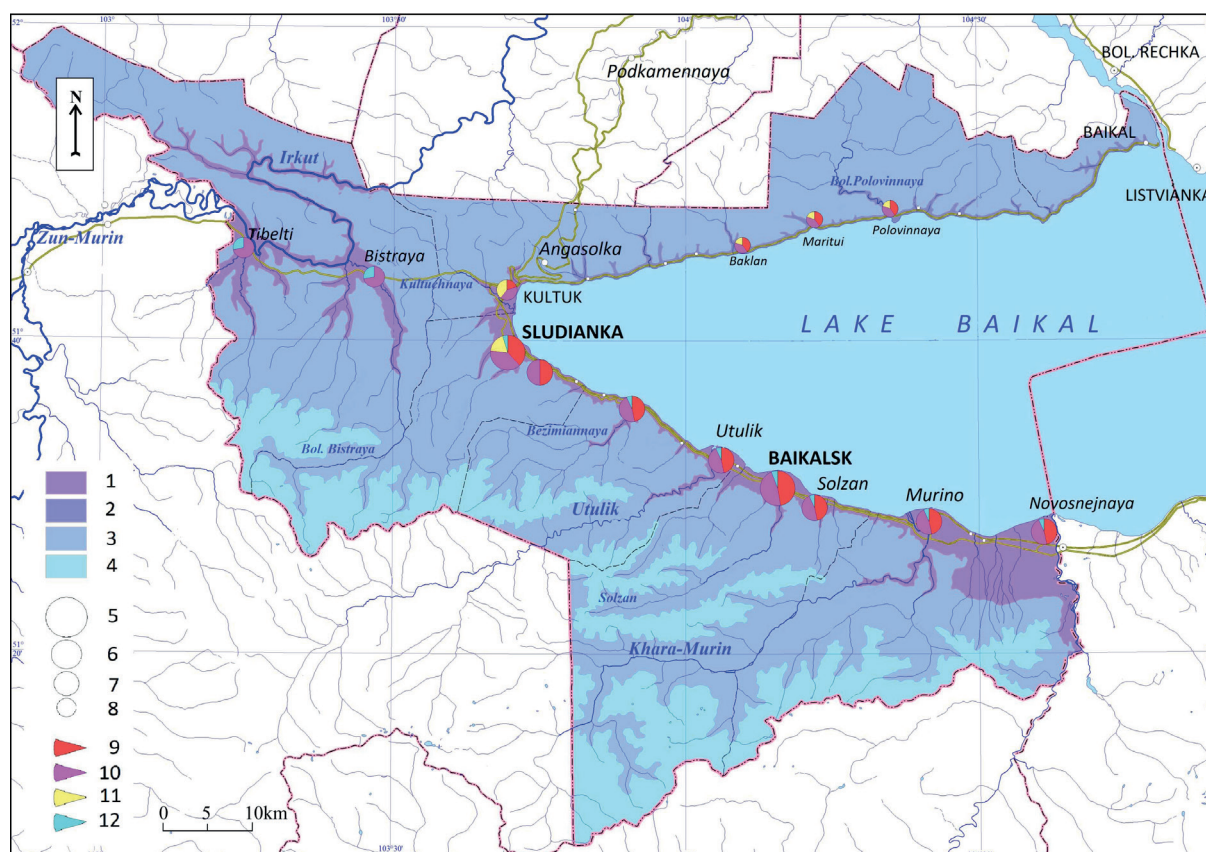


Fig. 3. Flood hazard for the Slyudyanskii district of Irkutsk oblast

Hazard: 1 – high, 2 – moderate, 3 – low, 4 – no floods. Degree of flood hazard for settlements: 5– very high, 6 – high, 7 – moderate, 8 – low. Flood genesis: 9 – debris flows, 10 – rainfall, 11 – aufeis, 12 – snow melt

also occurs in the southern districts of these subjects with the largest number of flooded settlements, including the cities of Tulun, Nizhneudinsk, Irkutsk, Cherekhovo, Zima, Angarsk, Ulan-Ude, Chita, Shilka, Nerchinsk and Sretensk. Floods present the highest hazard, although flooding of a mixed genesis is also possible (floods coupled with ice jams or rainfall). Damage to settlements and to agricultural and industrial enterprises in these densely populated and well developed areas can be very large. A *high hazard* is also typical for the northern districts of Irkutsk oblast within the Lena river basin: in the Kachugskii, Kazachinsko-Lenskii, Ust-Kutskii and Kirenskii districts. In spite of a relatively small population size of these districts, most settlements are situated along the river banks and have long been affected by flooding of a different genesis, such as Zhigalovo, Ust-Kut, Kirensk, Alekseevka, and others. Flooding of a different genesis is possible to occur there: ice-jam floods, snow-melt floods, rainfall floods and mixed floods (snow-melt floods coupled with ice jams or rainfall). A high hazard potential of rainfall-induced floods occurs in Mongolia in densely populated areas of the city of Ulaanbaatar and its vicinities in the Töv aimag.

Prospects for water resource mapping in the Baikal region

The cartographic program in the Baikal region is continued with the creation of a new fundamental atlas entitled «The Baikal region: society and nature». The contents of all relevant maps will be distributed in the following three large thematic directions: socio-economic factors for formation of the ecological situation, ecological status and transformation of the environment, and the medical-geographical situation; environmental protection, and rational nature management. It is intended to use a multilevel system of mapping to include maps of Baikal-Mongolian Asia, federal subjects of the Baikal region and

their municipalities, and large-scale maps of local areas influencing the natural environment.

Water resource maps should occupy an important place. But the lags in previous cartographic products must be filled in. In particular, special attention should be paid to the block of water economy maps to focus on the present status and future hydroelectric energy, water supply, water transport and water recreation uses of natural resources. The decision on the boundaries of the water protection zone of Baikal was taken. The theoretical framework for projecting the water protection zone is provided by the landscape-hydrological principles permitting the size and configuration of the water protection zone to be determined in accordance with the spatial differentiation of landscapes having individual hydrological properties. The processes of flow formation and control and natural water accumulation and filtration in vegetation and soil elements of landscapes are responsible for the different flow and purification regimes as the water mass approaches the lake.

The same principles of landscape-hydrological organization of the territory were used as a basis for the recreational zoning of an area on the southwestern coast of Lake Baikal within the boundaries of the Central Ecological Zone of the Baikal Natural Area. The landscape-hydrological map of recreational zoning illustrates a need for territorial restrictions in tourism development of the territory, defining the zones of absolute preservation and regulated use (Fig. 4).

Mapping and modeling of processes in deltaic systems opens up brand new vistas. It is suggested that river mouths be treated as open geosystems, volumetric geological bodies which are end components of global river systems. Special attention is given to the Selenga river delta, the main tributary of Lake Baikal. Cartographic material from different time periods was used to generate morphodynamical models of subaerial surfaces and neighboring aquatic areas which

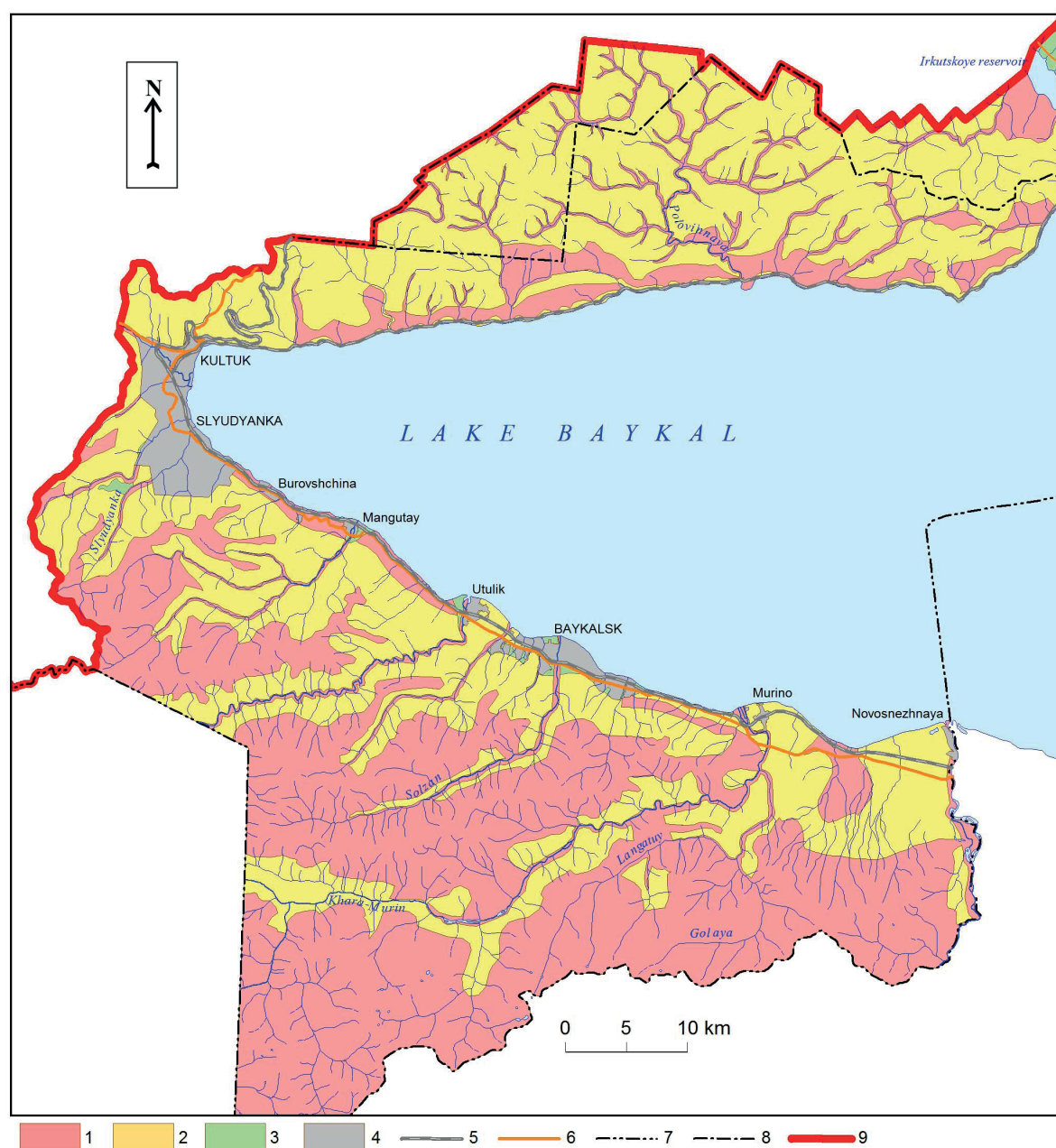


Fig. 4. Landscape-hydrological zoning of a section along Baikal's coast. Zones: 1 – preservation of the present status, 2 – limited development, 3 – development, 4 – settlements; roads; 5 – motor road, 6 – railroad; boundaries: 7 – boundary of the Slyudyanskii district, 8 – boundary of the Irkutskii district, 9 – boundary of the Central Ecological Zone of the Baikal Natural Area

characterize the dynamics of the bank line, the position of channels in plan, and hypsometry of the surface and bottom elevations of the channel network. An important applied aspect of these efforts is represented by schematic maps of natural risks, showing a relative stability of different portions of the river mouth geosystem for land use planning in particular hydroclimatic conditions. Many years of field investigations within the Selenga river delta and the implementation of the historical-cartographic method enabled us to determine zones of the most intense manifestation of erosion and accumulation processes within the main morphological elements of the deltaic plain (Dong et al. 2016, 2019). An objective rationale is given for the zones of relative stability and for the zones undergoing continual changes in the rate and direction of bank erosion. Long-term manifestations of modern tectonic processes are taken into consideration. The maps prepared by this technique were included in the latest (Ecological-geographical atlas-monograph Selenga-Baikal 2018).

CONCLUSIONS

In view of an ever-increasing role of water resources across the globe, it is emphasized that the role of water resource mapping conducted from the geographical perspective must become more prominent in atlas products. A wealth of experience gained from such mapping in the Baikal region might also prove useful in this regard. As our research has shown, the experience of which is summarized in this article, it is important:

- to consider a set of water resource maps as a system of interconnected works, covering all aspects of formation, spatial-temporal distribution and use of water objects and water resources;
- take into account the methodological specifics of creating of different groups of water resource maps in different geographical conditions;
- to recommend for study and application the examples of water resources maps of the Baikal region, including the continuation of atlas mapping. ■

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