An Evaluation Method of Ecohydrological Conditions in High Mountain Areas: An Applied Study of the Lake Baikal Basin

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Abstract

One of the urgent problems of hydrological and ecological research in mountainous countries is the evaluation of conditions and the forecast of behaviour of the natural environment subjected to human impacts. This can be carried out on the basis of the analyses of the transportation and transformation processes of polluting substances and revealed by the indicators of environmental conditions.

Introduction

The representation of territorial landscape geochemical systems (LGS) can serve as the basis for the division of landscape hydrology into districts possessing a determined level of geochemical immunity, i.e., self-regulation of migratory processes and refined technical genesis. It is necessary to note that the landscape may be considered not only as a result of the interaction of natural processes, but also as a system carrying out the work of this interaction. Each such system is characterised by specific interactions of its elements or blocks: atmospheric precipitation - vegetation - soils - mountain rocks, surface and underground water, all creating the individual features of such a system of migration, transformation, and accumulation of suspended and dissolved substances. The identification of these processes is effectively revealed on the basis of spatial-temporal variability research on the content of chemical elements in the water of rivers, as controlled by a structure of landscape pools drained by a river network. According to its organisation, LGS can be sub-divided into elements and a cascade. An elementary LGS forms lower steps and represents lithologically similar territories, ones covered by the same types of soils and, hence, certain vegetation communities (VC). Such a territory can be considered as an indivisible landscape - an individual. The channels of communication between the components of an elementary landscape are migration flows, consisting of the phase-carrier (moisture flows) and the phase-dissolved (firm substances). An elementary LGS set forms a cascade LGS, with each elementary landscape being a part or block of a columbine system. A detailed theoretical substantiation of the landscape-hydrological approach and the main concepts of the mountain flow formation model as applied to water flows are stated in Stepanov et al. (1987).

The accepted approach consists of the following: The flow formation in river pools is determined in general by two main processes that ensure the transformation of atmospheric precipitation and the accumulation and drainage of moisture. During the winter period this takes the form of an outflow of moistures accumulated in underground reservoirs. The flow at a hydrometrical station represents the total character of the columbine, which consists of quasi-homogeneous sites (chambers, rocks complexes, etc.). The river pool is considered as a linear system, in which the flow formation occurs under the essential influence of water loss, with a series of allocated heterogeneities. Heterogeneity indicators may be landscape elements consisting of river pools. Thus the heat-moisture relationship and, hence, the volumes of migration of dissolved substances, as well as their chemical composition, can reliably indicate dominating types of VC and soils for periods of mixed river feed.

The water holding capacity properties of mountain rocks are governed by their filtration properties. Generically similar flows in a winter period may be indicated by the distribution of different kinds of rocks (water-bearing complexes) along with the various values of filtration factors in the pool.

The standard basis for heterogeneity allocation can serve the needs of landscape maps or special vegetation maps, geology, and hydrogeology. A complete set of maps is possible in cases in which the dismemberment of the hydrograph of river flow into genetic sources of water flow is reliable.

The use of information about the spatial distribution of other area indicators is admitted: physical and mechanical properties of soils, geological formations, and thermics (including frozen ground). Thereafter area characteristics are model predicators (arguments) on which the spatial-temporal variability of flow characteristics depends. According to the formulation of the problem, the regression equations are solved stepwise for several columbines, corresponding to appropriate volumes of river flow. The factors in the equations are evaluations of the specific contribution of similar elementary columbine sites to basin flow; they define the differences in its formational processes inside the pool. In order to evaluate the dissolved substances, a system of linear equations was written, taking into account the heterogeneity allocation:

$$\sum_{i=1}^{n} M_i F_{i,j} = q_{i,f}. \qquad (1)$$

where,
$q_{i,f}$ = ionic flow of the j-th pool (mg/sec),
M_i = module of ionic flow (mg/sec/km^2) of the i-th, and
VC, $F_{i,j}$ = its area in the j-th river pool km^2.

A similar record can be also made for other physical and geographical area characteristics. Linearity of the model is a compulsory requirement, to the extent that the factors of equations involving non-linear approximation cannot be physically interpreted.

The second requirement is the stability of model parameters under conditions of minimum non-conformity of the calculated to the actual river charges. This can be reached by using a procedure of singular decomposition of a matrix of initial data (Forsate et al. 1980). This method permits one to reduce a general problem of minimum squares (MMS) to a problem involving a diagonal matrix, elements of which are singular data $\sigma_j (j = 1,..., n)$,

where,
$n =$ the number of variables in the left part of the equation.

Further a factorisation of the initial matrix of predicators is carried out, i.e., some linear but independent basic vector Z_j is entered (similar to the method of main components) which in the solving of a system of linear equations yields a minimal non-conformity of equations. Thus, all $\sigma_j \neq 0$, i.e., the uncertainty of equation factors, Z_j is reduced to a minimum, and a single decision is reached. The correctness of the decision from the point of view of the inverse problems is gauged by the compatibility of the reverse system of linear equations for particular river pools, i.e., their fitting a similar hydrological and geochemical region and methods of solution. The solution of similar problems by the method of least squares over a large number of equations produces unstable values for the calculated factors. Introduction into singular decomposition of matrix predicators by an orthogonal procedure results in an increased number of conditioned matrices and, hence, in the acquisition of steady equation factors. The solution is an iterative one, and use of orthogonal vectors ceases when a satisfactory solution is obtained (concurrence of actual and designed sizes $q_{i,t}$). The equation factors are characterised by dimensions M_i (mg/sec/km^2), which permits one to carry out a genetic interpretation of them and transfer the results of the calculation to identical LGS in unknown pools. This is one of the functional aims, namely, to solve the problems relating to ionic flow formation of rivers and the functional properties of LGS.

The concentrations of some elements in natural bodies of water, including dangerous toxins, are connected with the general mineral make-up of river waters (this depends on the size of river charges). Therefore, for a quantitative evaluation of their migration within landscapes, it is necessary first of all to learn the dynamics of general mineral macro-elements or ionic flow.

For the solution of our problem, data of 22 rivers flowing into Lake Baikal were used, as water chemistry is being studied there. The majority of measurements were made at the mouth of the rivers. The problem of uncovering the formational conditions of the ionic structure of waters within the boundaries of various LGS is becoming even more urgent. A sampling in separate months accompanied by an account of river flow was conducted during selection tests. This allowed us, with the help of a method for normalisation (Alekseev 1971), to establish a correlation dependence between mineralisation and flow. On the basis of the same probability parameters, the volumes of ionic flow for monthly periods were calculated. Such a calculation technique is called for by reason of the statistical discrepancy between average monthly river charges and mineralisation, owing to the non-linear relationship between them.

The calculation allowed us to evaluate the mean perennial size M_i and to calculate mineralisation flows in terms of annual dynamics from ten main types of floral communities. In all cases the authentic solutions were characterised by high multiple correlation coefficients (R=0.96 - 0.98) and steady factors in the regression equations (Khaustov et al. 1991). The largest values of M_i are typical of larch-pine mountain taiga forests and yield 42.3 tonnes/year/km^2; the least values apply to meadow communities, both high mountain and lowland (2.74-5.38 tonnes/year/km^2). The wide variation in M_i over a region and time testifies to the ambiguity of how the general landscape reacts to the humidifying of a territory and so validates the equations. Some VC, despite the various scales of their distribution, demonstrate similarity in the transformation mechanism of moisture into ionic flow. Thus for integrated VC (mountain tundra and thin forests on valley slopes) similar values of the parameter M_i are obtained for all phases of the water mode, which is explained by the unity within the formation mechanism of surface water flow and the brief contact with frozen soils and rocks. A significant role in the formation of river and ionic flow is played by dark coniferous mountain taiga forests and their restoration as aspen-birch and larch-pine forests, which appear in the wake of human changes to natural complexes (radical vegetation after clearance, fires, etc).

The geochemical stability of a natural system may be transformed as reflected in the quantitative and qualitative alteration of the geochemistry of the water mode that is formed within the limits of the landscape. If M_i found with dark pine forests and their restoration series are comparable (19 and 13-15 tonnes/year/km^2), the mineralisation of this series sharply grows to 109-126mg/l (for dark pine forests - 37mg/l). This fact is well mirrored in the annual course. In this connection, possible ways can be devised to forecast hydrochemical landscape mode changes as a result of economic activity.

The calculation of water mineralisation is also carried out on the basis of the model. In the beginning the modules of water flow M_{flow} were calculated for similar LGS and then, by the division of the parameter M_i over M_{flow}, the required value was defined.

An analysis of the annual water flow for various LGS has revealed the tendency to water budget atrophy according to exponential rule, and this is in line with representations of the river drainage network mechanism throughout the whole columbine.

Hydrographs of river modules of flow for territories of some VC are indicated in Figure 1. The hydrograph of restoration series (3) evidently reflects a sharp reduction of maximum flow, its large dynamics at recession, and the low steady values in the cold period of the year. This is connected with the regulating ability of a landscape. As the heaviest impacts of the regional human factor on Lake Baikal are connected with the clearance of forests, the offered method enables one to evaluate the negative effect on the quantitative parameters of water and ionic flow and to calculate possible economic damage from such clearance.

For the mineralisation values of river water, a clear-cut seasonal course is observed, which consists of recorded minima for May to June, when snowmelt water prevails in flow formation. Such minima correspond to VC mountain tund-

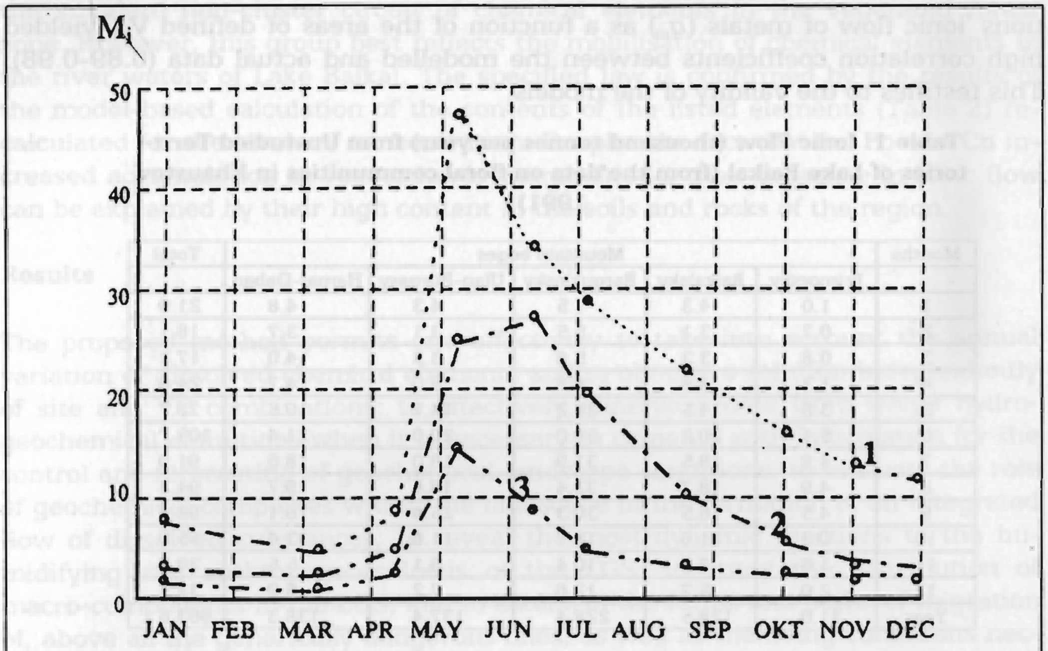

Figure 1:Hydrograph of River Flow with the Most Representative Floral Communities of the Baikal Region (Khaustov 1991): 1 - dark pine mountain taiga; 2 - larch-pine mountain taiga; 3 - birch restoration series from dark pine

ra and dark-pine mountain taiga forests. The mineralisation values are here close to those under atmospheric condensation, which testifies to the prevalence of surface water in river flow and an extremely insignificant share of underground supply. The maximum mineralisation is observed in March when depletion of the limited amounts of undergroundwater occurs.

For larch-pine VC there exists higher mineralisation at water minima as well as at maxima, which testifies to a slow down of water exchange within the limits of the territory of distribution. The reason for this is the low hypsographical location of the territories and the increase of the underground supply share.

As a result of M_i evaluations for particular LGS, data on the level of ionic flow from hydrologically unknown basins of Lake Baikal indicated in Table 1 could be obtained.

This volume is 664 thousand tonnes/year, while the total volume, including that of the investigated rivers, is 5,880 thousand tonnes/year. The proposed method is also effective for the study of micro-element migration.

For the solution of this problem, data on the metal content in affluents of Lake Baikal were used. These data are from the last decade of September 1978 and correspond to the stable phase of summer flow recession. As called for by the model, the q_m of metals were evaluated and their modules (M_m) calculated for the main VC (Table 2). On the whole, the solution of the system of linear equations 'ionic flow of metals (q_m) as a function of the areas of defined VC' yielded high correlation coefficients between the modelled and actual data (0.89-0.98). This testifies to the validity of the models.

Table 1: Ionic Flow (thousand tonnes per year) from Unstudied Territories of Lake Baikal (from the data on floral communities in Khaustov 1991)

Months	Mountain edges					Total
	Primorsky	Baikalsky	Barguzinsky	Ulan-Burgasy	Hamar-Daban	
1	1.0	4.3	7.5	4.3	4.8	21.9
2	0.7	3.1	5.5	3.1	3.7	16.1
3	0.8	3.3	5.8	3.3	4.0	17.2
4	1.3	4.8	8.8	5.0	4.7	24.6
5	3.8	14.5	26.2	14.7	19.5	78.7
6	5.4	20.2	38.0	20.0	21.4	105.7
7	4.9	18.5	31.9	18.0	18.6	91.9
8	4.9	18.7	32.4	18.6	19.7	94.3
9	4.5	16.5	30.3	25.4	16.1	92.8
10	0.3	11.6	18.7	11.6	13.4	55.6
11	1.6	7.3	10.4	6.1	5.5	30.9
12	2.0	5.7	12.6	7.2	6.9	34.4
Year	31.0	128.5	228.4	137.4	138.3	663.6

Table 2: Levels of Module Flow (μg/s km²) and Their Concentrations (μg/l) in Flows (denominator) from the Territory of Lake Baikal Basin (floral communities) in October 1978 (Khaustov, 1991)

No.	Cu	Pb	Al	V	Cr	Fe
1	24.8	3.4	1440.0	1.4	6.5	770.0
	0.68	0.09	39.7	0.04	0.21	21.5
2	2.1	0.4	307.0	0.3	1.4	173.0
	0.84	0.16	124.0	0.12	0.57	70.0
3	12.7	1.8	830.0	0.7	3.6	428.0
	0.68	0.1	44.9	0.04	0.19	23.1
4	24.7	6.7	5960.0	6.0	28.2	3360.0
	1.17	0.32	280.0	0.28	1.34	159.0
5	6.8	4.0	3910.0	1.6	14.9	1770
	1.28	0.75	738.0	0.3	2.81	334.0
6	0.1	1.0	1260.0	1.1	5.9	698.0
	0.1	0.3	420.0	0.37	1.98	233.0
7	16.9	2.1	623.0	0.4	2.3	276.0
	0.63	0.08	23.4	0.01	0.09	10.4
8	2.1	0.5	349.0	0.14	1.3	154.0
	0.7	1.66	116.0	0.05	0.43	51.3

1 - mountain tundra; 2 - alpine meadows; 3 - thin forests of dark pine on valley slopes; 4 - dark pine mountain taiga forests; 5 - larch-pine mountain taiga forests; 6 - larch-pine series from dark pine forests; 7 - cedar brushwood; 8 - larch-pine mountain hollow for-

For all metals, a notable stability of M_m over different VC was revealed. The maximum parameters of M_m obtain for dark and light pine communities, as well as mountain tundra; minimum ones, for meadow and alpine associations and restoration series.

In relation to the analysed metals, the values obtained for M_m can be submitted to a kind of group migration, Al-Fe-Cu-Cr-Pb-V, which does not correspond to the standard non-cluster circuit of chemical elements in the vegetated forest zone. However, this group best reflects the mobilisation of chemical elements in the river waters of Lake Baikal. The specified law is confirmed by the results of the model-based calculation of the contents of the listed elements (Table 2) re-calculated for the levels of concentration. Despite the fact that for Pb and Cu increased accumulation in vegetation is characteristic, their presence in ionic flow can be explained by their high content in the soils and rocks of the region.

Results

The proposed method permits one effectively to take into account the annual variation of dissolved chemical elements and to obtaine a solution independently of site and VC combinations; to effectively generalise data from single hydro-geochemical definitions when it is necessary to come up with information for the control and forecasting of geochemical landscape conditions; to evaluate the role of geochemical complexes within the landscape in the formation of an integrated flow of dissolved substances; to reveal the most dynamic reactions to the humidifying and anthropogenic loads of the LGS; to study the distribution of macro-components in the LGS; and to establish the forms and paths of migration of, above all the generically dangerous ones, as well as the living conditions necessary for the maintenance of vegetation with the purpose of preparing ecological geochemical maps; to assess the need to create base stations for monitoring representative sites in the main types of landscape in mountain countries; and to conduct searches for useful minerals subject to secondary aureole diffusion.

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