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Geostatistical Methods for the Analysis of Territorial Systems

Abstract

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The paper relies on the hypothesis according to which the transfer of statistical and mathematical instruments used in the analysis of ecological systems could be possible and beneficial to the analysis of territorial systems. In order to verify this hypothesis, the research process is organized according to the following objectives: (1) in order to provide for the theoretical background of the transfer, the concept of "territorial system" is thoroughly analyzed and compared to its analogue from ecology (discipline providing to the statistical methods to be transferred) and spatial planning; (2) a critical analysis is used to review the tools used in the analysis of territorial systems, underlining the lacks and limitations; (3) statistical methods with a potential use in the analysis of territorial systems are inventoried, focusing on those already utilized in ecology; (4) the transfer consists of case studies, as diverse as possible and at more spatial scales, and (5) the analysis of the results obtained in each step substantiates general conclusions, a hierarchy of the methods and an algorithm for using the tools.

The analysis of the concept "territorial system" indicates that it is an objective reality and not a theoretical construct. Territorial systems are defined as "*functional assemblies [...] constituted of elements and relationships aiming to reach some common goals*"[1]. Other authors limit their definitions to the composing elements[2]. These can be natural and anthropic[3] – <u>*Fig. 1*</u>. The structure of the two sub-systems, natural and anthropic, is substantially different. The concept of "territorial system" relies on another notion – the territory – defined as "*geographic*

space managed by a person, group of people, or another socioeconomic actor"[4], or, in economic geography, as "*material support of the relationships between actors, infrastructures and technologies*"[5]. The latest definition starts from the acceptation according to which territoriality is a "*primary geographic expression of social power*"[6]. According to the first definition, the concept of territory is based on another one – geographic space – "*determined area, characterized by a larger or smaller number of physical characters whose diversity and connections occur on the ground surface under our eyes*"[7]. The second definition regards the territory as an interface of the relationship between nature and society[8].

The term "territorial system" is also used by Christiane Rolland-May in 2000 and defined as "*system with a high degree of organization, increased complexity of the inner structure, relationships with the environment, articulation with its sub-systems and integrating system and capacity of defining its own objectives or means to reach them*"[9], in a paper proposing a model of implementing the systemic conception in human geography for the evaluation of territories. Due to the predominantly methodological focus of the paper, the concept is insufficiently crystallized and the definition applies to any large and complex system, and not only to the territorial ones.

In this context, it has to be stressed out that the homogeneity of territorial systems differs due to the anthropization degree, which determines differences between the two sub-systems.

– Natural territorial systems are more homogeneous from a physiognomic perspective[10] and exhibit very obvious vertical interconnections between the lithosphere, hydrosphere, biosphere and atmosphere; compensation, inter-conditioning and cooperation in carrying the flows of matter, energy and information ensure the coherence of the systems. From a territorial perspective, the homogeneity results from the physiognomic and functional similarity of the components and not from their interconnections[11].

– Strongly anthropisized territorial systems are heterogeneous, but exhibit spatial coherence and synergy. The functional coherence is due to territorial imbalances[12].

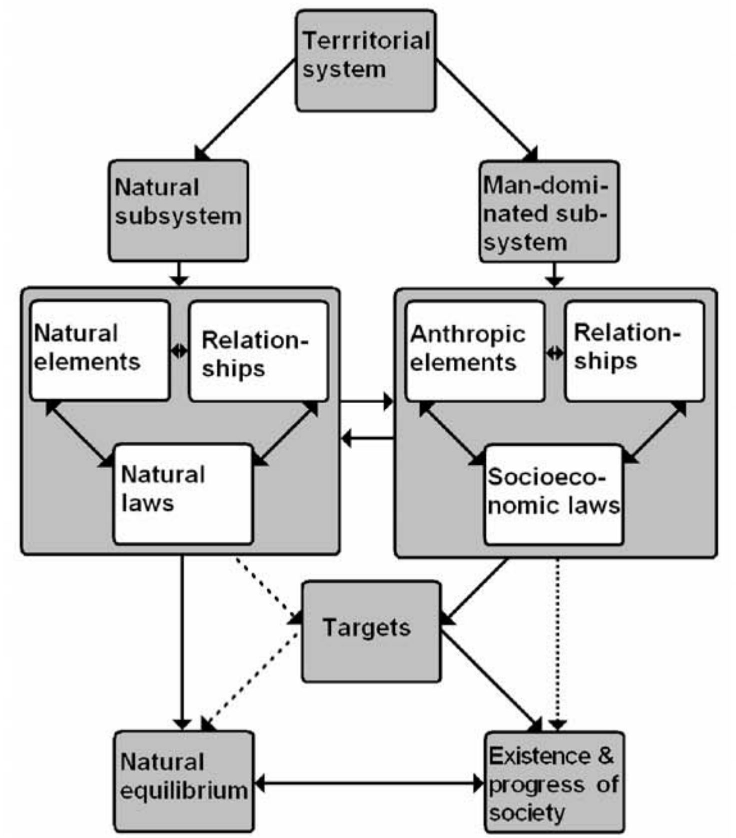

Fig. 1. Definition of a territorial system[13].

Despite of the differences, the territorial system results from the inter-relationships of the two subsystems; its physiognomy and functionality depend on the intensity and form of relations[14].

Finally, the critical comparative analysis of these concepts in the three disciplines and the spatial scale of interpretation

result into a correspondence of the hierarchical levels proposed in *Table 1* to which the analysis of specific diversity[15] can be added (*Table 2*).

Table 1. Critical analysis of conceptual delimitation and properties of systems in geography, ecology and spatial planning.

Concept, property	**Geography**	**Ecology**	**Spatial planning**
Name of system	Territorial	Ecological	Socio-spatial
Components of system	Components and processes[16]	Structure and functions[17]	Components and flows[18]
Difference in approaching components	Geosystem includes ecosystem	Ecosystem includes geosystem	Focus on anthropic systems
Dominant component	Depends on degree of anthropization	Depends on degree of anthropization	Human species
Hierarchy of systems	Fractal theory – system replicated at different scales; geo-system, geofacies, geotope, natural region, geographic region, domain, zone[19]	Ecosystem – complex of ecosystems – ecosphere	Nomenclature of Territorial Units for Statistics (Romania: ATU – county – region of development)
Operational unit considered optimal	Geosystem, though could reach the level of individual households	Ecosystem, though some distinguish its subunits[20]	ATU (Administrative-Territorial Units)
Concept of diversity	Geodiversity (perceived differently from geodiversity in geology[21])	Biodiversity[22]	Cultural diversity
Difference in approaching diversity	Geodiversity includes biodiversity	Biodiversity includes geodiversity	Focus on socio-cultural diversity
Dynamics	Territorial dynamics: urbanization – peri- and sub-urbanization – gentrification processes in spiral[23]	Move from the ecological succession model[24] to the theory of adaptive cycles[25]	Economic development

Table 1. Critical analysis of conceptual delimitation and properties of systems in geography, ecology and spatial planning.

Concept, property	Geography	Ecology	Spatial planning
Objective of dynamics	Satisfy human needs[26]	Natural: maximize energy flow[27], man-dominated: satisfy human needs	Satisfy human needs
Collapse limit	Carrying capacity[28], minimal and maximal eco-energies[8]	Natural resources, eco-energies[29]	Density of population[30]
Key properties	Complex, coherent, synergic, variable geometry, optimally open thermo-dynamic and informational systems with dissipative structure, resistant to change, diverse, global, unique, organized, integral, functional, self-regulating, causality, dynamic equilibrium[31]	Historical character, existence of programs, integral, self-regulating, dynamic equilibrium, informational, heterogeneous[32], non-linear, autopoietic, fractal, anti-entropic[33], stable, carrying capacity, evolution[34]	Diversity, dominated by human species, social, eco-social control[35], integral, predictable dynamics, fractal[36]
Object of discipline	ATU – landscape – global	Complex of ecosystems	Depends on the purpose
Methods of study and analysis	Field study, multi-scale approach, map, description, typology, dynamics, organization, way finding choremes[37]	Field and desk studies; isomorphic and homomorphous models[38]	History; predominant role of planning
Integration of systemic approach	Mixed, sectoral and systemic approach	Systemic approach	Sectoral approach

The analysis of the concepts "geodiversity" and "biodiversity" indicates their overlapping[39], even though some authors believe that geodiversity includes biodiversity[40], while others claim the opposite[41]. This confusion is mainly fed by semantics. The concept of "biodiversity" is etymologically built around the

Greek ßíoς (bios) – live, as in the definition from Rio de Janeiro Convention on biological diversity: "*variability among **<u>living organisms</u>** from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems*"[42]. Nevertheless, the definition allows for extensions, by adding lifeless (abiotic) components accounting for the inclusion of the diversity of ecosystems (embedding "*not only the organism-complex, but also the whole complex of physical factors*"[43]). This side of biodiversity was called *eco-diversity*, etymologically built around the concept of *ecosystem* and comprising both live and lifeless components. This is an option for including the concept of eco-diversity in the already established one (biodiversity) as an extension, despite of their inverse relationship. In fact, the approach is erroneous, as eco-diversity should include biodiversity, similar to the embedding of the hierarchy of biological systems with a rank higher than the species in the hierarchy of ecological systems (<u>*Fig. 2*</u>).

Table 2. Correspondence between the levels of the hierarchy of systems in geography, ecology and spatial planning and spatial interpretation of their diversity.

Hierarchy of ecological systems	Hierarchy of territorial systems	Hierarchy of socio-spatial systems[44]	Diversity (spatial)[45]
Structural and functional subunits of the ecosystem[46]	Nano-structures and micro-structures, house/ block, company/ unit/ department, street/ segment of street[47]	-	α, ω
Ecosystem[48]	Geosystem, geofacies, geotope[49], local system[50]	NUTS V (LAU III)	α, ω
Regional complex of ecosystems[51]	Natural region[52], geographic region[53], regional system[54]	NUTS III	ß, γ, ω
Macroregional complex of ecosystems[55]	Domain, zone[56], national, supra-national or continental system[57]	NUTS II, national territory, continent	γ, δ, ε, ω
Ecosphere[58]	Geo-sphere, planetary system[59]	Globe (Earth)	ω

Table 3. Correspondence of food levels in natural, anthropic and anthropizised systems.

Food level	Existence in natural systems	Existence in anthropic and anthropizised systems	Characteristic processes
Mineral trophy	Yes	Very low, due to permanent replacement of superficial layer	Interaction of rocks with natural agents – erosion, disaggregating, dissolution – minerals ready for assimilation[60]
Phyto-trophy	Yes (in some natural systems – abyssal depths, caves, energy comes from other systems – chemical)	Reduced to green spaces, modified; in fact urban ecosystems do not have primary gross production; energy taken from natural systems	Plants, through photosynthesis, transform minerals and atmospheric carbon dioxide in primary gross production; energy is stored in chemical bounds (circa 2%) and dissipated in metabolic processes as heat (circa 98%[61])
Zoo-trophy	Yes	Yes (from natural systems)	Primary consumers (herbivores) take from primary producers the primary gross production (circa 40-85% of it[62]). Most part is spent in metabolic processes and dissipated as heat, but a part is concentrated (some 10 times[63]) and transmitted to the next level; the process is repeated up to top consumers. Energy and matter – including pollutants – are concentrated circa 10 times.
Techno-trophy	No	Yes	Based on energy from natural systems (including fossil fuels), specific processes are carried: sedentarization, practicing agriculture, industrialization, urbanization etc.[64]
Noo-trophy	No	Yes	Research, management, education, financing – generally, processes supporting human development[65]

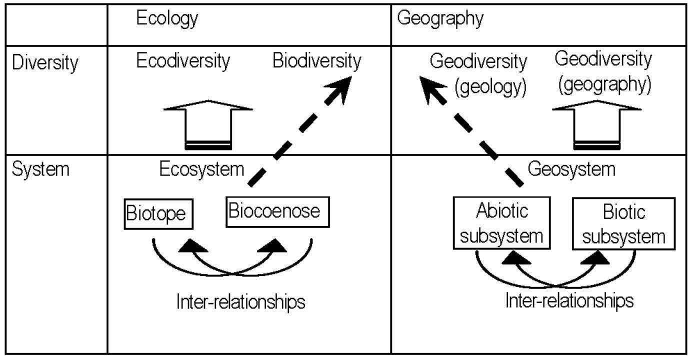

Fig. 2. Relationship between biodiversity, eco-diversity and geodiversity, correlated to the hierarchy of systems in ecology and geography[66].

A presentation of the functions of natural systems is required in order to understand their dynamics. Natural systems carry three functions: biogeochemical circuits and flows (of mass and, respectively, energy) and self-regulation[67]. The first two functions are coupled by food chains, webs and pyramids. Food chains, webs and levels underline the components of biogeochemical circuits, while food pyramids quantify in addition the numerical relationships. Food levels must be approached as a whole (*Table 3*), accounting for the coupling of socioeconomic systems to the natural ecological systems, understandable based on the theory of metabolic cycles[68].

Socioeconomic systems are coupled to the natural ones in all functional aspects.

– Flow of matter: taken from natural systems. Man intervenes as a (often top) consumer in food chains. Resources are taken directly from these systems or upon transformation in anthropisized systems, such as agro-ecosystems.
– Energy and resources are taken using the technologies developed by the human species[69] (*Fig. 3*). From the energy viewpoint, socioeconomic systems dissipate natural energy, introduced in many ways (fertilizers,

pesticides, soil works, care for green spaces, food etc.) in quantities greatly exceeding the contribution of primary producers[70]. The amount of energy absorbed by anthropic systems is magnified by increasing the complexity channels used to absorb resources by the human society, underlining the structuring character of human activities over the geographic space[71].

- The modification of biogeochemical circuits and loss of biodiversity results into a decreased stability of socioeconomic systems; therefore, their self-regulation becomes dependent on the human interventions.

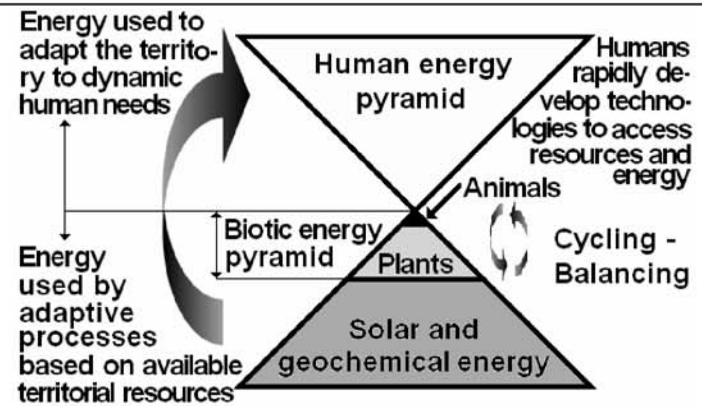

Fig. 3. Coupling of the human socioeconomic system to natural systems for the absorption of energy[72].

The dynamics is tightly related to the concepts of eco-energy and urbanization. Primary eco-energy is the initial energy of a territorial system before the conscious intervention of man in its structures, During the urbanization process, natural systems become anthropisized, then anthropic; the concentration of population and economic activities determines a differentiated consumption of resources, appreciated as primary eco-energies[73]. Their assessment is made in relationship with a qualitative appreciation of the level of degradation in initial geosystems, and the degree of anthropization is proportional in intensity

with the distribution of primary eco-energies, but inversely correlated with it and responsible for the increased complexity of geosystems[74].

The common feature of study methods currently used in geography is their **subjectivity**. This is manifested directly (*e.g.*, non-quantitative description is as subjective as possible, but even the quantitative one is influenced by the availability of data and manner of interpreting them in the absence of a "universal" (statistical) method), but also indirectly (SWOT or LFA analyses, even though sequential, depend on the characteristics of the research team, available information and contextual priorities). Moreover, another characteristic of these methods is the fact that they are purely qualitative or semi-quantitative, meaning that they record the general trends of a phenomenon, but do not allow for testing causal hypotheses.

In order to ensure the **objectivity** of the methodological instruments, this paper proposes its completion with the statistical methods, starting from previous transfers of concepts, theories and methods from other disciplines to geography.

The analysis of all standpoints and definitions related to statistics indicate that it can be approached as:

- **Fundamental science** (many place here mathematical statistics, governing its applied branches) or **applied** (clinical statistics, biostatistics – understood as statistics applied to biology, but also in medical sciences[75], environmental statistics, economic statistics, social statistics etc.); the second category includes statistics seen as a way of reasoning and instrument.
- **Activity** of applying statistical tools to collect, process and valorize the results of data analysis.
- **Result** of the activity of applying statistical methods (graphic or numeric synthesis[76]), or final results of simple classifications (understood here as identifying and

assigning entities to already defined categories[77]), *i.e.*, counts.

Scientific progress is made testing hypotheses and theories through studies (experimental, questionnaire-based etc.) where subunits of the analyzed populations (samples) are used, obtaining uncertain results. The generalization of results would be impossible without using the statistical methods, since the quantitative appreciation (measurement) of the degree of uncertainty would lack. Moreover, the utilization of statistical methods offers the possibility of validating the experiments, since analyses based only on raw data would be subjective, while the use of the same statistical methodology allows two researchers who obtain similar data to have similar results if they apply the same data analysis methods and the experimental design has comparable conditions.

In the literature, influenced by the Environmental Systems Research Institute, Inc. (ESRI) terminology, the term “**geostatistical methods**” refers strictly to spatial prediction techniques via interpolation and extrapolation based on the theory of regional variables (kriging)[78]. This paper extends the meaning, by analogy with biostatistics, to include all methods situated at the interference of statistical and mathematical techniques and geographical ones, from quantitative methods applied to geographic data to the geographic representation of the results of statistical and mathematical analyses.

In order to verify the hypothesis stated in the beginning, according to which the *transfer of statistical and mathematical methods used in ecology to the geography of territorial systems is possible and beneficial*, this paper analyzes several case studies based on such a transfer.

1. Geostatistical analysis of land use is used as an instrument for the study of the dynamics of diversity correlated with urban dynamics. Starting with the structure of territorial systems and one of their essential features, diversity, as well as from the fact that the process of anthropization is tightly related to the diversity of territorial systems and their spatial synergy and coherence, three types of processes influencing land cover and use are identified: expansion of cities and re-urbanization transform spaces initially belonging to other land cover classes to become urban or built up – phenomenon called urbanization; in opposition to it, deurbanization transforms areas classified initially as urban or built up in other land cover categories. Urban restructuring does not affect land cover, but land use and is exclusively characteristic to areas classified initially and finally as urban or built up. The study methods consisted of spatial prediction via ordinary kriging generalizing at the level of the national territory, and allowing for the identification of regions characterized by a high intensity of the processes mentioned previously. Based on the geographic principle of connecting to the territory, their emergence is explained by socioeconomic features of the regions, indicating that economic activities are the main causes of the processes specific to anthropisized regions, which at their turn induce land cover and use changes. Furthermore, the analyses revealed the dependence of changes on the spatial distribution of primary eco-energies and the degree of urbanization for both micro-scale (Sărățel river basin) and macro-scale (national territory).

2. The search of an indicator relevant for measuring territorial disparities in Romania (macro-scale analysis) and mountain and sub-Carpathian area of Ialomița hydrographic basin (micro-scale analysis) starts from analyzing theories attempting to explain the mechanisms of the territorial development process starting from the role of territorial disparities and methods used to measure them. The underlying hypothesis, partially verified by the results, is that

apart from the Gross Domestic Product (GDP) for such an approach there must be one or more indicators, even artificial, accounting for elements related to economy, demography, infrastructure and life quality. The study used a complex methodology consisting of correlation analysis, multiple regression, factorial analysis, ordinary kriging prediction, the Drane – Aldrich – Creangă test, Geographical Information Systems (GIS) modeling and their combinations, and led to apparently different, but convergent results. For the national territory, the study showed that such an indicator is an arithmetic combination of the GDP, number of people/room and rate of scholar abandon, while for the micro-scale analysis, of the number of high school graduates and population employed in the agriculture. Even though different, the two indices have a common element – represent a combination of indicators reflecting different aspects: economic, social or cultural. Other conclusions of the study concern the methodology and show that as the degree of abstractness of the methods increases, they tend to reflect almost exclusively some aspects, and only the sum of partial results could provide a realistic image, corresponding to what is known about a particular territorial system.

3. The application of methods used to study biological diversity to territorial systems demonstrated, by computing and mapping the spatial distribution of the values of diversity indices, the validity of such a methodological transfer even to one of the key properties of the systems. Moreover, the results indicated that, if the dynamics of systems is explained through the theory of succession cycles, anthropisized or anthropic systems can be assimilated to young ecological systems due to their reduced diversity. Furthermore, similar to the geostatistical analysis of land use, the results showed that the dynamics is influenced by socioeconomic and/or political factors. The fact that these results correspond to reality justifies the transfer of statistical methods from ecology to geography.

4. The study of the orientation of county, national and express roads, auto-routes and railroads in Romania employed a complex set of instruments consisting of the Analysis of Variance, regression and other statistical tests, and the mapping of results. Theoretically, such analysis could be ascribed to one or both of the following research directions: geopolitical and strategic analysis of Romanian highway and railroad connections with other European countries, and polycentric development at several levels, since in its analysis accessibility plays a key role; in a broader extent, the latest is tightly connected to the mechanism of the spatial development and role of territorial discontinuities in this process. Regardless of the perspective used in analyzing the results, they indicate an interruption of the connections between the regions of Romania with the remainder of Europe, mainly due to the configuration of the relief. The limits of this case study relate to the analyses addressing exclusively the orientation. Further research could account for other parameters, such as traffic flows or condition of routes, constituting important barrier against multimodal transportation.

5. Geostatistical analysis of the distribution of areas affected by clime change in Romania according to 2100 predictions constitutes a return to the applications placed at the border between ecology and the geography of territorial systems. Based on using the ordinary kriging and GIS modeling, the study shows that predicted changes will affect mostly the mountain region; the results vary slightly based on the method, but in essence converge to this conclusion. It is important to mention, from a methodological standpoint, that both abstract analyses, such as ordinary kriging prediction of the location of areas most affected by the changes, and concrete analyses, as establishing a hierarchy of the counties based on the possible impact of clime change against them, could be performed. Nevertheless, such analyses represent only a first step, determining the exposure. The risk due to clime change can be assessed

only after analyzing the vulnerability by looking at the distribution of their physical, geographical, ecological and socioeconomic characteristics.

6. The study of potential accessibility and optimization of the national security corridor based on an analogy with the least square method represents a geo-strategic analysis similar to the study of the orientation of county, national and express roads, auto-routes and railroads in Romania, but based upon a statistical and mathematical model, consisting of the construction of two indices. The first, called potential accessibility, starts from the universal definition of accessibility based on isochrones and consists of summing up the population of potentially accessible settlements. The second is built by analogy with the least square methods in order to quantify whether the route has the optimal path, minimizing the squared distances between the settlements with a railroad station and those potentially accessible, ignoring the configuration due to the relief. Such indicators demonstrate their usefulness in arguing the choice of a route or portion of it as optimal strategic route. The analyses were performed at the macro-scale (European continent) and micro-scale (national territory).

Overall, the case studies confirmed the underlying hypothesis of the paper, allowing in addition for establishing a hierarchy of the geostatistical methods, phrasing recommendations and restrictions related to their use, and finally an algorithm for their application, consisting of the following steps: (1) establish the category of development of knowledge (study or research), (2) establish hypotheses and objectives, (3) review the literature to identify conceptual and methodological lacks, (4) choose appropriate research methods helped by a statistician, (5) collect data, and (6) analyze them and interpret the results comparing them with those of similar studies or with the underlying hypotheses (*Fig. 4*).

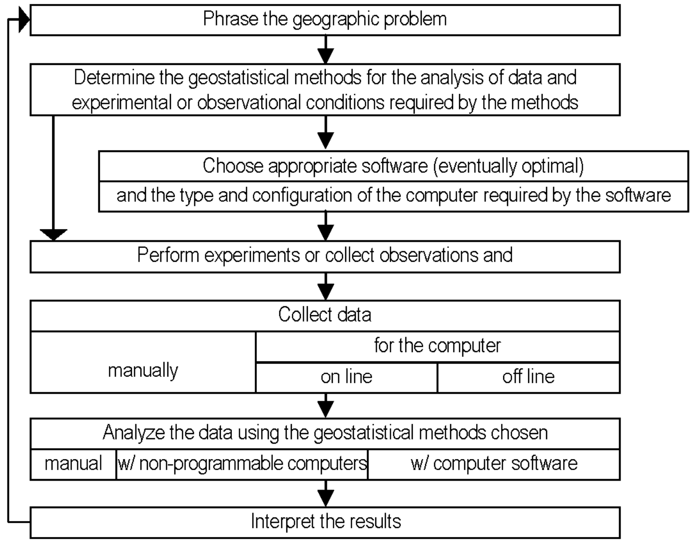

Fig. 4. Algorithm for the geostatistical analysis of territorial systems (adapted after Dragomirescu and Drane[79], 2007)

Fig. 5 presents a proposed hierarchy distinguishing five areas of interference: (a) “pure” statistical and mathematical methods, theoretical constructs; (b) strongly abstractive geostatistical methods; (c) pure interference; (d) weakly abstractive geostatistical methods, tightly related to the territorial reality, and (e) pure geographical methods, descriptive.

The position of some methods or algorithms in these areas results from the manner of transferring the methodology. If methods specific to geography are used, they will situate in zone (e). If the reality presented by a map is made abstract, even only by a simple grouping of data by categories, the method yields abstract results and enters zone (d). If data beyond a map are applied different statistical analysis to produce a new map or the results of statistical analyses are represented, but in any case the analyses report to the territorial reality, methods are situated in zone (c). If the link is ignored or made only in the end, to interpret the results, algorithms are placed in zone (b), and if the connection with the territory is lost and data are analyzed as if they would have another nature than the geographic one, the methods are placed in zone (a).

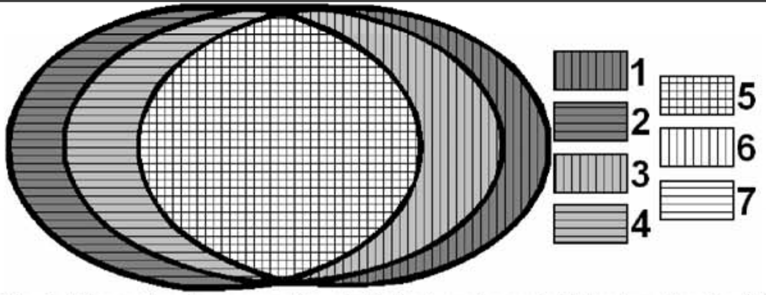

Fig. 5. Hierarchy of geographic, statistical and geostatistical methods: (1) "pure" statistical and mathematical methods; (2) purely geographical methods; (3) very abstract geostatistical methods, belonging more to the statistical and mathematical domain; (4) less abstract geostatistical methods, more characteristic to geography; (5) geostatistical methods situated at the confluence between geography and statistical and mathematical disciplines – domain of interference; (6) statistical and mathematical methods; (7) geographical methods

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