INTEGRAL ASSESSMENT OF ECOLOGICAL WELL-BEING OF FLUVIAL SYSTEMS

Master student Daniel Amaro Medina[1]
Prof. Dr. of Geographical Sciences Vasiliy Dmitriev[2]
[1] Saint-Petersburg State University, Department of Hydrology, Saint-Petersburg, Russian Federation
[2] Saint-Petersburg State University, Department of Applied Ecology, Saint-Petersburg, Russian Federation

ABSTRACT

The theoretical and methodological aspects of using the methods for characteristics of ecological well-being (EW) of fluvial systems are considered. The problems of development of multi-criteria classifications of EW, stages and results of assessment are discussed. Evaluation of EW can be performed on the basis of biocentric or anthropocentric approach that takes into account the planning of rivers use for various purposes with special attention to conservation of environment. The assessment scales were developed considering each evaluation component and indicator approach and can use incomplete, inaccurate, non-numerical assessments data. It was concluded that EW is an example of system emergent property that combines its ability to produce organic substances, to maintain high quality of habitat, high biodiversity, resistance to changes of natural conditions and anthropogenic impacts. This research is focused on the development of models for quantitative integral assessment of fluvial systems state, their systemic properties that are characterized by the necessity of new functional units (integral and summarizing indicators) that reflect the system integrity. The development of integral indicators of EW is discussed on hypothetical examples of the “river-drainage area” systems and on the base of assessment of EW of real natural object (Msta River) and its catchment area.

Keywords: *integral assessment, ecological status, fluvial system, system “river-drainage area”, ecosystem stability.*

INTRODUCTION

Assessment of ecological condition, ecological status and health of complex natural systems began to be actively discussed in scientific publications at the end of the 20th century due to the development of methods for evaluating emergent properties of complex systems in nature and society. The necessity to create an integral indicator of ecological well-being or “ecological certificate of a river” has been discussed since the end of the 1960s [1], [2]. The problem retains its relevancy due to the development of a system approach in assessment studies of eco-systems condition, unification of approaches to assessment of the condition of natural environment by international community from the perspective of an integrated approach and assignment of eco-regions. The Directive of the European Parliament and of the European Commission of 23 October 2000 (Water Framework Directive

- WFD) declared the attainment of ecological well-being or high ecological status for all water systems as the basic goal [3].

MATERIALS AND METHODS

The object of our research is a "river-drainage" system. Such system means a system consisting of two subsystems "river" and "drainage" which parameters will be determined; according to them ecological well-being (EW) will be assessed. For each subsystem, an integral indicator of ecological well-being (IIEW) for key geo-systems will be calculated. The *ecological well-being* is the main subject of our research. According to [4], this is a normal reproduction of main links of the ecological system of a water object. In order to assess EW, a number of features were introduced and used in frames of our study. The features of good eco-system of a water object were named: 1) maximum (optimal) production of resource element; 2) maximum diversity of the biota; 3) high water quality; 4) high resistance of the system to changing parameters of natural and anthropogenic conditions; 5) low speed and risks of contamination, acidification and anthropogenic eutrophication; 6) high speed of self-purification [5].

One of the important components of EW assessment is the ability of a system to retain its properties and condition parameters after external impact. Such system is called resistant to changes of condition parameters. It is considered that the concept of EW is wider and can include resistance of a system to changes in parameters of natural (potential stability) and anthropogenic conditions. It is proposed to determine the EW of a system on the basis of an axiological approach from the perspective of biocentrism and anthropocentrism [3].

To assess the state of complex systems in nature, various approaches are used including landscape, geo-system, geo-ecological, and geo-situational ones, as well as method of system simulation, analysis and synthesis of indicators in information deficiency (ASIID- and APIS-methodologies). Each method can use the following kinds of assessment: 1) *single* (direct and indirect) assessment by separate initial characteristics on the basis of comparison with certain levels and norms; 2) *multi-criteria* assessments imply the necessity for a procedure of compression of information that is a target-oriented process based on clearly formulated principles of selection of the most informative variables, indicators of state (impact); 3) *integral* assessments combine dissimilar (multi-criteria) assessments taking into account their contribution to the overall assessment [5].

In most cases for evaluation of ecological status and EW composite indicators as *d – functions* or *desirability functions* are used. They allow to translate natural values into a unified dimensionless numerical scale with fixed boundaries. The necessity to introduce desirability functions is determined by various dimensions of variables composing the indicator, which does not allow them to be averaged without transformations, and the necessity to change the weight ratios when changing the assessment priorities.

This study uses, as an analytical *d-function,* a linear or non-linear convolution of normalized values of criteria. To normalize, a non-decreasing piecewise power function of the following form [7] is used:

$$q_i = q_i(x_i) = \begin{cases} 0, & x_i \le \min_i, \\ \left(\dfrac{x_i - \min_i}{\max_i - \min_i}\right)^{\lambda}, & \min_i < x_i \le \max_i, \\ 1, & x_i > \max_i \end{cases} \qquad (1)$$

Such function can be used when an increase in the value of the i-th initial characteristic does not entail a decrease in the well-being assessed according to the i-th criterion.

If the value of the i-th initial characteristic of some emergent property assessed by the i-th criterion increases, it does not grow, a non-increasing piecewise power function of the following form [6] can be used:

$$q_i = q_i(x_i) = \begin{cases} 1, & x_i \le \min_i, \\ \left(\dfrac{\max_i - x_i}{\max_i - \min_i}\right)^{\lambda}, & \min_i < x_i \le \max_i, \\ 0, & x_i > \max_i . \end{cases} \qquad (2)$$

The range of change of q_i is within 0 and 1. The value $q_i=1$ can evidence the well-being of a system by the i-th criterion, and the value $q_i = 0$ can evidence its degradation (or vise versa). In current research "0" corresponded to the highest value of ecological well-being, and "1" to the lowest.

After normalizing the values of parameters, an interpreting function $Q(q)=Q(q_1,\dots,q_m)$ is introduced that transforms the normalized indicators $q_1,\dots,q_m$ into a single integral indicator $Q = Q(q)$, collating to the j-th property certain numerical assessment $Q^{(j)}=Q(q^{(j)})=Q(q_1^{(j)},\dots,q_m^{(j)})$. As a synthesizing function, the presented formula was chosen:

$$Q=q(q,w)= Q(q_1,\dots,q_m;\ w_1,\dots,w_m)=\sum q_i w_i \qquad (3)$$

The solution of a problem of selecting the weight factors w_i is of great importance. Usually calculations begin with using the idea of equal weight of characteristics. Then a series of calculations is performed to take into account the justified non-equilibrium setting of parameters inside units and between units. The obtained results are analyzed. Depending on the total number of levels and units, as well as total number of necessary and sufficient parameters of assessment a conclusion is made on the possibility or inappropriateness to use equal weights. It is recommended to make simulation of the weight factors based on ASIID - (Analysis and Synthesis of Indicators in Information Deficiency) or APIS - (Aggregated Preference Indicators System) methodologies that allow incomplete, inaccurate, non-numerical information to be accounted for setting the weights. To evaluate the ecological well-being of natural eco-systems the method of consolidated indicators (MCI) and the method of randomized consolidated indicators (MRCI) were used [7].

RESULTS AND DISCUSSION

To build a classification of ecological well-being of fluvial systems, we selected 63 criteria (parameters) of evaluation. The parameters for “river” and “drainage” were set by units separately for a river (33 parameters) and for its drainage (30 parameters). The classifications were built using the author evaluative scales that are part of various evaluating classifications: of productivity, environmental qualities (water, atmosphere, soil), stability, etc. The singling out of 5 EW classes were justified, since this number of classes is distinguished by most authors of reference scales and is contained in WFD.

To assess EW of a river, several parameters were selected that form the groups: 1-morphometric and physico-geographical, 2-climatic, 3-hydrological, 4-hydrochemical, 5-hydrobiological, 6-self-purification, 7-risks of contamination and stability of the river. For the drainage EW, the evaluating criteria was selected forming the units: 1-favorable climate, 2-quality and contamination of atmospheric air, 3-quality and contamination of soil, 4-potential stability of drainage, 5-stability of soils.

As a result of normalization, for the river and drainage subsystems the scales of integral indicators were obtained inside each group of parameters (integral indicator of the 1st level of convolution) and among the groups of parameters (integral indicator of the 2nd level of convolution or scales of consolidated indicators). At the first stage the value of the integral indicator was calculated under the condition of setting equal priorities (weights) for the parameters in the “river” groups and for the parameters in the “drainage” group.

Since the further research requires the scales of the last levels of convolution to be available, the article focuses on obtaining the values of these integral indicators and the boundaries of the classes of ecological well-being for them. The results of calculating the consolidated indicators between the groups (second level of convolution) are presented in tables 1 and 2 for the river and the drainage respectively. In these tables, the acronym II means integral indicator of the 1st level of convolution.

Table 1. *Integral indicators for groups and consolidated indicator for river*

EW feature / class	I Maximum EW	II EW above average	III Average EW	IV EW below average	V Minimum EW
II-1 (Morphometric and physico-geographical parameters)	0-0.21	0.21-0.49	0.49-0.68	0.68-0.87	0.87-1
II-2 (Climatic parameters)	0-0.21	0.21-0.33	0.33-0.55	0.55-0.73	0.73-1
II-3 (Hydrological parameters)	0-0.22	0.22-0.38	0.38-0.60	0.60-0.81	0.81-1
II-4 (Hydrochemical parameters)	0-0.15	0.15-0.26	0.26-0.43	0.43-0.64	0.64-1
II-5 (Hydrobiological parameters)	0-0.17	0.17-0.34	0.34-0.55	0.55-0.78	0.78-1
II-6 (Self-purification)	0-0.07	0.07-0.14	0.14-0.24	0.24-0.50	0.50-1
II-7 (Risks of contamination and river stability)	0-0.24	0.24-0.39	0.39-0.60	0.60-0.76	0.76-1
Consolidated indicator	0-0.18	0.18-0.33	0.33-0.52	0.52-0.73	0.73-1

Table 2. *Integral indicators for groups and consolidated indicator for drainage*

EW feature / class	I Maximum EW	II EW above average	III Average EW	IV EW below average	V Minimum EW
II-1 (Favorable climate)	0-0.26	0.26-0.45	0.45-0.59	0.59-0.75	0.75-1
II-2 (Quality and contamination of atmospheric air)	0-0.17	0.17-0.22	0.22-0.30	0.30-0.65	0.65-1
II-3 (Quality and contamination of soil)	0-0.13	0.13-0.23	0.23-0.38	0.38-0.61	0.61-1
II-4 (Potential stability of drainage)	0-0.37	0.37-0.42	0.42-0.61	0.61-0.80	0.80-1
II-5 (Stability of soils)	0-0.18	0.18-0.41	0.41-0.61	0.61-0.80	0.80-1
Consolidated indicator	0-0.22	0.22-0.35	0.35-0.50	0.50-0.72	0.72-1

One of the stages of the research important for proving the adequacy of the obtained results was development and implementation of test scenarios. Such calculations are accounted for by the necessity to prove the applicability of the developed classification model to do further research for rivers and drainages differing in their properties and their combinations. In relation to this we discuss 8 test scenarios: four for a river and four for drainage.

On results of calculations by the scenarios 1 - 8 a conclusion was drawn to the effect that the developed classification objectively reflects various combinations of properties of a river and drainage in a way that various EW classes correspond to various sets of combinations. This is reflected with the results from which it follows that the values of the integral indicators of ecological well-being (IIEW) calculated for rivers and drainages that are clean, stable, various in composition, having low risks of contamination, comparatively high self-purification etc., have higher EW classes (I and II), and for rivers and drainages having alternative properties, lower classes (III - V).

To evaluate the impact of priorities (weights) on IIEW of a fluvial system, the calculations for three options of the setting of the weights were made at the second level of convolution of indicators (between the groups of parameters): 1 - equal weight; 2 - anthropocentrism (focus on sustenance of people, society, their resource provision, use of sanitary regulations and health-based exposure limits etc.); 3 - biocentrism (preservation of habitat for aquatic organisms, priority of using methods of biological control of the environment etc.). For options 2 and 3 “APIS” capacities were used.

Table 3 shows the designations of priorities (weights) for each group of parameters.

Table 3. *Designations of weights for each group of parameters*

Subsystem	Group of parameters	Designation
River	Morphometric and physico-geographical parameters	w_1
	Climatic parameters	w_2
	Hydrological parameters	w_3
	Hydrochemical parameters	w_4
	Hydrobiological parameters	w_5
	Self-purification	w_6
	Risks of contamination and river stability	w_7
Catchment	Morphometric and physico-geographical parameters	w_1
	Quality and contamination of atmospheric air	w_9
	Quality and contamination of soil	w_{10}
	Potential stability of drainage	w_{11}
	Stability of soils	w_{12}

After that, the priority of the groups in each option was determined on the basis of non-numerical (serial) information. Then, using APIS system and taking into account the introduced priorities and the reading accuracy, the numerical values of weight ratios were calculated for the groups of characteristics, the accuracy of calculating the integral indicators evaluated. As a result, the average quantitative values of the weight factors were obtained for all options on the basis of the qualitative priority setting:

1) The value of the weight ratios for the groups of characteristics with an equilibrium approach for a river: $w_1 = w_2 = w_3 = w_4 = w_5 = w_6 = w_7 = \mathbf{0.14}$**;** for drainage: $w_8 = w_9 = w_{10} = w_{11} = w_{12} = \mathbf{0.20}$**;**

2) The value of the weight ratios for the groups of characteristics with an anthropocentric approach for a river: $w_2 = w_3 = w_4 = w_7 = \mathbf{0.16} > w_1 = w_5 = w_6 = \mathbf{0.12}$; for drainage: $w_8 = w_9 = w_{10} = \mathbf{0.28} > w_{11} = w_{12} = \mathbf{0.08}$**;**

3) The value of the weight ratios for the groups of characteristics with a biocentric approach for a river: $w_5 = w_6 = \mathbf{0.30} > w_1 = w_2 = w_3 = w_4 = w_7 = \mathbf{0.08}$**;** for drainage: $w_{11} = w_{12} = \mathbf{0.388} > w_8 = w_9 = w_{10} = \mathbf{0.08}$**.**

At the next stage, the IIEW construct for the second level of convolution (consolidated indicator) for a river and drainage for the three discussed options was implemented. The results of the calculations are presented in tables 4 and 5.

Table 4. *Scales of EW integral indicators for a river calculated for the three options of the priority setting*

IIEW / EW class	I Maximum EW	II EW above average	III Average EW	IV EW below average	V Minimum EW
IIEW1 (equal weight)	0-0.18	0.18-0.33	0.33-0.52	0.52-0.73	0.73-1
IIEW2 (anthropocentrism)	0-0.18	0.18-0.34	0.34-0.52	0.52-0.73	0.73-1
IIEW3 (biocentrism)	0-0.16	0.16-0.29	0.29-0.47	0.47-0.69	0.69-1

Table 5. *Scales of EW integral indicators for drainage, calculated for the three options of priority setting*

IIEW / EW class	I Maximum EW	II EW above average	III Average EW	IV EW below average	V Minimum EW
IIEW1 (equal weight)	0-0.22	0.22-0.35	0.35-0.50	0.50-0.72	0.72-1
IIEW2 (anthropocentrism)	0-0.20	0.20-0.32	0.32-0.45	0.45-0.69	0.69-1
IIEW3 (biocentrism)	0-0.25	0.25-0.39	0.39-0.56	0.56-0.77	0.77-1

The analysis of data presented in these tables showed that the divergences between IIEW boundary values for the evaluative scales by EW classes of a river (table 4) are not high. The boundary divergence between the classes was: 12.5% (I-II); 17.2% (II-III); 10.6% (III-IV); 5.8% (IV-V). In all classes the maximum differences are inherent in the third option of priority setting (biocentrism).

For drainage (table 5) these differences are somewhat higher. The boundary divergence between the classes was: 25% (I-II); 21.9% (II-III); 24.4% (III-IV); 11.6% (IV-V). In all classes the maximum differences are also inherent in the third option of priority setting (biocentrism).

At the next stage the key fluvial system was discussed and its ecological well-being evaluated on the basis of the reviewed criteria. As an example, the Msta River and its drainage were chosen located in the North-West region of the Russian Federation. For setting the separate characteristics the parameter values inside the groups averaged for a number of the recent years (the first level of convolution) were used.

The ecological well-being of the Msta River and its basin was determined by calculating IIEW according to three options discussed above. The EW class of the object in question was determined according to same rules as in options 1-3.

An important part of the research was checking the assumption whether a fluvial system will go to another EW class if the anthropogenic load in number of parameters is increased hypothetically at the same time. In nature such event has low probability; in this case however the investigator was interested in the obtained result in terms of developing the technique for assessing the impact of loads on the state of the system. To check the impact of a hypothetic load, it was decided to select the groups of parameters most vulnerable to anthropogenic impact. For a river the groups of hydrochemical and hydrobiological parameters were selected, and for drainage the groups “quality and contamination of atmospheric air” and “quality and contamination of soil” were selected.

In option “1n” the load inside the named groups was increased by 30%, and in option “2n” it was increased by 2 times (by 200%). The calculation was made according to the normalized parameter values. The weights (priorities) were set according to option 1 (equal weight).

The analysis of the IIEW values for the Msta River and its drainage obtained in options "1n" and "2n" showed that both subsystems (river and drainage) were noticeably impacted by an increased load on the selected groups of parameters in option "2n". The obtained IIEW value of the Msta River evidences the transition of the system from the left boundary of class II (0.25) to its right boundary (0.32), i.e. practically to one class. The consolidated EW indicator for the drainage changed insignificantly. In the experiment it was shown that with the two-time increase of the load (in 2 groups out of 5) the river's drainage was able to retain its properties and condition parameters within the limits of the class in which it was before the impact, and the two-time increase of the parameter of conditions in the river (in 2 groups out of 7) caused the transition of the river to a superior class (the lowering of EW class).

CONCLUSION

1. The advantages of the suggested approach to an integral assessment of ecological well-being of a "river-drainage" system was demonstrated clearly.

2. In building the classification models the investigator: a) introduces the ecological well-being classes, b) uses an axiological approach and axiometry (ecological qualimetry) to build evaluative scales, c) justifies the type of an integral indicator, d) solves the problem of normalization of initial data taking account the type of link (direct, reverse) and its non-linearity, e) accounts for information on the evaluation priorities, f) works with evaluative scales of the necessary and sufficient evaluating criteria.

3. A series of experiments was performed to assess ecological well-being of fluvial systems. They are represented as calculations of test scenarios, of evaluating EW of a real natural object, as well as scenarios for considering a hypothetical anthropogenic load on a system.

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