Landscape-hydrochemical aspects of geocological monitoring

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Abstract. A comprehensive geocological monitoring program is implemented in the Lake Baikal basin. The methodology is guided by the principle of mixing. Identification of anthropogenic sources of substance and observation of connections between them and environmental objects occurs by considering objects as a mixture, and sources as their components, using landscape monitoring approach. The main research methods are landscape science and hydrochemistry. The pollution structure of geosystems is revealed by analyzing the spatial-temporal distribution of pollutants and subsequent reconstruction of their composition from sources. A cartographic basis has been developed to substantiate the observation and control network, extrapolate the monitoring results and represent operational information about the geosystem state. The mapping procedure is based on the main provisions of the teaching about geosystems by V.B. Sochava. We mapped differentiation, migration and accumulation of pollutants using modern methods of geoinformation analysis and modeling, adapted to the research region and analyzed the main parameters of landscape-geochemical differentiation of the Lake Baikal basin. A zoning scheme for the territory according to the ability to provide a specific composition of waters has been compiled. The ability of surface waters of the basin to self-purification is estimated. An approach for the conjugate assessment of the permissible pollution load on aquatic and terrestrial ecosystems is developed.

1. Introduction
Technology development for monitoring and forecast of environmental state to prevent its pollution and minimize environmental risks is one of the most important tasks of applied geography and geocology. For Baikal, as a unique natural object and the largest reservoir of drinking water, it is necessary to identify the sources and routes of potential pollutant entry into the lake. Despite the large number of publications devoted to water pollution and bottom sediments of Lake Baikal [1-10], the sources and routes of their entry into the lake are still unclear. There is a tendency to assume that the sources located near the lake (directly on the shore or on its tributaries) are the main pollutants of the adjacent water area [4, 5]. However, this does not always correspond to the truth: our research showed that the link between the source and the pollutant, which seems obvious, can often be absent [11]. Activities for reducing the pollutant content in surface and ground waters of Lake Baikal and prevention of negative impact of pollutants on human health in the region should be based on the
results of studies of the spatial-temporal pollution structure of the lake basin, taking into account the analysis of its landscape organization and the patterns of pollutant distribution. To this end, a program of comprehensive geoecological monitoring of the Lake Baikal basin has been developed.

2. Materials and methods
The research objects are Lake Baikal, its tributaries, catchment areas of the lake and tributaries, as well as their individual geosystems. The authors selected and analyzed samples of lake, river, ground and snow waters, samples of soil, rocks, bottom sediments, suspended sediments in accordance with standardized methods. Methods of statistical data analysis, multicomponent mix using systems of linear equations were used to solve the research problems.

We used the methodology of complex geoecological monitoring, based on the principle of mixing. Mixing is a natural process of integration of a substance disintegrating in the process of hypergenesis, which leads to the formation of new, complex multicomponent objects [12]. The identification of pollution sources and observation of connections between them and environmental objects are carried out by considering objects as mixtures, and sources as their components [13].

The indicator of the correlation ratio between the pollution source and object is the contribution volume of the source to the pollution of the object. Its change in space and time means a change either in the operation of the source or in the route of pollutant. Relationships are assessed not only qualitatively (identifying migration pathways of a substance from a source to a receptor), but also quantitatively (determining the ratio between the substance amounts in sources and in the receptor).

To calculate the source contribution, the mixture of their emissions is presented in the form of a geometric model, and the values of contributions are calculated by solving systems of linear equations where the variables are the segments of sources and the coefficients are the relative concentrations of pollutants, and the sum of the variables is equal to one. Identification of sources is carried out by overlaying maps of the prevalence of pollution and the values of sources’ contributions to pollution on maps of economic activity structure (location of industrial, municipal and agricultural facilities) using GIS programs. The concentration of isolines of contributions (or color intensity) of a hypothetical source near a real object of economic activity means that the source has been identified [13].

Changes in environmental components are forecasted by determining the changes in the ratio between the original proportions in the receptor and the ratio of the contribution of initial substance to the receptor. This approach should provide a joint assessment of the pollution scale of geosystems, identification of sources and routes of pollutants into Lake Baikal and the components of geosystems in its catchment area. The main research methods are landscape science and hydrochemistry. The methodology for creating a cartographic basis for monitoring is based on the basic structural and dynamic concepts of landscape science [14-16]. It includes an assembly of methods and approaches proposed to represent not only the spatial patterns of differentiation and integration of natural formations but also to show their temporal changes [17-20]. Since our research object is the catchment area of Lake Baikal, then the basin approach is also used in mapping, since the basins are frame formations with clear orographic boundaries (watersheds), which have a strict hierarchy, which remains at any scale, as well as the unidirectionality of matter flows, which enables closing their balances at specific sections. The GIS database contains layers of spatially coordinated data that are linked in time. It should provide the ability to analyze the variability (dynamism) of objects or their components both on the basis of tracking the variability of their boundaries, and on the basis of comparison of attribute data linked to asynchronous layers of spatial information [21, 22].

3. Results and discussion
The comparison of data on pollution structure with data on the economic activity structure allows identification of pollution sources. To identify the economic activity structure within the Lake Baikal basin we analyzed the structure of land use in the whole study area (figure 1), as well as the infrastructure for electricity production in the Central Ecological Zone of the Baikal Natural Territory.
The analysis of the land use structure and location of polluters was carried out using statistical, cartographic materials and interpretation of satellite images; data on the location of polluters of geosystems with combustion products were taken from the corresponding publication [20].

![Land use structure of the Baikal Natural Territory.](image)

**Figure 1.** The land use structure of the Baikal Natural Territory.

To fill in details we identified the spatial patterns of formation of the chemical composition of atmospheric precipitation (snow), sources of air pollution, as well as an assessment of the polluters’ contribution to snow cover pollution. Snow cover was used as an indicator of air pollution, and elements most common in the Earth's crust (Si, Al and Fe) were used as indicators of pollution sources. The research materials were snow survey data from Lake Baikal and the Selenga delta in February 2019 and 2020, as well as literature data [21-24]. Si and Fe concentrations of normalized to Al were used as coordinates in the mixing diagrams and as coefficients of variables in the mixing equations. The mixing diagrams showed that the main sources of pollution were coal and fuel oil boilers and wood-burning stoves. We considered the elemental composition of snow cover as a
mixture of two (burning oil and coal) and three (burning wood, coal, and oil) sources to rank the main sources according to their relative importance. The calculated values of the contribution of sources to pollution were mapped.

We analyzed the main parameters of the landscape-hydrochemical differentiation of the Lake Baikal basin in accordance with the research program, ranked the uniform indicators of water composition that relate their pollution to natural conditions, and developed a zoning scheme for the territory in accordance with the possibility of providing a certain water composition. These data allow assessing the self-cleaning ability of surface waters and permissible loads. Several hydrological and hydrochemical surveys were carried out in the Baikal basin, which were associated to a certain extent with various aspects of assimilation processes of pollutants in river and lake waters. In particular, the assessment of the suspended sediment recession and subtraction of bottom sediments in the Selenga River and its delta [25-27] can be considered as an assessment of the river’s self-cleaning from solid particles. The resistance of rivers to anthropogenic impact was assessed to a certain extent using the morphometric and hydrometeorological characteristics of their basins [28]. The results of several researches concerning the chemical composition of river and lake water can be considered as qualitative assessments of water self-purification. A decrease in the concentration of macro- and microelements from the source to the mouth of the Selenga can be interpreted, for instance, as sequestration of elements due to dilution [29-33], different concentrations of biogenic elements [33, 34] and heavy metals [35] in different delta channels as different water capacity for self-purification in these ducts, and changes in the concentration of solutes along the ducts as changes in the self-purification ability.

We have identified that one of the main processes responsible for the removal of pollution is a filtration decrease of river waters into groundwater, and the most important chemical process for the removal of pollution from freshwater reservoirs is the co-precipitation of organic and inorganic solutes with solid particles, insoluble hydroxides and authigenic aluminosilicates. The efficiency of these processes increases with an increase in water mineralization and turbidity and decreases with an increase in the organic matter concentration. The intensity of self-purification processes depends mainly on the morphometric characteristics of the catchment areas that control the most important parameters of freshwater ecosystems (biological activity, hydraulic residence time and area of mineral surfaces exposed to water impact). The highest rates of pollutant elimination were observed in Baikal, which is characterized by the longest water residence time. The highest rates of pollutant elimination from inflow waters were observed in summer, when the maximum length and width of river channels coincided with the maximum mineralization and density of microbial and algal populations. The waters of the upper reaches of the Selenga River with higher salinity and turbidity than in the lower reaches are also characterized by higher rates of pollutant elimination. The minimum values were found for the small Krestovka river with high concentrations of organic matter4.

Today’s concept of permissible loads assumes a separate approach to the determination for terrestrial and aquatic ecosystems [36]. The river and the mountain slopes rising above it are a classic example of geochemical conjugation of terrestrial and aquatic landscapes connected by a downdraft of matter [37], and a coupled assessment of pollutant loads for them is not only possible, but also required. The river is a recipient of matter coming from the catchment area, therefore, the calculation of loads for the ecosystems should be based on the results of calculating the load on the river ecosystem.

The load should take into account not only the criteria of ecosystem sustainability, for instance, maximum permissible concentrations (MPC) and classic items of the pollutant budget (values of atmospheric deposition of a pollutant, removal as a result of felling, etc.), but also the ability of

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4 Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads & Levels and Air Pollution Effects, Risks and Trends 2004 (Berlin: Federal Environmental Agency) Income accessed online on 22th August 2020 via https://www.um weltbundesamt.de/sites/default/files/medien/4038/dokumente/manual_complete_english.pdf
ecosystems to self-purify. A coupled assessment of the permissible loads of pollutants on aquatic and terrestrial ecosystems should be based, in our opinion, on the assessment of recession (assimilation) rate or input of a pollutant in the lower and upper sections of the selected section of the river depending on the difference in its mass flow rate. This rate was considered as the value of the current load of the pollutant on the river ecosystem. The maximum allowable input of a pollutant between the sections, calculated on the basis of MPC, was considered as the maximum allowable load, and the difference between these values was the balance of the emission limit (allowable load) of the river ecosystem. The rate of atmospheric pollution was considered as the current load of the pollutant on the ecosystem as a whole, the sum of the rate of pollutant elimination as a result of felling and the rate of assimilation/input of the pollutant in the river, referred to the area of the drained catchment area, was considered as the maximum permissible load, and the difference between them was the balance of the emission limit (allowable load) for the ecosystem as a whole [38].

4. Conclusion
We developed the main approaches to the methodology of geocological monitoring of the ecosystem state in the Baikal basin. It is based on identifying anthropogenic sources of matter and surveys of connections between them and environmental objects by considering objects as mixtures and sources as their components. The methodology for cartographic support for monitoring the structure of pollution and distribution of pollutants in the Lake Baikal basin was substantiated on the principles embedded in the theory of ecosystems. We analyzed the main parameters of the landscape-hydrochemical differentiation of the basin, an assembly of maps was compiled, the self-cleaning capacity of surface waters was assessed, and a method for the conjugate assessment of the permissible loads of pollutants on aquatic and terrestrial ecosystems was developed.

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