Methodology For Environmental Monitoring With Use of Methods of Mathematical Modeling

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Abstract

The article is aimed at developing methodological support for environmental monitoring using modeling methods, which will optimize the number of studied indicators and facilitate the processing, interpretation and visualization of the results. Developed methodology envisages the following stages: formation of the initial set of partial indicators; factor analysis of partial indicators and reduction of those with a factor load of less than 60%; structuring a set of partial indicators (selection of components and calculation of integrated indicators); application of matrix analysis for grouping of monitoring objects.

Keywords

Environmental monitoring, sustainable development, modeling, factor analysis, integral indicator, partial indicators.

1. Introduction

Sustainable development involves the harmonization of development and functioning of environmental, economic, and social areas. The interaction between these areas is embodied in the formation of the outline of direct and indirect relation between the supervision and dynamics of their development and the results achieved. The problem of sustainable development is complex, as part of its solution it is advisable to monitor the economy, social area, and the state of the environment using methods that would take into account the complexity and difficult predictability of this process.

ICT play a significant role in the transformation of sustainable development approaches. Issues of organization and digitalization of monitoring the functioning of certain areas of sustainable development, of large amounts of information (variety baselines), of the complexity of their processing and interpretation of results, and of the formulation of conclusions require knowledge-intensive approaches.

This article is aimed at developing methodological support for environmental monitoring using modeling methods, which optimize the number of studied indicators and facilitate the processing, interpretation and visualization of the results.

2. Methodology

Ensuring environmental monitoring within the developed methodology envisages the following stages: formation of the initial set of partial indicators; factor analysis of partial indicators and reduction of those with a factor load of less than

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60%; structuring a set of partial indicators (selection of components and calculation of integrated indicators); application of matrix analysis for grouping of monitoring objects.

As the initial set of monitoring indicators is large, in conditions of insufficient time it is advisable to use methods of data reduction [1]. One of such methods is the factor analysis which is widely applied in ecological science in various directions [2–5].

Within the framework of the proposed approach, the first stage determines the number of factors that should be identified within the reduction of monitoring indicators. The initial set of partial indicators takes part in the analysis.

The essence of the analysis is that during the sequential selection of factors, they include less and less variability of monitoring indicators. Therefore, the decision on when to stop the procedure for the selection of factors depends largely on the analysis purposes, but one of the recommendations to streamline the process of selecting the number of factors is to consider the scree plot.

Next, it is proposed to structure the initial set of indicators for monitoring, which remained after the factor analysis. Structuring is done by identifying the components that will be followed by a generalized assessment of the environment. All selected components correspond to the main components of the living environment for monitoring of which the initial set was formed and which includes the following indicators:

I_A – integral indicator of the atmosphere assessment;

I_W – integral indicator of the water resources assessment;

I_S – integral indicator of the soil assessment;

I_{Ws} – integral indicator of the wastes assessment;

I_F – integral indicator of the forest resources assessment;

I_{NR} – integral indicator of the nature reserves and hunting grounds assessment.

To calculate the integrated components of the above indicators, it is proposed to use the entropy method [6], the stages of which (adapted to the objectives of the environmental monitoring) are the formation of a set of partial indicators and their assessment, standardization of partial indicators taking into account their impact on the environment, and calculation of the value of entropy of the environment features and integral indicators for estimation of its components.

This approach allows us to take into account that the greater the entropy of any partial indicator that characterizes a certain feature of any component of the environment, the more disordered the ecological system would be as a whole. If the entropy of the trait, expressed as a partial exponent, is insignificant, then its weight in the total set of traits is also insignificant [6]:

$$R(S_i) = \sum_{j=1}^{n} H_j b_{ij}\,, \quad i = \overline{1, m}, \qquad (1)$$

where $R(S_i)$ – integral value of the object;
H_j – the entropy of *j*-th feature;
b_{ij} – quantitative assessment of *j*-th feature of *i* object;
m – number of objects;
n – number of features.

Matrix analysis is used in this work to visualize the results of monitoring which facilitates their interpretation and the possibility of obtaining homogeneous groups of objects of the study by positioning them in different quadrants of matrices. Having a group of objects in the study we can isolate their common characteristics. To do this, we offer three matrices or positioning planes:

- Atmosphere – Water resources ($I_A – I_W$).
- Soil – Wastes ($I_S – I_{Ws}$).
- Forest resources – Nature reserves and hunting grounds ($I_F – I_{NR}$).

Accordingly, the axes of these matrices are integrated indicators for assessing the six selected components of the environment.

To determine the boundaries of the quadrants of the matrices, the range of values of the integrated indicators for environment components estimation can be divided into three parts by the golden ratio. The golden ratio is such a proportional division of a segment into unequal parts in which the whole segment belongs to the larger part as much as the largest part belongs to the smaller one; or in other words, the smaller segment refers to the larger as the larger segment refers to all [7]:

$$\frac{YB}{AB} = \frac{AB}{YA} = \alpha, \qquad (2)$$

where *YB*, *AB*, *YA* – parts of a segment or numerical series.

Depending on the defined conditions and features of research objects development, as well as properties and role which they carry out in a system, nine functions of distribution of the investigated sample are allocated: chaos, development of elements, development of properties, development of relations, balance of functions of development and preservation, preservation of relations, preservation of properties, preservation of elements, and collapse [7,9]. Environmental monitoring objects can be considered as systems with connections and elements. Since the development of this system is unbalanced, in certain periods of time it even contains signs of chaos, the most suitable function to describe these processes can be defined as "development of elements" with the appropriate percentage distribution of parts of the range of values: [0,0; 0,328) – low, (0,329; 0,735) – medium level, (0,736; 1,0) – high level].

3. Results

At the first stage we formed an initial set of partial indicators for assessing the ecological sphere of sustainable development of the country – its environment.

The environment has the following main components that affect health and quality of life: air, water, soil, wastes, forests, nature reserves and hunting, etc. These components are reflected both in international indices that assess various aspects of habitat quality and in statistics to assess the development of regional environments. Based on this, it is proposed to monitor the environment using the following partial indicators (Table 1).

Table 1

Partial indicators for environmental monitoring

Symbol	Partial indicators
n.1	Emissions of carbon dioxide into the air from stationary sources of pollution, thousand tons
n.2	Emissions of pollutants into the air from stationary sources of pollution, thousand tons
n.3	Emissions of pollutants into the air from stationary sources of pollution per square kilometer, tons
n.4	Emissions of pollutants into the air from stationary sources of pollution per person kilometer, kg
n.5	Emissions of suspended solids into the atmosphere from stationary sources of pollution, thousand tons
n.6	Emissions of sulfur dioxide into the air from stationary sources of pollution, thousand tons
n.7	Emissions of nitrogen dioxide into the atmosphere from stationary sources of pollution, thousand tons
n.8	Emissions of carbon monoxide into the air from stationary sources of pollution, thousand tons
n.9	Emissions of non-methane volatile organic compounds into the atmosphere from stationary sources of pollution, thousand tons
n.10	Emissions of ammonia into the atmosphere from stationary sources of pollution, thousand tons
n.11	Emissions of methane into the air from stationary sources of pollution, thousand tons
n.12	Drawing of water from natural water objects, million m^3
n.13	Drawing of water from natural water objects per person, m^3
n.14	Water loss during transportation, million m^3
n.15	Use of fresh water, including fresh and sea water, million m^3
n.16	Use of fresh water, including fresh and sea water, used for the needs of the national economy and population, million m^3
n.17	Water saving drawing through the circulating and recycling water supply, million m^3
n.18	General drainage, million m^3
n.19	Discharge of return waters into surface water objects, million m^3
n.20	Discharge of contaminated return water into surface water objects, million m^3
n.21	Discharge of contaminated return water without purification into the surface water objects, million m^3
n.22	Discharge of insufficiently treated contaminated return water into surface water objects, million m^3
n.23	Discharge of normatively clean without treatment return water into surface water objects, million m^3

Symbol	Partial indicators
n.24	Wastewater treatment facilities, million m^3
n.25	Application of mineral fertilizers per hectare of acreage, kg
n.26	Application of organic fertilizers per hectare of acreage, tons
n.27	The area of crops fertilized with mineral fertilizers, thousand hectares
n.28	The area of crops fertilized with organic fertilizers, thousand hectares
n.29	Areas where pesticides were used, thousand hectares
n.30	Waste generation, thousand tons
n.31	Waste generation of I–III classes of danger, thousand tons
n.32	Waste generation per square kilometer, tons
n.33	Waste generation per capita, kg
n.34	Waste disposal, thousand tons
n.35	Utilization of wastes of I–III classes of danger, thousand tons
n.36	Waste incineration, thousand tons
n.37	Waste disposal in dedicated places and facilities, thousand tons
n.38	Removal of waste of I-III classes of danger in specially designated places and facilities, thousand tons
n.39	Waste disposal in fly-tipping, thousand tons
n.40	Total amount of waste accumulated during operation in waste disposal sites, thousand tons
n.41	Total amount of waste accumulated during operation in waste disposal sites per square kilometer, thousand tons
n.42	Total amount of waste accumulated during operation in waste disposal sites per person, thousand tons
n.43	Area of forest destruction, hectares
n.44	Number of forest fires, units
n.45	The area of forest lands covered by fires, hectare
n.46	Area of burned and damaged forest, m^3
n.47	Area of reforestation, hectares
n.48	Area of afforestation, hectares
n.49	Area of transfer of forest areas of natural regeneration into land covered with forest vegetation, hectares
n.50	Area of transfer of forest areas into land covered with forest vegetation, hectares
n.51	Number of illegal felling, units
n.52	Damage caused to forestry, millions of Ukrainian hryvnia
n.53	The area of hunting lands provided for use, thousand hectares
n.54	Land area of nature reserves, biosphere reserves and national nature parks, hectares
n.55	Number of wild animals (ungulates) by objects on the territory of which the lands are located, thousand heads
n.56	Number of wild animals (fur animals) by objects on the territory of which lands are located, thousand heads
n.57	Number of wild animals (game birds) by objects on the territory of which the lands are located, thousand heads

The composition of environmental monitoring objects may vary and depends on the objectives. In particular, it can be conducted at the global and national levels: for countries, regions, cities or other territories and settlements.

In this article, the objects of monitoring are defined as regions (administrative-territorial units) of Ukraine which have different characteristics of the environment due to different levels of industrial development, climate, geographical location, state of natural resources, and other factors.

Data collection of partial indicators for environmental monitoring in statistical sources allowed us to establish that the objects of monitoring have significant differences in the values of partial indicators n.1 – n.57. For example, the discrepancy between the maximum (233,7 thousand tons in the Donetsk region) and the minimum (0,2 thousand tons in the Transcarpathian region) values of sulfur dioxide emissions into the air was 1168,5 times (Table 2).

Table 2

Values of partial indicators for environmental monitoring, 2017 (fragment) [8]

The monitoring object	Values		
	n.5	n.6	n.7
Vinnytsia region	17,0	71,9	10,6

The monitoring object	Values		
	n.5	n.6	n.7
Volyn region	1,4	0,4	0,5
Dnipropetrovsk region	86,5	66,8	31,2
Donetsk region	76,2	233,7	44,8
Zhytomyr region	2,7	1,0	1,6
Transcarpathian region	0,4	0,2	0,7
Zaporizhya region	13,1	79	31,9
Ivano-Frankivsk region	37,3	129,6	14,5
Kyiv region	12,4	14,3	4,8
Kirovograd region	4,0	0,9	1,4
Luhansk region	10,4	33,3	8,1
Lviv region	8,4	39,8	6,8
Mykolayiv region	3,6	0,7	2,6
Odessa region	3,6	1,9	2,4
Poltava region	6,3	7,4	10
Rivne region	2,6	0,6	2,8
Sumy region	3,5	3,1	3,2
Ternopil region	1,5	0,3	1
Kharkiv region	6,5	11,3	7,8
Kherson region	1,2	0,7	0,3
Khmelnytsky region	2,8	2,5	5,3
Cherkasy region	8,8	5,0	10
Chernivtsi region	0,9	0,4	0,3
Chernihiv region	3,9	6,4	3,6

Consideration of the scree plot (Fig. 2) allows a researcher to determine the place where the decline in the eigenvalues of the factors from left to right is slowed down as much as possible. In this graph, this place corresponds to the number of factors equal to six. But the maximum variability of the initial indicators is explained by the first and second factors (Table 3).

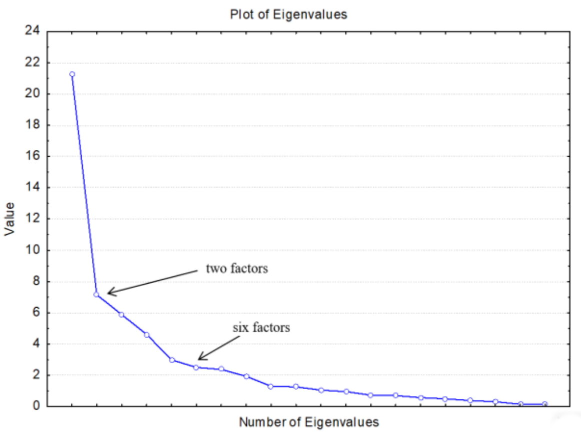

Figure 1: Graph of eigenvalues of environmental monitoring factors (scree plot)

Table 3
Eigenvalues of factors obtained by the principal components' method

Factor	Eigenvalue	% Total – variance	Cumulative – Eigenvalue	Cumulative – %
1	21,2	37,28	21,2	37,3
2	7,2	12,6	28,4	49,8
3	5,9	10,3	34,3	60,1
4	4,6	8,1	38,9	68,3
5	3,0	5,3	41,9	73,5
6	2,5	4,4	44,4	77,9

As can be seen from table 3, the first and second factors explain 49,83%, i.e. half of the variance of the initial indicators of environmental monitoring, and all six factors – 77,92% of the total variance. Therefore, in the process of factor analysis, it is possible to identify either two main factors (factor 1 and factor 2) and to reduce those indicators of environmental monitoring that are not included in their composition or to identify six factors and to reduce those indicators of environmental monitoring that are not included in their composition.

Leaving for analysis factors 1 and 2 and reducing the indicators of environmental monitoring which have a factor load of more than 60% and explain 49,83% of the total variance, the following results were obtained:

- Composition of factor 1 "Dangerous": n.1, n.2, n.3, n.4, n.5, n.6, n.7, n.8, n.11, n.18, n.19, n.20, n.21, n.22, n.24, n.33, n.34, n.35, n.37, n.40, n.41, n.42.
- Composition of factor 1 "Permissible": n.12, n.13, n.15, n.16, n.25, n.44, n.45, n.46, n.47, n.49, n.51, n.55, n.56.

Thus, factor 1 includes monitoring indicators that characterize the negative phenomena of the environment: emissions of hazardous substances into the atmosphere, different types of waste generation, etc. Given the composition of the indicators that fall into factor 1, it can be called "Dangerous" because it has a negative impact on the environment.

Factor 2 includes monitoring indicators that characterize less dangerous phenomena: water intake and its use for various purposes, application of mineral fertilizers to soil, etc. Given the composition of the indicators of factor 2, it can be conditionally called "Permissible" because it has a permissible and, in some cases, positive impact on the environment.

According to the criterion of factor load less than 60%, the following indicators were reduced: n.9., N.10, n.14, n.17, n.23, n.26, n.27, n.28, n.29, n.31, n.32, n.36, n.38, n.39, n.43, n.48, n.50, n.52, n.53, n.54, n.57.

The six selected factors include indicators that characterize areas of environmental monitoring such as air and water pollution by various types of hazardous substances (factor 1 and factor 3); wastes management (factor 3); use of natural resources for different purposes (factor 2); restoration of forest resources (factor 4); soil management (factor 5); loss of forest stands (factor 6).

Factors 1–3 were the largest in terms of the number of included indicators, and only one indicator was included in factor 6, which corresponds to the general rule of factor analysis – reduction of the number of indicators included in each subsequent selected factor due to reduced variability of indicators.

The analysis allowed us to conclude that the minimum number of factors that can be identified is two factors, and the maximum is six factors. And in addition, the logic of this study allowed us to recommend the second option of factor analysis according to which there are six factors influencing the environment which explain the maximum indicators variability.

Thus, as a result of the reduction, the initial set of environmental monitoring indicators was reduced from 57 to 45.

After calculating the entropy of integrated indicators that characterize the state of the selected components of the environment (Fig. 1), we carried out the positioning of monitoring objects in three matrices, for example, the matrix “Soil–Wastes” is presented in Fig. 2.

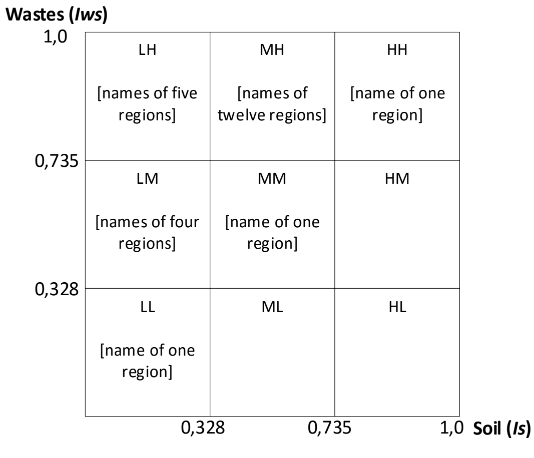

Figure 2: Positioning of monitoring objects in the matrix “Soil–Wastes”

Characteristics of matrix quadrants are the following:

HH – high assessment of soil – high level of wastes management;

HM – high assessment of soil – medium level of wastes management;

HL – high assessment of soil – low level of wastes management;

MH – medium assessment of soil – high level of wastes management;

MM – medium assessment of soil – medium level of wastes management;

ML – medium assessment of soil – low level of wastes management;

LH – low assessment of soils – high level of wastes management;

LM – low assessment of soil – medium level of wastes management;

LL – low assessment of soil – low level of wastes management.

Coordinates of positioning points in the matrix are the following: Ukraine (0,371; 0,735); Vinnytsia region (0,134; 0,773); Volyn region (0,623; 0,775); Dnipropetrovsk region (0,144; 0,234); Donetsk region (0,384; 0,710); Zhytomyr region (0,462; 0,777); Transcarpathian region (0,707; 0,776); Zaporizhzhya region (0,109; 0,761); Ivano-Frankivsk region (0,671; 0,769); Kyiv region (0,574; 0,772); Kirovograd region (0,072; 0,639); Luhansk region (0,392; 0,769); Lviv region (0,571; 0,764); Mykolayiv region (0,241; 0,762); Odessa region (0,072; 0,775); Poltava region (0,321; 0,686); Rivne region (0,710; 0,775); Sumy region (0,215; 0,738); Ternopil (0,469; 0,776); Kharkiv (0,070; 0,740); Kherson region (0,352; 0,761); Khmelnytsky region (0,354; 0,774); Cherkasy region (0,362; 0,776); Chernivtsi region (0,658; 0,777); Chernihiv region (0,230; 0,775).

The quadrants that are on the line of development of monitoring objects from the worst to the best condition are Dnipropetrovsk, Donetsk, and Rivne regions.

4. Conclusions

The given methodology for environmental monitoring with use of methods of mathematical modeling allows a researcher to draw conclusions with regard to a habitat condition as a whole in the country, to define the most dangerous state of ecology according to its administrative units, and to analyze results of an environment condition assessment according to its components.

The proposed methodology support provides the implementation of the complex approach to the establishment of monitoring of an ecological component of sustainable development and to strengthen its scientific substantiation. Its advantage is the ease and high implementation opportunities through ICT tools to reduce the time of monitoring and systematic analysis for clear conclusions and recommendations for more effective implementation of the concept of sustainable development.

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