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RESEARCH ARTICLE

Hierarchical System of Landscape-geographial Spaces and Mechanisms of its Formation

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Abstract: A strategy for quantitative analysis of mono- and polysystemic organization of multi-level geospaces is described, with the construction of a series of empirical models of inter-component and inter-complex connections. The "micro-" and "macrosubstrate" approaches to the structural and functional analysis of the state of the natural environment are combined. As a methodological basis, a provision on the structural levels of natural-territorial organization is proposed, based on the conceptual cybernetic model of the natural complex as a hierarchical control system. A cybernetic model of the natural complex has been created as a hierarchical control system; the model has enriched modern ideas about the mechanisms and structural levels of the spatial organization of the natural environment. Model has enriched modern ideas about the mechanisms and structural levels of the spatial organization of the natural environment. An experiment was performed in order to analysis the state of geographical spaces by three blocks of cybernetic model: landscape frame, processor, and landscape pattern. Based on this model, a system of conjugation of different-level characteristics of natural components with the taxonomic rank of geographic spaces (from the geographical sector and natural zone to landscape facies and biogeocoenosis) was constructed. Using the Volga River basin as an example, a comparative assessment of environmental factors in their landscape-forming influence was carried out.

Keywords: geographical space, hierarchical organization, cybernetic model of the natural complex, structural levels of geosystems, comparative assessment of environmental factors

1 Introduction

The concept of geographic space developed along with the theoretical base and terminological apparatus of geography itself. Defined initially as some "... totality of places of action" of natural and social phenomena [1], this concept was further deepened significantly. In a modern interpretation, geographical space is a lot of Earth surface objects, consisting of individual elements, which have certain substrate properties and multichannel territorial connections – both internal and external [2–4]. Wherein, any medium transmitting a signal can serve as a communication channel actions from factor to the phenomenon [5].

The geographical aspect of the organization of systems consists in the mechanisms of connecting geo-components that are heterogeneous in genesis and rate of change, as well as complexes of the lowest rank into a single holistic formation [6]. The organizational principle is intended to help solve the key problem of synthesis in modern geography – understanding the essence of the processes of creating a whole, unified one from disparate parts and finding the keys to managing geosystems. This principle is in the full sense ecological, if we consider the concept of ecology (in its broad meaning) "... as the science of the structure and functioning of nature" [7, 10].

The most important attributes of geospace are: a) the integrity of geographical formations; b) the scale of their manifestation on the earth's surface; c) orderliness as the relationship of objects or processes in a certain repeating sequence. The leading system-forming role here is played by the physical surface of the Earth itself as a universal integrating factor that transforms the inter-component interactions occurring in the field of insolation and gravitational forces into certain territorial structures. Therefore, geospace is considered not only as a container of earthly bodies and phenomena, but also as a certain image of them, as well as a structure determined by the movement, displacement of substance. One of the key concepts of geography is also associated with the earth's surface – location, which serves as a cell of geographical space, its local expression (Ramensky 1971). "A place serves as an individual code for any element of the geosystem according to the relations of spatial ordering" [3].

The most important peculiarities of functioning of the "lithogenic geom – pedon – phytobiota" triad are the incomparability of the temporal frequencies of oscillations, or times of relaxation, of its components, according to [8], as well as the absence of any reliable correlations between them with a more than 3–4-fold difference between their relaxation periods [9], including the age of their modern state. A multi-speed ladder of characteristic times is a prerequisite for the development of any multi-substrate ecosystem [10], and the stable, equilibrium state of such a system is ensured by its spatial and temporal hierarchical organization [9], in which the "principle of functional integration" is of decisive importance" [7, 13]. Such are the real fundamental laws of formation of the biosphere.

In the study of geospace, the concept of integrity and inseparability of geographic environment proposed by Dokuchaev [11] and then developed and substantiated by Grigoriev [12] takes the central place and provides the most complete knowledge of the theory of geographical zonality. This theory as a general planetary bioclimatic phenomenon is closely related to landscape studies and ecology, which reflects the general trend of convergence between geography and ecology. The ecological approach allows expanding the scope of the already traditional object of physical geography such as natural zonality [13–17].

This message outlines the mechanisms of multi-level organization of geospaces created by transit, *i.e.* functional-dynamic, geo-components, but consisting of structural units (natural complexes) distinguished by fixed components – conservative (lithogenic) and soil-biotic. We are talking about studying the mechanisms of transformation of extraterritorial transit, or microsubstrate, according to [18], geocomponents under the influence of a lithogenic framework into territorial geocomplex, or macrosubstrate, structures.

2 Conceptual cybernetic model

The need to simultaneously account for both inter-component and inter-complex connections requires more sophisticated modeling methods for landscape studies. First of all, there are two key geometrical parameters of space, vector, and gradient, to be entered into the model. It is efficient to calculate the informational-statistical measures of inter-component coupling by the specific vectors of geo-flows, and the similarity (difference) between and inclusion of sites with respect to a particular set of natural attributes, aside from their modular values, should be supplemented with their gradients (also by fixed directions).

As the main working methodological basis for studying different-level natural-territorial formations, we have developed a *statement of the structural levels of landscape organization based on the author's conceptual model of the natural complex as a hierarchical system of control* (Figure 1). The model is in the form of a block diagram of similar figures (Shubnikov 1975) constructed by the symmetry operations of glide reflection and transfer (translation) with the simultaneous variation of the scale of parts of the system and the distance between them.

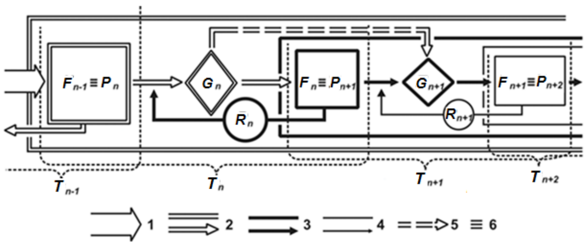

Figure 1 The conceptual cybernetic model of landscape-territorial complex as a hierarchic system of control

In Figure 1, T_{n-1}, T_n,... are the taxonomic ranks of complete and incomplete natural complexes. 1–4 – *T*he outlines of model units and directions of connections within the first- and forth-order structural levels. The units of the cybernetic model: *F* – landscape framework; *P* – landscape pattern; *G* – processor (complex of geoflows); *R* –feedback regulator. 5 – The background influence of the higher level of geosystem on the lower level. 6 – sign of identity. The glide reflection plane is perpendicular to the pattern plane.

The identity of outliners of the geosystem rank and the respective landscape framework to geoflows implies that the "vertical" ranging of natural complexes [14] should be based on finding their different-level structural invariants.

The choice of similarity symmetry for comparative demonstration of hierarchical landscape levels is not random. It comes from the properties of similarity of system organization of Earth physical environment and its parts. As is commonly known (Armand, 1975), the processes of territorial differentiation of natural complexes at all structural levels are subordinate to the same regularities common to all complexes. That is why there are no fundamental differences between the levels. The main difference consists in the scale and complexity of phenomena and processes under consideration, which corresponds to the nonequivalent landscape-forming "force" of different natural components. Hence follows the concept of background and space-differentiating properties of the same geo-components, which has already been established in physical geography. The landscape-formation significance of each component qualitatively changes depending on the ratio of land area to the spatial scale of manifestation of its particular properties. Hence, a researcher performs the generalization of component attributes under study.

Physical-geographic background **(*B*)** characterizes the state of any natural complex or its particular component with a kind of low-level spatial resolution. The background is a continuous distribution of an attribute, without marked leaps. The background function at each spatiotemporal point is a certain average value taken from the values of the given element in the neighborhood of this point [19]. Consequently, the background field parameters characterize a particular taxonomic "norm" of matter and energy resources of landscape formation at each site. There is a common potential level of the involvement of natural components in landscape organization associated with the background properties. As a special case of physical-geographical background, considered the zonal-regional "norm" of natural conditions for the mid-Siberian physical-geographic domain. Analogous "norms" can be established, e.g., for the natural district, locality, or stow, as well as for zone or land.

The transition from the background value of geo component to its space-differentiating role can be observed each time when the size of territory reaches its own minimum of particular geospace where this component is organized. The space minimum is a critical level, above which territorial variations of the factor exceed the error of its measurement or comparative assessment and the spatial resolution of geo component structure becomes quite important.

The space-differentiating influence of the geo component is associated with its intra-background variations and is most marked under the conditions of scale-adjusted proportionality of the compared components. Such variations are created by the difference between the actual and bakground values of the component at each point of the spatiotemporal domain [19, 20]. By localizing territorial natural interactions, components form the spatial structure of the landscape – its framework and pattern, depending on the scale of localization. Landscape framework and pattern are the input and output variables, respectively, for the *cybernetic model* (see Figure 1), which describes the natural complex as *a functional condition – process – structure system* capable of self-regulation.

The landscape framework **(*F*)** is formed by first-order localization processes. It is a complex of the most spatially extended and the least temporally variable structural elements, which conform to the territorial scale of this system and determine the relatively closed network of matter and energy transfer corresponding to this scale, as well as the junction points and the turning lines of geo-flows. The framework creates conditions for the formation of vector structures. It depends primarily on the geographical position of the territory, *i.e.*, exposure, in the broad sense of this term [21, 22]. At the regional level of geosystems, it includes the gravity, insolation, and circulation factors determined by morphotectonics and morphostructure, the background (belt, zonal and sectoral) values of radiation balance, and precipitation. Their superposition creates three necessary preconditions for the emergence of geographical backgrounds [4, 23]: material carriers of the field, the gradient of energy potential, and sources – the driving force of geo-flows. Of great significance is also the morphostructural "memory" of landscape: the first-order paleogeographical factor imposing certain constraints on flow activity. On a scale of local natural complexes (sites, stows, facies), the landscape framework is determined by morphosculpture of the respective order, the characteristics of small river systems, meso-climate, and, finally, phytocoenosis. On the territories of land development, the major elements of the framework are various engineering structures.

The attributes of landscape framework characterize the so-called isopotential structure of natural-territorial complexes: zonal, altitudinal-zonal, layer, strip, *etc.* [24], manifested to the extent appropriate to the territorial scale of geosystems.

According to Sochava (1978) [25], such structure in a sense can be called *invariant*, as it is precisely the one that determines the boundary conditions for the realization of the entire diversity of geosystem structures associated with exchange processes over its territory. The isopotential structure also corresponds to a certain vertical stratigraphy of interacting natural objects (bodies) and environments (habitats). Thus, it is possible to convert the term of geosystem invariant from a rather abstract category, as formulated by Sochava, into a category with more precise landscape content, which allows this term to be used as a tool of landscape analysis. Indeed, the linear and nodal elements of the geosystem framework of the given hierarchic level can be easily distinguished directly in the field using a map or aerospace photographs. The landscape framework is a "configurator" of geoflows, determining their intensity, interaction and spatial order.

The processor, *i.e.* ***geoflow complex*** (***G***), is the second functional unit (module) of the conceptual model. It combines a variety of matter-energy flows working under the boundary conditions of the given framework. There is a certain taxonomic periodicity of the system-forming role of geo-flows of different substrate nature [26]. Thus, on the planetary and superregional levels of geosystems, the major factors are the air flows of heat and moisture exchange; beginning from the regional scale, these are water flows creating river systems of different orders.

The links between elementary natural complexes are realized through the surface and groundwater flow, gravity-induced movement of loose material on slopes, and the aerial transfer of elements of the phytobiota. Natural transition can be complicated by technogenic flows. The identity of outliners of the geosystem rank and the respective landscape framework to geoflows implies that the "vertical" ranging of natural complexes (Armand 1975) should be based on finding their different-level structural invariants.

The landscape pattern (***P***) is a materialized representation of geo-fields and geo-flows, a "frozen" image (cast) of processes of the past and ongoing matter and energy transfer. It includes mostly soil-biotic and geochemical attributes, bio productivity of landscape, and low-order morphosculptural and microclimatic characteristics. However, like in the case of the framework, the attributes of landscape patterns are quite clearly differentiated by the structural levels of geosystems. The development of landscape structure under the influence of directed geo-flows includes two main processes: (1) complication of the vertical componential stratification of the landscape; and (2) "overgrowing" of the framework with elements of the pattern. In the former case, it is important to note the appearance of the so-called contact geo components, e.g., a "contact relief layer" [27] along with soil as a derived biocosus. Thereby, the "conditions–process–structure" essence of the cybernetic model of the natural complex is consistent with Neo-Dokuchaev's "factors–process–attributes" paradigm in soil science [28].

The feedback regulator (***R***) can be considered as the "memory" of geosystems. Fixed components developing along with the work of geo-flows themselves influence these flows, strengthening or, on the contrary, weakening them, thereby causing further development or stabilization of the structure. This is a manifestation of one of the mechanisms of geosystem self-regulation with either positive or negative feedback. The "conductors" of geosystem self-regulation can be, e.g., the "moisture–vegetation" or "soil heat–vegetation" links [25]. The change of the sign of feedback is typical of the logistic trajectory of the change in the functional attribute over time. It is necessary to determine the outlines of feedback with different signs for assessing the resistance of natural complex to external impacts. Negative feedback is the main attribute that differentiates self-regulation of a system from external control [23].

This conceptual model applies to natural complexes of any rank. A series of such different-level models will be subordinate and the landscape patterns of the higher-rank geosystem (its output variables) should be viewed as a landscape framework, *i.e.*, as external conditions (input parameters) for a lower-rank geosystem. Hence follows the *relative character of the concept of structural invariant of the natural complex*.

The same characteristics of landscape structure can be epigenetic (functionally determined) for one geo-complex and invariant to another one being a component of the former. Thus, the *model represents the multilevel character of landscape organization*, which fundamentally differentiates it from the known "dimensionless" landscape models [29]. At the same time, geospace structure, *i.e.* inter-complex connections, is studied through inter-componential interactions, due to which it is easier to disclose the causal mechanisms of formation of landscape lateral structure and to find out the directions with different resistance of this structure to external impacts. Preobrazhensky [30] noted the necessity of such considerable addition to the methods of landscape research.

3 Structural levels of natural territorial complexes

The structure and function of zonal types of landscapes and natural ecosystems, first of all, the complex structure of phytobiota and its productivity, seem to be manifestations of the higher organizational form of the biosphere (Table 1). Physical-geographical background, landscape framework, and landscape pattern are relative concepts and have conceptual meaning only as applied to a certain hierarchic level of the natural complex. Usually, the same attribute of a geo-component, being a localizing factor for a higher-order landscape, consistently enters the state of natural background as the rank of the system decreases. It occurs first of all with geological-geomorphological factors and last of all with biotic components. On the other hand, geo-components also differ from each other about the upper hierarchic level, where their space-differentiating influence begins from. This level in each case corresponds to the landscape taxonomic unit with its territorial dimensions being a fortiori greater than the critical scale of manifestation of significant spatial variations of geo-component or its particular attribute. Thus, *the "background–framework–pattern" triad is a certain gliding system representing the simultaneously subordinate-inserted character of landscape organization*, which is also represented in the model considered above. Distinguishing and analyzing different structural levels of natural complexes, we implement the systematic approach to comprehension of the structure and function of landscapes (see Table 1).

Table 1 Correlation of different-level properties of natural components and factors with the taxonomic rank of landscape systems

Nature components and factors	Physical-geographical units, by Armand [14]							
	Sector and country	Zone and sub-zone	Domain and province	Regional landscape	Locality	Stow (land-type association)	Group of facies	Bio-geocoenosis
First order morohostructures	P	F	F	B				
Macroclimate	P	P	F	F–B	B			
Second order morphostructures			P	F	F–B	B		
Large river systems			P	F	F–B	B		
First order morphosculptures				P	F	B		
Mesoclimate				P	F	B		
Small river systems					P	F	B	
Second order morphosculptures						P	F	B
Plant community						P	P–F	F
Microclimate						P	P–F	F
Soil complex						P	P	P–F
Soil-base flow						P	P	P–F

The spatial and temporal hierarchy of geosystems is a necessary condition for their equilibrium state [30]. It has been empirically established that each natural-territorial unit is formed on several spatial scales [31]. The multi-scale character of the organization of natural complexes is their most important immanent attribute, also providing the stability of the whole system of hierarchic structure of the biosphere.

In this respect, it is crucially important to separate the attributes of the framework, on the one hand, and pattern, on the other hand. This task is coupled with the problem of correspondence of the spatial and temporal frequencies of different natural attributes, which is still far from its satisfactory solution. In light of the known methodological developments [6], we can adopt the following statement: at each taxonomical level of natural complexes, the areas of isopotential structure, with respect to their linear dimensions, must be no less than 3–4 times larger than the areas corresponding to the epigenetic structure. Such chorological correlation between landscape framework and landscape pattern approximately corresponds to the difference between their chronological frequencies. Only in this case, both the framework and the pattern as two neighboring structural levels remain relatively independent of each other, providing the spatial-temporal stability of systemic hierarchy.

The background, framework, and pattern characteristics can be distinguished from the general ensemble of territorial variations of geo-components on the basis of collected empirical data of rout studies, interpretation of aerospace photographs, or mathematical processing of cartographic data. Here it is useful to be guided by the following rule [19]. As the compared points move away from each other, the connections between them with regard to the background values of geo-components weaken much slower than the connections with regard to the pattern-framework attributes, and at a certain distance, the strength of connections in the former case is greater than in the latter case. At the next stage, the characteristics of landscape patterns can be analogously separated from those of the framework using the data sample with already excluded background connections.

The same statistical estimates of attribute variation that are used to distinguish homogenous units can apparently be applied to vector landscape structures. For example, the measure of territorial variability of landscape pattern can be the mean square deviation of the respective parameter or approximately one-third of the maximal difference of its values in the given area [20]. Then the nodal lines of the isopotential field are drawn through the intervals equal to the double value of the measure of landscape pattern variation. The method of comparing the functions of the density of distribution of spatial frequencies of an attribute measured on the site by the map or the aerospace photograph is also used [32]. This method can be applied on the condition that each taxonomic level of vector structures corresponds to a certain homogenous aggregate of the spatial frequencies of this attribute, described by a single-humped (unimodal) curve of the normal or log-normal distribution. If the mean values of the two compared curves are no less than 3–4-fold different, then these curves apparently represent two different-scaled categories of landscape structure or, what is the same, two neighboring structural levels.

As we can see, the taxonomic rank and structural level of the natural complex are not identical categories. Each rank embraces two neighboring structural levels forming a dynamic *framework–pattern* pair, while ranks per se mutually overlap at one structural level performing two structure-forming functions: of pattern for the higher-rank system and of a framework for the lower-rank system.

The natural-territorial complex (NTC) is expressed by a certain area on the map. The first, vector coordinate of this two-dimensional model of NTC is a geo-synergic catena spreading towards system-forming geo-flows and combining a number of sites – from eluvial to accumulative or sub-aqual – into a relatively isolated system. The second, "geo-synchoric" [33] coordinate, which is generally perpendicular to the first one, characterizes the direction of crosslink (network-forming) connections between the elements of the neighboring catenas. The landscape systems of this hierarchic level are revealed, systematized, and classified on the basis of coupled analysis of both structures. The borders of geosystem areal are drawn: (1) by the synergic coordinate, through closing the opposite poles of catenas; (2) by the synchoric coordinate, in the places of replacement of one network-forming series of site homogeneity by another series of homogeneity. At the same time, the vector and isopotential series of geosystems are composed, *i.e.*, those with the comparable intensity of processes, which are part of the given NTC.

It would be more reasonable to begin the multi-level chorological analysis of a region from the simplest landscape complexes (the ranks of stows and localities), and then move to larger units based on a generalization of the properties of each preceding level. In generalization, the correct choice of representative points is of crucial importance. For solving the most of "resource" tasks, it would be reasonable to distinguish the *typological centers of catenas* [34] representing the background norm of natural complexes of the given rank. These will be mostly the upper elements of landscape coupling (trans-eluvial) in the regions with excessive humidity, the medium elements under the conditions of moderate humidity, and the lower elements of the catena (trans-accumulative) under the conditions of moisture deficiency. However, if the task is to reveal the regions and directions on the ecotones, which are the least resistant to external impacts, then representative points should be apparently determined by absolutely different criteria. In particular, to evaluate the extent of technogenic pollution of landscapes, primarily accumulative locations should be selected [35]; with other types of anthropogenic impacts (deforestation, pasture load, *etc.*) and under climatic fluctuations, the first and foremost indicators of ecological shifts will be the upper elements of catenas – eluvial and trans-eluvial sites with the minimum ecological reserve [36].

The analysis of horizontal landscape connections by the maps of geosystems should reveal first of all *the spatial changes in geo-component coupling between the attributes of the framework and the pattern, which represents the general level of the natural complex.* These changes indicate the most significant structural shifts in geosystems under external impacts. Here it would be reasonable to use the informational-statistical measures of connections. According to [21], the sought representation of "spatial processes in a spatial structure" can be obtained by cross-sectional analysis of the vector and isopotential series of inter-component coupling.

4 Ecology of the Volga River basin in light of cybernetic model of geosystems

The results of information analysis of landscape systems with characteristics, which belong to different blocks of the cybernetic system of natural complexes that we have considered, give the most general idea of the ecology of regional ecological-geographical space. Figure 2 shows a fragment of the landscape map of the headwaters of the Volga River basin. The entire map is presented in the book [36]. The landscape classification and the respective legends to the landscape map made by V.P. Yunina at a working scale of 1:2 500 000 are based on the classification system proposed by Khoroshev [31]. The classification criteria are latitudinal zonality, longitudinal sectoral, altitudinal layering of the landscapes, and lithogenic factors (the geological foundation of a landscape with inherent tectonics and relief). The zonal groups corresponding to zonal subdivisions of the terrestrial parts of the world were accepted to be classification associations of the highest rank. The *zonal-sectoral types and sub-types of landscapes* can be distinguished by combining the zonal and sectoral criteria (associated with the degree of continentality of the climate). The types include landscapes with the common bioclimatic characters, demonstrating the most general features of hydro-thermal regime that determine the development of a certain class of plant formations and type of soils. The groups of plant formations and soil sub-types correspond to the sub-types of landscapes [37, 38].

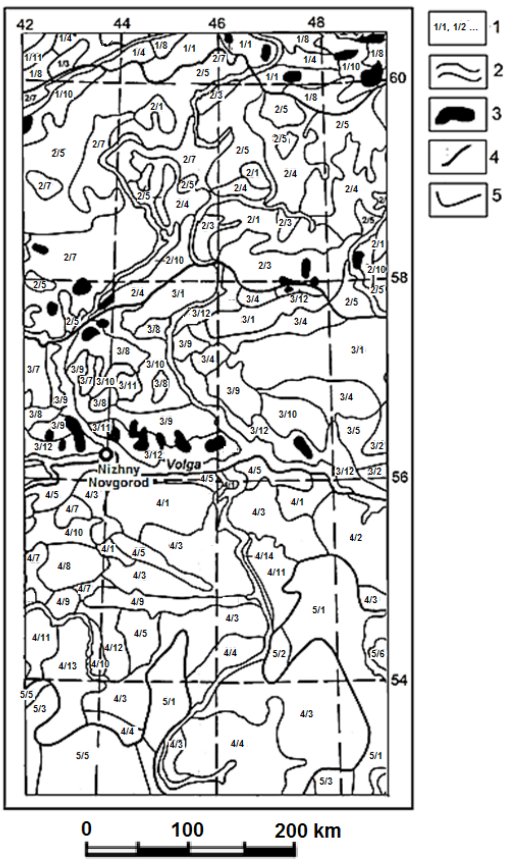

Figure 2 A fragment of the landscape map of the Volga River basin (compiled by Yunina [39])

In Figure 2, 1/3. 1/4. ... – the symbols for kinds of landscapes. The numerator is the number of a natural zone or sub-zone: 1 – middle taiga; 2 – south taiga; 3 – mixed forests; 4 – broadleaf forests; 5 – forest-steppe). The denominator is the ordinal number of the kind of landscape).

The sub-regional and local attributes of the lithogenic factor are determinative criteria at the lower steps of landscape classification. The genesis, common features, and age of the morphogenetic complexes of relief are used for distinguishing *landscape genera*, *i.e.*, genetic groups (erosion-denudation, moraine, outwash, *etc.*). Lithological and mechanical compositions of soil-forming rocks and the forms of meso-relief predetermine discrimination of *landscape kinds;* however, soil and plant characteristics are widely used here as diagnostic attributes.

It was absolutely obvious that it was necessary to increase the rank of the initial landscape units, with the unification of landscape types into larger categories. To designate such categories, we used the definition of "landscape groups" as interpreted by Nikolaev [39]. This definition is based on the same B.B. Polynov scheme on the scale of regional types of locations. These are fairly high-ranking unities that follow the historical-genetic classes and subclasses of landscapes and stand above their zonal types. According to Nikolaev, landscape groups are distinguished by the types of water and geochemical regimes: the ratio of atmospheric, ground and drip moisture, the degree of drainage of the territory, the prevalence of removal, transit or accumulation of mobile chemical elements.

In Figure 3, Conventional meanings: 1–20 – numbers of landscape groups; *a* – territories and water areas of the water valleys, lakes and water storages; *b* – swampy territories; *c* – boundaries of landscape groups; *d* – boundaries of the natural zones and sub-zones.

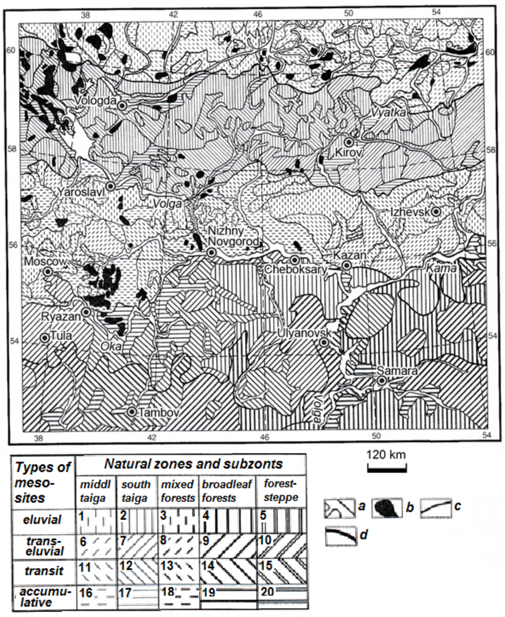

Figure 3 Map of landscape groups for the headwater of the Volga River basin

On the generalized meso-catena for all zones and subzones, we identified four types of sub-regional locations: eluvial, transeluvial, transit and accumulative (together with transaccumulative location). All 61 types of landscapes of the Volga River basin were distributed among these types. The type of location, or group of landscapes, according to Nikolaev [39], is a "cross-cutting" taxonomic unit not only for the landscape types and sub-types themselves, but also for the corresponding groups and classes of plant formations and types (subtypes) of soils. In order to bring landscapes, vegetation and soils to a single taxonomic rank, we combined the types of landscapes into higher-ranking groupings, taking into account their belonging to both the natural zone (sub-zone) and the type of location, and obtained 20 *typological groups of landscape kinds – GLK* (Figure 3). This is an "ecologized" landscape map for the headwater of the Volga River basin.

Each typological group of landscapes is diagnosed by its inclusion in a particular natural zone (subzone) and location type, as well as by a property derived from these initial features – the ratio of the factors "lithomorphism–hydromorphism", which replace each other when changing types of locations on meso-catenas. As a result, it was possible to briefly characterize the most important features of each typological group of landscapes and bring closer the ranks of the landscape units we are considering with the units of plant and soil covers.

The initial information for statistical data analysis was taken from any of the landscape maps, as well as from 25 maps of landscape-geophysical conditions of the headwaters of the Volga River basin (Table 2). For this purpose, the well-known method of biogeographic grids was used [40, 41]. The step between the nodes of the square grid (points) was usually less than the

Table 2 List of landscape-geophysical factors, were used in modeling [40]

No.	Name of sign	Simbol
1	Annual total radiation, MJ/m^2	Q_{sum}
2	Annual radiate balance, MJ/m^2	R_{ann}
3	Average January temperature, ^{o}C	t_{Jan}
4	Average July temperature, ^{o}C	t_{July}
5	Sum of the biological active temperature, ^{o}C	$\sum t_{\mathrm{daily}} \geq 10^o$
6	Annual potential evaporation, mm	E_{o}
7	Duration of vegetation period, days	T_{veg}
8	Totals of precipitation per year, mm	r_{ann}
9	Sum of the precipitation of the cold period, mm	r_{cold}
10	Maximum height of snow cover (field), cm	$h^{\mathrm{snow}}{}_{\mathrm{max}}$
11	Osokin's indicator of snowiness	I_{Osokin}
12	Sum of the precipitation of the warm period, mm	r_{warm}
13	Annual evapotranspiration, mm	E_{c}
14	Annual complete flow, mm	S_{com}
15	Annual surface flow, mm	S_{ann}
16	Annual groundwater flow, mm	U_{ann}
17	Flow coefficient	C_{flow}
18	Total humidification	W_{tot}
19	July soil moisture resources in stratum 0-20 cm	*W-20*
20	July soil moisture resources in stratum 0-50 cm	*W-50*
21	July soil moisture resources in stratum 0-100 cm	*W-100*
22	Budyko's radiate index of the drought	I_{Bud}
23	Bazilevich's index of aridity	I_{Baz}
24	Vysocky-Ivanov's atmospheric humidity factor	F_{hum}
25	Selyaninov's hydrothermal coefficient	*HTC*
26	Rikhter's snow-temperature coefficient	*STC*
27	Simonov's coefficient of continentality	C_{contin}
28	January latitude continentality, by Polozova	C_{JanC}
29	July latitude continentality, by Poloziva	C_{JulC}
30	Annual primary productivity of natural ecosystems, t/h	B_{prim}

average cross-section of the landscape contour. The entire territory was covered by 1467 points. Various published and cartographic fund materials were also used [39].

Even a cursory glance at the results of information analysis (Table 3) shows the leading role of not only the primary input (background-frame) but also the processor material-energy parameters, which, as is known clearly indicate the general zonal structure of the territory of the Russian Plain. The initial input variables with the maximum mutual independence are as follows: annual total radiation (Q_{sum}), annual precipitation (r_{ann}), types of morphostructures and morphosculptures (*MST* + *MSC*), and mechanical composition of soil-forming rocks (MC_{soil}). According to the method proposed in Puzachenko [41], we expressed the dependence of distribution from the groups of landscape kinds (*GLK*) over the Volga River basin from the specified input variables in the form of the following linear polynomial:

$$GLK = 0.24 \times Q_{sum} + 0.30 \times r_{ann} + 0.32 \times (MST + MSC) + 0.12 \times MC_{soil} + 0.02 \times X \quad (1)$$

where the coefficients of the arguments are the coefficients *C(A/B)* of information receive by phenomenon *A* from factor *B* (see Table 3). This coefficient is calculated using the formulas [42]:

$$C(A/B) = \frac{T(AB)}{H(A)} \quad (2)$$

$$T(AB) = H(A) + H(B) - H(AB) \quad (3)$$

$$H(A) = -\sum_{i=1}^{N} p(a_i) \log_2 p(a_i) \quad (4)$$

$$H(AB) = -\sum_{ij=1}^{N} p_{ij} \cdot \log_2 p_{ij} \quad (5)$$

Under the conditions of complete mutual independence of the input variables, the sum of all coefficients in equation (1), including the coefficient for the unknown argument *X*, must be equal to 1.

Table 3 Information indicators of the relationship of groups of landscape kinds of the Volga River basin with geocomponent signs of various blocks of the cybernetic model of regional natural complexes

Geocomponent indicators (name and designation)	Parameters of the relationships	
	C(A;B)	*C(A/B)*
Physical-geographical background and landscape frame		
Annual total radiation, Q_{sum}	0.120	0.238
Average January temperature, t_{Jan}	0.085	0.224
Coefficient of winter continentality, C^{Jan}_{contin}	0.168	0.357
Sum of the precipitation of the cold period, r_{cold}	0.062	0.173
Annual surface flow, S_{ann}	0.145	0.350
Maximum height of snow cover, h^{snow}_{max}	0.099	0.251
Snow-temperature coefficient, STC	0.104	0.267
Types of the morphostructures, MST	0.199	0.273
Morphostructutre and morphosculpture, MST+MSC	0.140	0.321
Steps of absolute heights, H_{abs}	0.174	0.100
Modern tectonic movements, TM	0.067	0.176
The mechanical composition of soil-forming rocks, MC_{soil}	0.125	0.183
Genuses of landscapes, GL	0.249	0.321
Unpartitioned "frame-processor" block system		
Annual radiate balance, R_{ann}	0.166	0.343
Totals of precipitation per year, r_{ann}	0.122	0.298
Annual groundwater flow, U_{ann}	0.183	0.395
Runoff coefficient, C_{flow}	0.129	0.295
Total humidification of territory, W_{tot}	0.031	0.093
Depth of ground water-table occurrence, Z^{gr}_{water}	0.174	0.175
Ground lithology and moistening, LW_{gr}	0.175	0.253
Processor (inside geo-flows)		
Average July temperature, t_{Jul}	0.187	0.379
Sum of the biological active temperature, $\sum_{t\geq 100}$	0.206	0.404
Annual potential evaporation (evaporativity), E_0	0.210	0.362
Sum of the precipitation of the warm period, r_{warm}	0.140	0.317
Annual evapotranspiration, E_c	0.036	0.099
Summer moisture resources in soil, W_{summer}	0.296	0.203
Budyko's radiate index of drought, I_{Bud}	0.162	0.361
Vysotsky-Ivanov's annual atmospheric humidity factor, F_{hum}	0.169	0.376
Hydro-thermal coefficient, HTC	0.184	0.379
Primary bioproductivity, B_{prim}	0.081	0.166
Landscape pattern		
Group of soil kinds	0.125	0.309
Groundwater chemistry, J^{gr}_{water}	0.183	0.212
Soil-geochemical complexes, SG	0.142	0.379

As can be seen from the equation (1), the differentiation of species groups of landscapes of the Volga River basin is almost entirely determined by the influence of four of these factors. At the same time, the roles of climatic (exchange-transit) and lithogenic (conservative) input variables are quite proportional, with some "advantage" (up to 54%) of climate group factors. In the latter group, the effects of incoming solar energy and atmospheric moisture are also approximately the same; in the lithogenic group of factors, the crucial role is played by the genetic types of relief expressed by a combination of certain morphostructures and morphosculptures. The eigenvalue of the mechanical composition of soil-forming rocks at the regional level was much less significant.

Unaccounted factors (*X*) include, first of all, advective heat sources, which have a certain weight in the energy resources of the Russian Plain, as well as anthropogenic changes in landscapes, in particular, reducing the role of solar radiation in the latitudinal distribution of landscapes. However, the annual advection of heat is proportional in all zones and subzones of the Volga River basin, which reduces its spatially differentiating role. So far, the influence of human activity on the material and energy bar remains sufficiently localized balance and distribution of regional geosystems.

The above polynomial covers only four "starting" factors. To identify the landscape-forming role of the remaining factors traced in the functional background–frame–processor–pattern chain, a whole series of similar polynomials was obtained (by groups of factors), where the corresponding values of normalized coefficients reduced to 1 are presented as "weighted" normalized coefficient of interrelation *C(A;B)*:

$$C(A;B) = \frac{2^{T(AB)} - 1}{2^{H(\min A,B)} - 1} \tag{6}$$

This made it possible to comparatively assess the significance of each factor in its group.

In the group of external climatic factors of landscape organization of geographical space, the leading isopotential (frame) role is played by winter latitudinal continentality, according to Polozova [43], and the associated duration of occurrence of stable snow cover, which is included in Osokin's snowiness coefficient – $C_{\text{snowiness}}$. The contribution of the second component of this coefficient – the height of snow cover, judging by the h_{snowmax} parameter – is relatively small. The normalized conjugation coefficient *C(A;B)* of specific groups of landscapes with these factors is 0.17–0.20. Judging by the values of information reception coefficient *C(A/B)*, the spatial variation of species landscape units by more than 60% is due to the combined effect of these two factors. The value of *C(A;B)* for the factors H_{abs} and $Z^{gr}{}_{water}$ turned out to be abnormally high due to the disproportionately small (only 4–6) number of their gradations.

The following linear polynomials were obtained:

a) According to the initial climatic and lithogenic factors,

$$\mathrm{GLK} = 0.29 \times \mathrm{MCT} + 0.24 \times \mathrm{R_{ann}} + 0.20 \times \mathrm{r_{warm}} + 0.18 \times \mathrm{MC_{soil}} + 0.09 \times \mathrm{r_{cold}} \tag{7}$$

b) For the group of heat-energy factors,

$$\mathrm{GLK} = 0.22\times\mathrm{E_0}+0.21\times\sum t \geq 10^0+0.19\times\mathrm{t_{July}}+0.17\times\mathrm{R_{ann}}+0.12\times\mathrm{Q_{sum}}+0.09\times\mathrm{t_{Jan}} \tag{8}$$

c) According to the values of climate continentality,

$$\mathrm{GLK} = 0.79 \times \mathrm{C^{Jan}_{contin}} + 0.21 \times \mathrm{C^{July}_{contin}} \tag{9}$$

d) According to the conditions of atmospheric humidification,

$$\mathrm{GLK} = 0.27 \times \mathrm{r_{ann}} + 0.13 \times \mathrm{r_{cold}} + 0.31 \times \mathrm{r_{warm}} + 0.07 \times \mathrm{W_{tot}} + 0.22 \times \mathrm{h_{snow-max}} \tag{10}$$

e) Along the river flow,

$$\mathrm{GLK} = 0.31 \times \mathrm{S_{ann}} + 0.40 \times \mathrm{U_{ann}} + 0.29 \times \mathrm{C_{flow}} \tag{11}$$

f) For the components of the water balance,

$$\mathrm{GLK} = 0.29 \times \mathrm{U_{ann}} + 0.23 \times \mathrm{S_{ann}} + 0.22 \times \mathrm{C_{flow}} + 0.20 \times \mathrm{r_{ann}} + 0.06 \times \mathrm{E_c} \tag{12}$$

g) For annual and seasonal integrated parameters,

$$\mathrm{GLK} = 0.20 \times \mathrm{I_{Bud}} + 0.21 \times \mathrm{F_{hum}} + 0.22 \times \mathrm{HTC} + 0.24 \times \mathrm{C_{snowiness}} + 0.13 \times \mathrm{STC} \tag{13}$$

i) By factors of the lithogenic base as a whole,

$$\mathrm{GLK} = 0.30\times\mathrm{Z^{gr}_{water}}+0.16\times(\mathrm{MST}+\mathrm{MSC})+0.20\times\mathrm{H_{abs}}+0.14\times\mathrm{MC_{soil}}+0.20\times\mathrm{LW_{gr}}+0.08\times\mathrm{SG} \tag{14}$$

j) By genetic types of relief,

$$\mathrm{GLK} = 0.34 \times \mathrm{MST} + 0.42 \times \mathrm{GENUS_{land}} + 0.24 \times (\mathrm{MST} + \mathrm{MSC}) \tag{15}$$

k) Under conditions of lithomorphism-hydromorphism,

$$\mathrm{GLK} = 0.29 \times \mathrm{Z^{gr}_{water}} + 0.32 \times \mathrm{W_{tot}} + 0.20 \times \mathrm{J^{gr}_{water}} + 0.19 \times \mathrm{LW_{gr}} \tag{16}$$

l) By the integrated output parameters of the functioning of the landscape,

$$\mathrm{GLK} = 0.64 \times \mathrm{SG} + 0.36 \times \mathrm{B_{prim}} \tag{17}$$

Under conditions of flat terrain, an important generalizing factor in the structural and functional organization of geo(eco)systems are known to be the degree of drainage of the territory: a rather complex feature that depends on both conservative and exchange-transit factors. The degree of drainage of the territory is determined by a combination of the following factors:

1) annual rainfall r_{ann}, which determines the initial level of moisture supply of the territory;

2) annual total evaporation as an expendable part of the water balance;

3) morpho-sculpture characterizing the geomorphological and physical-chemical conditions of infiltration and precipitation and flow;

4) absolute height of the terrain, which somehow determines the depth of the erosive dissection of the relief and, consequently, the ratio of surface and underground flow;

5) depth of groundwater-table occurrence as a result of a superposition of the above and other (unaccounted for) factors and as a direct indicator of the relative drainage of the territory.

If we use the values of information reception coefficient *C(A/B)*, then it turns out that a combination of these factors describes the almost complete dependence of the distribution of landscapes on drainage conditions. The linear polynomial has the form of:

$$\mathrm{GLK} = 0.30 \times \mathrm{r_{ann}} + 0.10 \times \mathrm{E_0} + 0.32 \times (\mathrm{MST} + \mathrm{MSC}) + 0.10 \times \mathrm{H_{abs}} + 0.18 \times \mathrm{Z^{gr}_{water}} \quad (18)$$

Thus, judging by the given empirical dependencies, it can be assumed that the following factors make the largest contribution to the natural-territorial organization of the Volga River basin (listed in a very conditional order of decrease in their significance):

Annual radiation balance;
Annual underground flow;
Types of morphostructures;
Annual rainfall
July average temperature;
Morphosculpture;
Sum of active temperatures;
Soil moisture (in spring);
Annual evaporation;
Annual humidify factor;
Winter latitudinal continentality;
Hydrothermal coefficient;
Amount of precipitation of the warm period;
Snowiness coefficient;

Depth groundwater-table occurrence, surface runoff, Budyko's radiation index of the drought and complex parameter "lithology and soil moisture" are somewhat less significant. Among the listed exchange-transit features, there are almost no merely background and very few frame factors; all of them relate to the processor unit or the undivided part of the "frame processor". By the way, the initial information parameters of connections among the factors of the processor turned out to be generally higher than the background frame factors. All the above indicates a very significant refracting role of internal geo-flows (primarily vertical insolation and lateral soil-geochemical) in the formation of landscape appearance of zonal-regional geospace of the Russian Plain.

Among the input energy factors, the annual radiation balance and winter latitudinal continentality take the first place; in the processor group, this is the complex of thermal parameters of the warm period (t_{July}, $\sum t_{\mathrm{daily}} \geq 10^0$). The influence of these factors on the natural-territorial differentiation has not only regional but also subplanetary proportions. For example, the main biomes and zonal classes of the vegetation cover of Northern Eurasia are quite clearly differentiated along the axes of continentality and heat supply. Judging by the values of *C(A/B)* for $C^{\mathrm{Jan}}{}_{\mathrm{contin}}$ and r_{cold}, the thermal factor makes the main contribution to the winter continentality of the Volga River basin, while the role of advective precipitation in the cold period is relatively low.

Advection of atmospheric moisture is much more significant in the warm period and in the whole year, which is clearly seen in the level of relations of landscape differentiation with r_{worm} and r_{ann}, as well as with the annual surface flow (S_{ann}).

Unexpectedly, a very weak effect on the distribution of landscape ranges over the ecotone was found by the gross humidification of the territory and annual evapotranspiration – the parameters that link the thermal and water balances of the earth's surface. At the same time, the differentiating role of underground flow is rather significant.

Among the factors of the lithogenic basis of geosystems in the framework of the block of landscapes, the factor "landscape genus" is of paramount importance, which is used as a guiding feature at a certain level of distinguishing the classification units of landscapes themselves. This explains the abnormally high connection between this factor and landscape kinds. The types of morphostructures that essentially lay the network-forming basis of the landscape areas and their boundaries are also clearly distinguished. The role of elements of morphosculpture and mechanical composition of parent rocks is somewhat less, and modern tectonic movements are insignificant.

Finally, one cannot but notice the obvious imbalance between the territorial differentiation of landscapes and the two integral parameters of their functioning: primary biological productivity as the most general landscape-geophysical indicator [2] and soil-geochemical complexes displaying the migration and transformation of matter in geosystems [44]. The relationship of the distribution of landscape areas with the sign *SG* is almost two times stronger than its relationship with the B_{prim} factor. This fully corresponds to the notion of primary bio productivity of geo(eco)systems as their most important invariant (Sochava 1978), which has the greatest autonomy from structural phytocoenotic and abiotic factors [41].

5 Conclusion

The presented framework concept of the hierarchical organization of geographic spaces, with three different-level principles: physical-geographical background, landscape frames and landscape pattern, is consonant with a number of theoretical and methodological developments of other authors in the field of spatio-temporal analysis of geographical objects. For example, the concept of invariant and variable properties of geosystems is widely known (Sochava, 1978). These properties can be considered as adequate characteristics of the frame and pattern. In this interpretation, invariant and variable properties of a natural complex are considered as relative structural categories, with their consistent subordination to each other. At each hierarchical level of geosystems, the variable characteristics of the structure are subordinated to their invariant, however, when moving from a lower level to a higher one, these invariant properties become (fully or partially) variable properties.

The theory of the geographical field puts forward the "positional principle" (Rodoman 1999), which is essentially a broader interpretation of the concepts of background and spatially differentiating properties of geocomponents (Krenke, 1984).

The closest analogy to the concept we are developing is found in the idea of structural levels of vegetation cover (Masing, 1984). For each of these five levels (planetary, regional, landscape, coenotic, population), external (exogenous) and internal (endogenous) factors of vegetation development are distinguished. It is emphasized that endogenous factors at one level of the hierarchy turn into an "invariant background," that is, into environmental factors at each lower level of phytogeographical systems.

The concept of structural levels of the biosphere underlies numerous classifications of complete and incomplete natural complexes. As is known, "classification is a "horizontal" division of objects of equal rank" (Armand, 1975). Each hierarchical level corresponds to the generic category of the object, and classification is carried out according to its species differences, which are considered as signs of a landscape pattern. The totality of such species categories of natural complexes within a given genus forms a certain invariant of a given territory, *i.e.*, its isopotential structure.

Conflicts of interest

The author declares no conflict of interest.

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