The concept of sustainability management of the ecosystem of cities and small settlements

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Abstract. Critical risks of ecosystem identity violation in the structure of landscape-recreational formation of the environment of cities and small settlements are identified. The dependence of the functional load of urban areas with industrial and civil facilities and the ability to restore the ecosystems of the adjacent small rivers and reservoirs is established. The necessity of modeling urban areas based on the "attraction zone" and "exclusion zone", the verification of technical solutions for engineering systems of water protection complex harmonized with the natural environment is substantiated. A conceptual model for controlling the risks of developing urban areas is proposed, that is focused on the mechanism for managing water body renovation programs taking into account risk factor analysis. A technique has been developed for restoring water bodies to the level of harmonized functioning by means of anticipatory diagnosis of risk-failures of the danger of environmental disruption. The introduction of digital indicator that determines the level of harmonized stability of functioning of engineering systems of water protection complex in the environment as an additional indicator of the economic and environmental activities of the regions will improve the accuracy of assessing environmental benefits and losses in planned projects.

1. Introduction

The landscape topography of urbanized territories includes various water bodies, technical and engineering structures that deharmonize the state of the natural environment. Given the globality of such deharmonization, it is clear that the creation of a mechanism for environmental sustainability management systems is required.

Don Goldstein [1] reported options for adaptive strategies at the regional level that can be identified and evaluated using a scenario-building methodology that includes the interaction between several variables and the actions of decision-makers over time.

Kerstin Hötte [2] studied the problem of slow involvement of innovative "green" technologies. Using the ecotechnological extension of the macroeconomic agent-oriented model Eurace@unib, it is...
shown how the effectiveness of various climate policies depends on the type and strength of diffusion barriers.

The investigations [3] present the results of empirical study on theoretical relationship between innovation in the field of "green" technology and efficient use of natural resources. The mechanism of influence of "green" technological innovations on efficiency of the use of natural resources is clarified based on the method of stochastic border analysis; positive and negative factors of "green" technological innovations are analyzed.

Andreas Schäfer [4] shown the relationship between population dynamics, technological change and the depletion of natural resources. The factors were studied in evidence-based form, that allows taking into account signs of the intertemporal secondary effects of R&D with respect to existing technological knowledge. Also, it is shown that an increase in the relative productivity of research or educational subsidies contributes to the long-term growth of technology.

Chris William Callaghan [5] proposed four technological scenarios for identifying and determination of key issues associated with the spread of hazardous technologies.

The research of Xiang Xiang Sun et al. [6] was devoted to study the market segmentation and mechanism of its influence on the environmental performance of electric power industry from point of view of technological innovation. It has been proven that market segmentation hinders the way to technological innovation. It has been established that this fact manifests itself more significantly in provinces with weak institutional quality.

It was found by [7] that technological innovations benefit society by improving communication and productivity in the supply chain. Although, technological innovations provides more opportunities for environmentally conscious choice and better infrastructure, its availability is ambiguous. Further research suggests considering efficiency as a key factor to decide on the promotion of certain technologies to add value to the social good. Similar studies have been conducted in related fields [8-12].

2. Materials and Methods

The analysis of regulatory acts for a ten-year period was aimed at finding out achievements and problems when the implementation process, as well as setting tasks for the future, taking into account existing technological innovations (The Decree of the Government of Moscow №1004-PP edited of October 28, 2008 «About the city target medium-term program for the remediation of small rivers and reservoirs in Moscow city 2009-2011»; The Resolution of the Government of the Moscow Region of 25.10.2016 N 795/39 (edited of April, 24, 2018) «On approval of the state program of the Moscow region «Ecology and the environment of the Moscow Region» for 2017-2026»).

The key aspect of these programs is the task of scientific and methodological support of a complex of actions for restoration and remediation of water bodies as well as to improve the management, operation and protection of water bodies.

Technically, this problem can be solved by taking the following actions:
- reduction the load on water bodies by developing programs that exclude changes in the water regime and water quality;
- rehabilitation of water bodies and coastal zones by clearing channels, dredging, designing the coastline, reconstruction of hydraulic structures, etc.;
- optimization of drainage networks through structural reconstruction and modernization of water bodies.

To achieve the proposed result, it is required to develop a scientifically and technically justified complex of actions focused on the formation of urban wastewater for an indefinite period of implementation; with a designated period of remediation; harmonized activity and advancing risk factor consideration of the danger of environmental disruption, i.e. long-term stable improvement of water quality in water bodies.

Hypothesis of the study: due to a large number of water bodies in the structure of landscape-recreational formation of the environment of cities and small settlements, taking into account the
complexity of the engineering systems that arise during reconstruction, it takes a long time and significant costs to complete the remediation of water bodies water system, the remediation program requires the simultaneous resolution of many related programs. This requires a structural modernization of the system, which provides targeted regulation of tasks for the remediation of water bodies and coastal areas.

Study goal: harmonization of ecosystems and landscape-recreational urban areas through the conservation of green planting and the remediation of small rivers and water reservoirs.

Methods: the studies are focused on the integration of the theory of large systems and probability theory with digital regulation mechanisms, which allow composition a control path adapted to correction in case of deviation when creating a mechanism for controlling the ecosystem of functioning of water bodies burdened by the urban environment.

3. Results

3.1. Justification of modeling of urban areas based on the «attraction zone» and «exclusion zone»
The algorithm of engineering measures for the reconstruction of urban water bodies characterizes the systematic use of all available theoretical and practical innovative resources of the object formation of a sustainable environment with improved technical and environmental conditions [13-18].
The systematicity of the problem involves the use of all theoretical and practical, innovative resources. Integration of the theory of large systems and the probability theory with digital control mechanisms allows creation of controlled path with possible correction of it in case of deviation (Fig. 1).

![Figure 1. Modeling algorithm of rehabilitation measures for restoration of water bodies](image)

The modal analysis of algorithm presented in Fig 1, includes the following parameters:
- probability of achieving the objectives;
- control activities;
- corrective actions;
- stage of the program realization.

The fixed state of the system during the design period of remediation is presented as the initial A stage, with the idealization of the linear translation to the key B stage.
Linear model allows description for implementation of each stage. The probability model of risky failures \( R_n \) for development of the programs \( V_n \) is expressed by the equation (1):

\[
R^V(0) = R_1 + R_2(1 - R_1) + R_3(1 - R_1)(1 - R_2) + ...
\]  

(1)

**Modeling of probability hypotheses of development**

To increase the accuracy of the model convergence, some hypotheses of development scenarios \( A_n \) were discussed.

For each hypothesis significance level, a weight characteristic \( w_n \) calculated discretely with a step, limited by the gradation \( h = \frac{1}{n} \) of the number of hypotheses were assigned.

The numerical value of the weight indicator was calculated with the following equation:

\[
w_n = \left\{ \begin{array}{ll} 1, & n = 1 \\ \frac{1}{n}, & n = 2, \ldots, \frac{n-1}{n} \end{array} \right. 
\]  

(2)

3.2. **Verification of technical solutions for engineering systems of water protection complex, which are harmonized with the natural environment**

Normally, risk theory offers an assessment of acceptable risk from the point of view of the mathematical expectation of damage when implementing a scenario of dangerous situations. Quantitatively, the value of acceptable risk is determined by the parameter, and the actual result \( (P_i) \) of the hazard level, that is compared with the normalized value and indicates on the criticality of the situation. To implement the program of remediation of water bodies at all stages, the adaptation of the basic model of risk assessment, calculated by the following equation was proposed:

\[
R_i = \frac{M[U]}{M[A_i]} - \frac{M[C_i]}{M[A_i]} = \frac{\sum p_i U_i}{M[A_i]} - \frac{M[C_i]}{M[A_i]} 
\]  

(3)

where \( U_i \) is physical damage in case of a negative scenario for implementation of the program stage; \( M[A_i] \) is the mathematical expectation of a positive result when implementation of the program stage, the monetary equivalent of economic efficiency; \( M[C_i] \) is mathematical expectation of resource investments (costs) for implementation of the program stage.

It is a commonly accepted design parameters, estimated in monetary terms, to be presented over a period of time per year, by introducing an indicator of the differentiated vulnerability of objects \( V_{ij} \) from the complex realization of hazards at various stages of the life cycles of objects.

The socio-ecological and natural-ecological risk of the \( j^{th} \) damage caused to the \( i^{th} \) water body in the spatial boundaries of the territories from a hazard situation is mathematically described by the following model:

\[
R^V_{ij} = V_{ij}(i) V_{ij}(i) 
\]  

(4)
where $V_{1i}; V_{2i}$ are probabilities when implementation of a complex of hazards during the annual cycle; $V^{P}_{i}$ is differential vulnerability of objects from the integrated implementation of hazards during the remediation of water bodies.

Considering the importance of the objects, development of a model for advanced development of situational hazard elimination when implementing programs to prevent factor risks was used as an alternative to the situation of eliminating consequences in the case of a negative scenario.

Calculation methodology for assessment the degree of damage caused to water bodies consists of the cost of restoring the disturbed state. It should be noted that this value increases with prolonged and intensive exposure to pollutants over time.

Using this assessment methodology (Ministry of Natural Resources and Ecology of the Russian Federation. Order of April 13, 2009 N 87 "On approval of the methodology for calculating the amount of harm caused to water bodies as a result of violation of water legislation" (amended on August 26, 2015)), an algorithm to control the level of contamination by introducing a multiplex digital indicator was applied.

There is a number of parameters in this technique that serve as input indicators:

- $K_{\text{season}}$ is a varied calculated coefficient that accounts for climate and environmental conditions within a given season;
- $K_{w}$ is a varied coefficient that determines environmental factors as well as conditions of water bodies;
- $K_{in}$ is an indexation coefficient that determines an inflationary component of economical development;
- $K_{i.p.}$ is a coefficient that accounts for intensity of negative impact of pollutants to a water body. A coefficient with the values of 1, 2 and 5 defines an exceedance of pollutants with III-IV class of hazard up to 10 times, from 10 to 50 times and more than 50 times, respectively;
- $K_{dur}$ is a coefficient that defines duration of negative impact of pollutants to water bodies without taking any remedial actions. A coefficient value of 5 describes a solubility of pollutants in water;
- $K_{\text{pollut}}$ is a coefficient that stands for a level of contamination of water body polluted with municipal and industrial waste;
- $Q_{w}$ is a volume of water required for remediation to prevent an atrophy of water body and taken as a double volume of non-recoverable take out of water from the water body;
- $T$ is a duration of sewage discharge with elevated amounts of contamination, from the moment of discharge indication to its complete discontinuation, hours.

Amount of pollutants in total volume of water body can be determined based on the equation (6):

$$M_{t} = Q (C_{f} - C_{N}) T \cdot 10^{-6}, \text{t.}$$

$Q$ is a sewage flow rate, m$^3$/hour;
$C_{f}$ is an average effective concentration of a substance in sewage water for a calculated time period, mg/dm$^3$;
$C_{N}$ is a permissible concentration of a substance within a limit of allowed volume of discharge for a calculated time period, mg/dm$^3$;
$T$ is a duration of sewage discharge with elevated amounts of contamination, from the moment of discharge indication to its complete discontinuation, hours.
Figure 2. Coefficient that determines environmental factors ($K_w$) (state of water bodies) of modeling remediation measures for the restoration of water bodies

Figure 3. Coefficient that accounts for climate and environmental conditions within a given season ($K_{season}$)

The forecast model is created with the correction of the result taking into account the temporary factor technospheric impact on the ecosystem. It is also necessary to carry out analytical adjustments.
of the complexity of the impact of related areas and infrastructures on water bodies, i.e. it is necessary to solve volumetric problems with the maximum allowance for the factor influence of the state-forming system of water bodies and adjacent territories (construction of probability-determined and probability-statistical models of mathematical analysis).

3.3. The mechanism of scientific and technical support activities focused on formation of sustainable urban ecosystems, including coastal zones and municipal effluents

Nowadays, specialists are faced with the situation of the already implemented negative scenario of the impact of territorial development on water bodies. In this regard, it is necessary to assess the environmental damage and establish the level of shift from the initial natural state of the water body.

Development of a forecast remediation program includes the selection of instruments for a technical assistant with a “zero” additional environmental load during the program implementation.

It seems clear that the predictive model designed by the information-weighted analog algorithm will not allow for consideration of many specific factors for a particular object.

With respect to the complexity and significance of this task, it is proposed to apply an individual remediation simulation programs to restore the environment. Algorithm of the designed model is shown in Fig. 4.

![Algorithm of the designed model](image)

Figure 4. Algorithm of the designed model

The «road map» of the mechanism of scientific and technical support for activities focused on providing the sustainability of the ecosystem of the urban environment, including coastal zones, municipal effluent consists of combination of deterministic-probabilistic modeling and probabilistic-statistical analysis.

3.3.1. Deterministic-probabilistic modeling [18]. The model is considered as a complex of predictive elements which are grouped into deterministic and probabilistic category. Predictive variability is described by periods of advance control of parametric change in the value factor. Probabilistic-statistical processing of the obtained results of assessing the criticality of the state of a water body is carried out; the relationships and the nature of the influence for a time period and a factorial feature are established. Then an extrapolation of a continuous series of values is performed, including the identification of the level of influence and degree of hazard for the future period. Deterministic-probabilistic modeling provides with the study of multifactorial correlation between the rate of occurrence of a hazard and its identifying factors at different monitoring periods.

3.3.2. Probabilistic-statistical analysis [18]. The research is carried out by combining multifactorial correlation models, which allow for establishment of relationship between hazard indicators and its determining factors. It should also be noted that the effectiveness of developing the theory of graphs model, which allows for representing the implementation of a program for the remediation of water

\[
R^P_{ij} = V_{ij}V_{ij}^P
\]

\[
R_I = \frac{M[U]}{M[A_i]} - \frac{M[C_n]}{M[A_i]} - \frac{\sum p_iU_i}{M[C_n]}
\]
bodies as a controlled dynamic space-and-time system, that is influenced by human activities as a hazardous factor.

Further studies suggest a detailed research of the digital twin model of a personified water body when landscape-recreational formation of the environment of cities and small settlements with a scenario module of augmented reality for managing ecosystem sustainability.

4. Discussion
The long-term program provides for the restoration of water bodies up to the level of harmonized operation of them. It can be achieved by proactive diagnosis of failures risk of an environmental contamination.

The intensive development of digital technologies allows an introduction of the calculated value of a digital indicator that determines the level of stability of the harmonized operation of engineering systems for the water protection complex in the natural environment as an additional indicator of the economic and environmental activities of the regions. This helps to improve the assessment accuracy of the environmental benefits and damages in planned projects.

It is necessary to give an assessment of ecosystem services in Russia as soon as possible and to use it as one of the indicators of the economic and environmental activities of the regions. This mechanism will allow more complete consideration of environmental benefits and damages in planned projects [19-22].

5. Conclusion
The necessity of modeling of urban areas based on the «attraction zone» and «exclusion zone» principle, as well as the verification of technical solutions for engineering systems of the water protection complex, which are in a harmony with the natural environment was demonstrated.

A conceptual model for control of the risks of developing urban areas was proposed, focusing on the mechanism for managing by water body renovation programs taking into account risk factor analysis. A technique for remediation of water bodies up to the level of harmonized operation by proactive diagnosis of failures risk of an environmental contamination was developed. Introduction of a digital indicator that determines a level of stability of the harmonized operation of engineering systems for the water protection complex in the natural environment as an additional indicator of the economic and environmental activities of the regions allows to improve the assessment accuracy of the environmental benefits and damages in planned projects.

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