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A SYSTEMATIC APPROACH TO MODELING COMPLEX PROCESSES OF INTERACTION BETWEEN WASTE DISPOSAL FACILITIES AND THE ENVIRONMENT IN THE ECOLOGICAL SAFETY OF ANTROPOGENIC GEOECOLOGICAL SYSTEMS MANAGMENT

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Long-term localization of waste products at waste disposal facilities (WDS) forms anthropogenic geoecological systems (AGS), which are in constant material and energy relationship with the external environment and have a multifaceted negative impact on it. The present study is devoted to the development of methodological aspects of the adaptation of the system approach to the study and modeling of complex processes of geoecological systems to create an algorithm for assessing and managing their environmental safety. The object of the study is a facility for local storage of waste — a landfill of municipal solid waste (MSW). Authors' methodical developments of complex geoecological assessment of municipal solid waste landfills in Voronezh region based on geoecological analysis and zoning of the region's area by placment conditions of such facilities, statistical data on organization of MSW, methods of system and geoecological analysis, information modeling, analysis of environmental risks were used. The use of a systematic approach with the differentiation of inputs (essential factors) and outputs (state indicators) of the system to analyze its interaction with the external environment made it possible to develop a conceptual model of the AGS “Waste disposal facility” (WDF) in relation to its various states. The algorithm for assessing the environmental safety of the system includes the following stages: identification and analysis of system’s inputs and outputs at different stages of the WDF life cycle; development of a conceptual model of the AGS “Waste disposal facility”; qualitative and quantitative assessment of the facilitie’s environmental risks and its location in order to select the most significant (environmentally hazardous) system output; analysis of its correlation with the parameters of the inputs by assessing the density of the connection; selection of system inputs that have a significant impact on the formation of the output. The results of the assessment of the environmental sustainability of the AGS “Waste disposal facility” make it possible to determine the priority directions for minimizing the negative impact of the facility on the environment at any stage of its life cycle.
Keywords: Anthropogenic geoecological system, waste disposal facility, system analysis, information modeling, assessment of environmental sustainability, environmental safety.

INTRODUCTION

At the present time in Russia the main way of waste management is their containment in special facilities, the number of which exceeds 15 000, and the total area of the occupied territory is about 4 million hectares [1]. The scale of wastes formation, their organized and not organized accumulation in various geoecological conditions for a long time allow to consider wastes and processes of their transformation, as the factors influencing all components of ecogeosphere and forming an open, being in constant material and energy connection with external environment, anthropogenic geoecological system (AGS) “Waste disposal facility” [2].

The results of various studies [3, 4, 5, 6, 7] confirm the long-term negative impact of such systems on the environment, expressed primarily in the pollution of its components.

However, the multiplicity and variability of AGS elements, the multitude of interactions between them occurring in the space closed to direct observation, significantly complicate both the simultaneous study and assessment of all interrelations of the anthropogenic object with the environment, and the management of the environmental safety of such a system.

The aim of the study is to develop methodological aspects of the adaptation of the system approach to study and modeling of complex processes of anthropogenic geoecological systems to create an algorithm for assessing their environmental sustainability — the basis for solution development of environmental safety management for such systems.

MATERIALS AND METHODS OF RESEARCH

The object of the study is considered a landfill of solid municipal waste (MSW) as a special structure, the organization and operation of which are regulated by federal standards [8, 9, 10].

T. Ashimina's studies in the field of the geoecological analysis and zoning of the Voronezh region, development a technique of the complex geoecological territory assessment for MSW landfills served as a basis of the present work [2].

Development of a conceptual model of the AGS "Waste disposal facility" and an algorithm for assessing interdependencies of its interaction with the environment was carried out by analyzing and generalizing statistical data of federal and regional registers of MSW, archival inventory data, projects of organization and reclamation of MSW in the Voronezh region.

The following methods were used:

– methodological approach to the application of systems analysis to assess the environmental safety of complex biological and natural-technical systems [11, 12, 13, 14];

– methodological approach to the application of geoecological analysis for natural and anthropogenic-altered territories [15, 16];

– methodological approach to the application of information models to describe and analyze complex natural complexes [17, 18, 19, 20, 21];

– methodological approach to the analysis of environmental risks of natural-anthropogenic systems and territories [22, 23, 24, 25].

RESULTS AND DISCUSSION

Characteristics of any system are defined by a set of its elements, structure, list of possible states and behavior. As the elements of geoecological system "Waste disposal facility" can be taken as the basic components of this object: soils and ground, water (atmospheric, in the waste, underground), wastes and products of their transformation, vegetation and fauna (including communities of microorganisms). The structure of the system is formed in the process of establishing direct and inverse relationships between the elements of the system. The state of the system is defined as the state of all its elements. Changes in the states of elements in time and space can occur continuously or discretely.

The behavior of the system is understood as its natural transition from one state to another, due to the properties of the elements and the structure. A distinction is made between dependent or forced motion of the system and self-motion. In the first case, the system follows the changing external conditions, while in the second case, the changes occur under unchanged environmental conditions and are determined by the structure. The state of the “Waste disposal facility” system changes under the influence of variations of climate and weather conditions, chemical composition and quantity of wastes, operational measures. Each system, changing forcedly, reacts to external influences in its own way, depending on the age of the system, a set of its elements and structure.

Long existence of landfills allows to assume essential changes of a geo-ecosystem “Waste disposal facility”, caused both by dynamics of external factors [26], and internal physico-chemical and biochemical processes (fig. 1).

Self-movement of a geoecological system can be observed at a single sharp change of external conditions, for example, conservation or recultivation with application of insulating screens of AGS “Waste disposal facility”. However, even in this case, it seems incorrect to completely exclude the influence of external factors on the system.

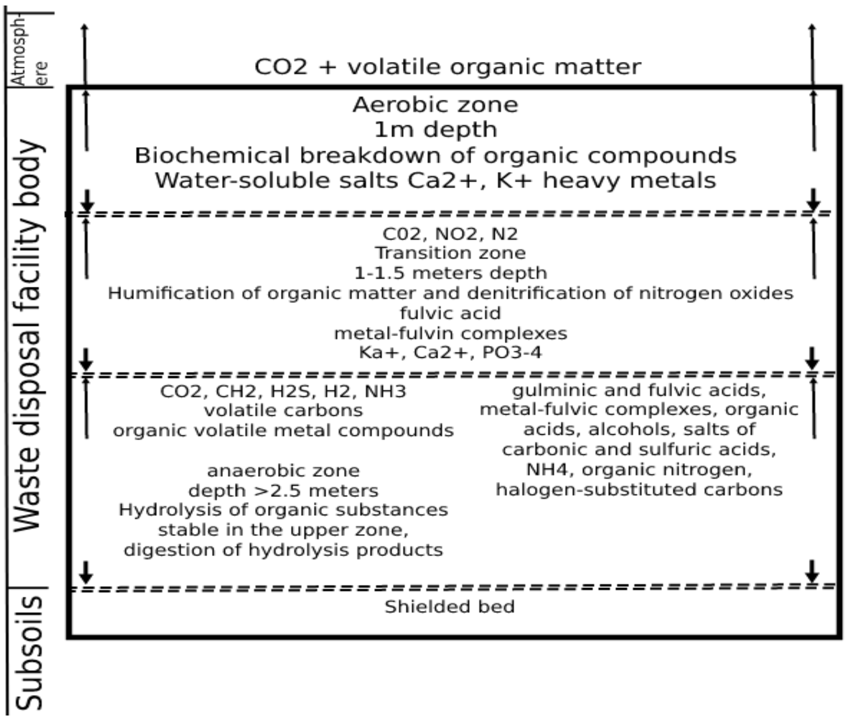

Fig. 1. Self-developing anthropogenic geoecological system “Waste disposal facility”.
Source: developed by the author.

To characterize the system’s interaction with the external environment, it is important to distinguish inputs and outputs of the system. Input can be any of the elements, through which the influence from the outside is carried out. Reverse influence on the environment can occur, apparently, through any elements of the system and each of them to some extent is an output.

The multiplicity and variability of elements of natural-anthropogenic systems as well as the multitude of interactions between them requires a special approach to their study and makes relevant the use of modeling which allows:

– introduction complexity scale, when the mutual influences of two or few elements are studied, which allows to obtain some insight into the behavior of the system as a whole, requiring, however, to be complemented with the use of other modeling techniques, such as the black box method;

– introduction of a time scale, which allows reproducing and studying processes on models, the duration of which significantly exceeds a human lifespan;

– introduction of a system size scale which allows to operate with values convenient for research and calculations.

When building the information conceptual model of AGS "Waste disposal facility" the first step is to make a list of inputs (essential factors) and outputs (indicators of the system state) (table 1).

Table 1.

Elements of interaction with the external environment AGS "Waste disposal facility"

System inputs (SI)	**System outputs (SO)**
Quantity and composition of components (waste and isolating primer) (SI 1)	Emission of biogas from the body of the landfill (SO 1)
Outside air temperature (SI 2)	Leachate emission from the body of the landfill, surface runoff (SO 2)
Atmospheric pressure (SI 3)	Formation of technogenic terrain (SO 3)
Moisture inflow (precipitation and wetting in the fire period) (SI 4)	Formation of pathogenic microflora (SO 4)
Waste mass compaction (SI 5)	Formation of technogenic soil (SO 5)
Changes in solar insolation (SI 6)	
Advections (SI 7)	

Source: developed by the author.

The main distinguished feature of natural systems is the uncertainty and probabilistic nature of inputs and, especially, outputs. Most anthropogenic technical systems have clearly distinguishable input and output, unambiguously fixed in the system structure. The combination of natural and anthropogenic factors (inputs) affecting the state of such a system is a characteristic feature of the AGS "Waste disposal facility" (table 2).

The conceptual model of geoecological system "Waste disposal facility" can be represented in the form of a flowchart (fig. 2).

Table 2.

Antropogenic and natural factors (outputs) of AGS "Waste disposal facility"

System inputs (SI)	**Antropogenic**	**Natural**
Components inflow (waste and isolating primer)		
Outside air temperature (SI 2)		
Atmospheric pressure (SI 3)		
Moisture inflow (precipitation and wetting in the		
Waste mass compaction (SI 5)		
Solar insolation (SI 6)		
Advections (SI 7)		

Source: developed by the author.

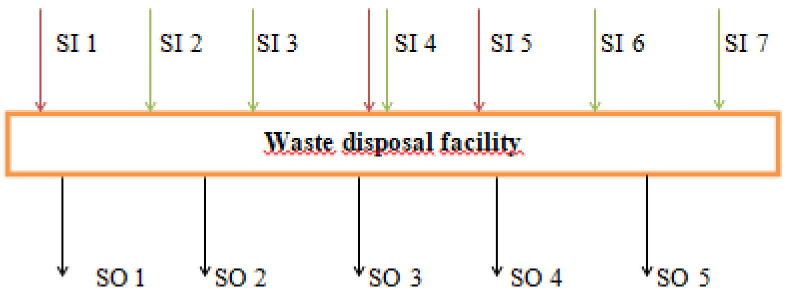

Fig. 2. Flowchart of the anhropogenic geo-ecosystem "Waste disposal facility"

— anthropogenic factor; — natural factor.

Source: developed by the author.

Qualitative and quantitative parameters of the system outputs can be considered as indicators of its behavior and state at different stages of existence. As applied to the system "Waste disposal facility", monitoring and evaluation of its output parameters is the key aspect of environmental safety, the basic concept of which is the environmental sustainability.

The ecological stability of the system "anthropogenic object — natural environment, in which it is included" is understood as a dynamic equilibrium of system components, at which numerical values of parameters of natural environment components and parameters of AGS state, characterizing this stability, do not go beyond the currently permitted values, defined by various kinds of agreements, regulatory documents [27].

During its existence the AGS "Waste disposal facility" undergoes significant changes, passing from one state to another as a result of energy, material and informational interaction with the natural environment (tab. 3).

Table 3.
Characteristics of the stages of existence of the states of the AGS "Waste Disposal Facility"

Life-cycle stage	**Approximate lifespan**	**Facilities purpose**	**State of system**
Pre-operational	0–5	Land uptake, design, construction	Natural environment, local ecosystem
Operational (initial)	5–7	WDF, waste allocation accoring to a scheme	Beginning of transformation processes of waste components accompanied by emissions of gaseous and liquid substances into the environment — waste accumulation, filling of the area
Operational (accumulation)	7–30	WDF, accumulation of waste, filling the area	Deepening transformation and emission processes
Conversion	30–32	Closed WDS, cessation of waste inflow	Deep transformation processes involving interaction of secondary components formed from original ones in the waste, accompanied by emissions into the environment
Recultivation	32–42	Reclamation of the landfill area with the installation of an upper isolation screen, minimizing the impact of external factors on the object	The formation of emissions due to internal transformations
Post-recultivation (assimilation)	42–10 000	Use of the facility in accordance with direction of reclamation and permitted land use	Formation of technogenic soil, including products of waste decomposition, soil used to isolate waste, etc., assimilation of technogenic soil by the environment

Source: developed by the author.

The structure of inputs and outputs of the system at different stages of development can also be represented in the form of flowcharts (fig. 3).

In turn, each stage, i.e. each state of the system, is characterized by different levels. The time of existence of each state is determined by significant factors (inputs) of the system. Change of levels and states of the system is determined by activity, intensity, speed and direction of both external and internal processes in the system. Variations of the AGS "Waste Disposal Facility" states are reflected in emissions of this system into the environment (outputs), which parameters control allows evaluating and managing the system stability. Essentialy, a similar approach [28], in relation to the object under consideration, allows to use models of white, gray or black box type, to operate with input parameters and output parameters and introduces a concept of feedback between them. Loss of stability in such system can occur when the positive links exceed some threshold values and the processes occurring in the system become unmanageable.

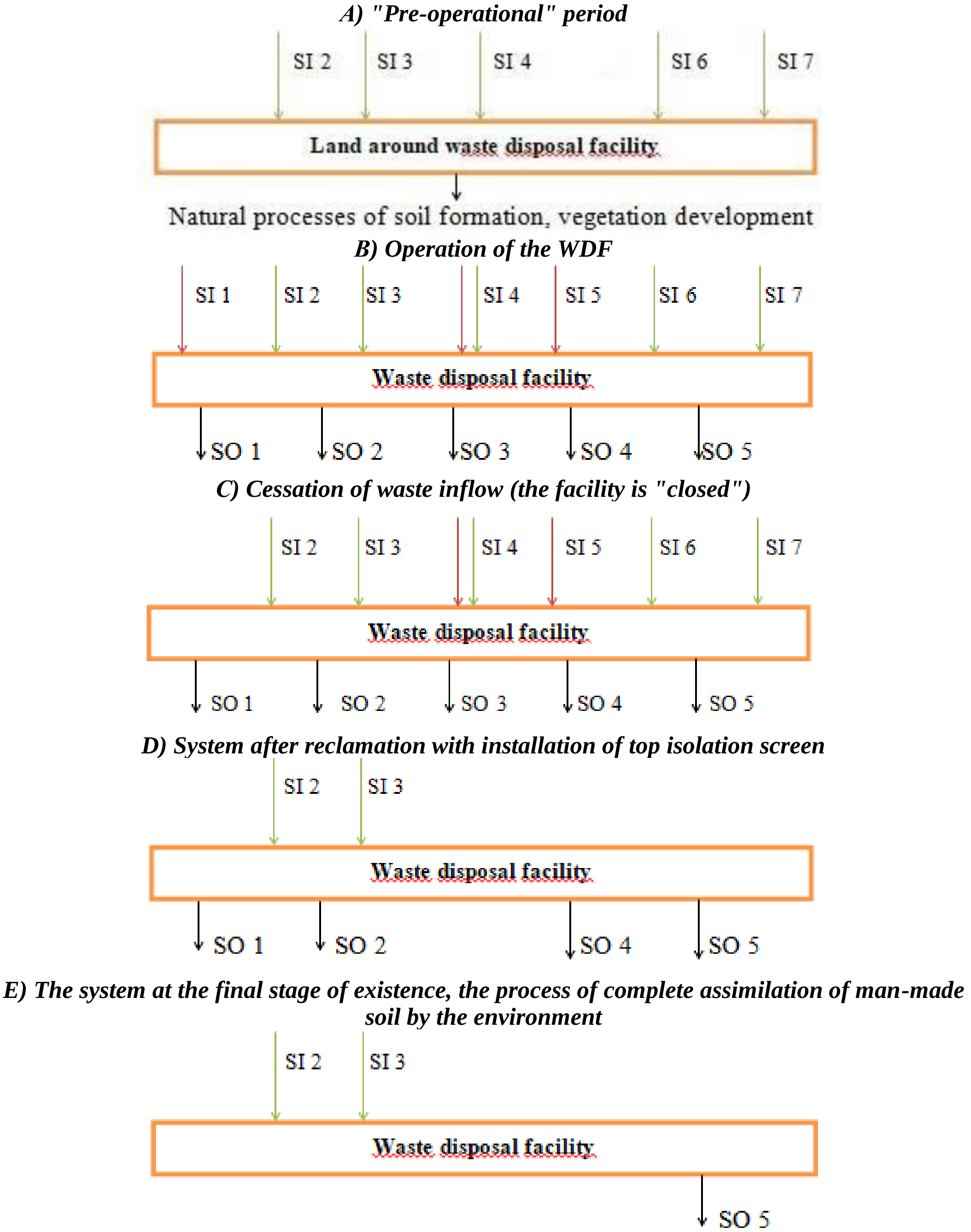

Fig. 3. The structure of inputs and outputs of the AGS "Waste Disposal Facility" at different stages of its development.

Source: developed by the author.

Methodological approaches to the assessment of environmental sustainability in natural-anthropogenic systems are presented in the works of Russian and foreign researchers [29, 30, 31, 32].

As applied to the AGS "Waste Disposal Facility", the key issue of assessing its stability is the methodology of establishing the relationship of inputs and outputs of the system.

Taking into account multicomponent system under consideration, complexity and "closedness" of physical-chemical, biochemical processes of waste transformation inside the landfill body, it is reasonable to establish and evaluate the interrelation of inputs and outputs using "black box" model. This approach studies the quantitative side of the energy exchange, information and substance between the anthropogenic object and the environment, but does not reveal the qualitative aspect of the transformation of substances from one form to another.

The degree of influence of the system's inputs is evaluated by calculating density indices, or the strength of connection. In this case, it is necessary to have for each input-output pair a representative series of values, where each value of system inputs corresponds to the value of system outputs. For some types of calculations it is necessary that observations are carried out for all variables simultaneously; as a rule, these series of values are the result of synchronous observations for one site. Under some conditions, the counts are made at different sites.

There are different ways of estimating relationship density, but they all have the same meaning. If the variations of the variables are presented as graphs, the resulting curves may be more or less similar in form. The similarity of the curves shows how closely variation of values of one indicator is related to the other. When there is full dependence of SO on SI, curve shape will be similar, only differences in amplitudes and positions of the curves on the time axis are permissible. Mirror similarity is also possible if there is a negative dependence between the variables.

If there is no relationship, there is no similarity. If the dependence is partial, the graphs do not repeat each other completely. It is this degree of similarity of the curves, and, therefore, similarity in the behavior of subsystems SI and SO that is reflected in the values of coupling density.

The relationship density can also be assessed using numerical indicators - correlation coefficient, comparison of partial and total variance (correlation ratio), and conditional probability.

The available statistics of inputs and outputs states of the AGS "Waste Disposal Facility", including series of parallel observations can be used to determine the transfer functions, i.e. the mathematical form of dependence between inputs and outputs. Mathematical statistics has methods for selection of the best regression equation, by means of which states of inputs, as arguments, are connected with outputs - functions. Thus it is necessary to consider probabilistic character of system, allowing to define not only possible, but the most probable condition of function. At the same time, we calculate the confidence intervals within which the numerical value of the output can appear for the given states of the inputs.

The main problem in determination of mathematical form of dependence between inputs and outputs in the system under consideration is lack of sufficient statistical data. Such situation can be explained, on the one hand, by absence of the WDF monitoring system necessary for calculations, on the other hand, quantitative characteristics of the outputs of the AGS "Waste Disposal Facility", in most cases, have calculated values (formation of biogas, leachate, microbiological pollution). In field studies it seems possible to estimate the parameters of the formed technogenic relief. The indicators of the output of the system "Formation of technogenic soil (SO5)" at present can only be predicted, since the process of waste transformation takes a very long time.

Modeling of inputs (essential factors) and outputs (indicators of system state) in laboratory and micro-field experiments allows to obtain and scale necessary statistics.

In the study of substance, energy and information transformations in the AGS "Waste Disposal Facility" using the black box method, only empirical coupling equations can be obtained within the framework of building inductive (qualitative) models. This is the first stage of the study of anthropogenic geoecological system, allowing to obtain material for comparisons, generalizations and assumptions, further work with which gives the opportunity to build more detailed, theoretical and deductive models.

Development of AGS "Waste Disposal Facility", which allows to estimate ecological stability of a system by means of establishment of interrelation of its inputs and outputs, provides possibility for optimized management of such systems in various natural-climatic and geoecological conditions.

The key aspect of effective management of AGS "Waste Disposal Facility" is the allocation of the most significant outputs of the system, which, within the framework of the research object, are characterized by the greatest impact on the environment. Realization of this aspect seems to be possible because of application of the risk-oriented approach which allow to assess the danger of any output in the system within specific environmental conditions.

As applied to the object under consideration, the ecological risk is the risk of disturbance of dynamic equilibrium in the AGS "Waste Disposal Facility", which leads to changes in the parameters of its abiotic and biotic components as a result of natural and anthropogenic environmental factors and restructuring of the system into a state with new properties.

In turn, the transformation processes of the object elements, accompanied by various emissions into the environment, also have a significant impact on it and are a source of environmental risk (primarily, the risk of pollution of environmental components with toxic substances) for external geoecological conditions of the site and adjacent to it.

Thus, the allocation of the most ecologically significant outputs AGS "Waste Disposal Facility" should be made on the basis of a comparative analysis of the priority of the environmental risks of this system in the current geo-ecological conditions (tab. 4).

Table 4.

Comparative priority analysis of environmental risks in AGS "Waste Disposal Facility"

Outputs of AGS "Waste Disposal Facility"	Priority of environmental hazards	Assessable environmental conditions
Biogas emissions from WDF territory (SO 1)	– Impact on the component composition of the atmosphere (greenhouse effect). – Unpleasant odor and pollutants in the air of nearby settlements (habitat quality). – Dispersal and subsequent deposition of pollutants on the territory adjacent to the facility.	– Meteorological parameters. – Location of populated areas
Filtrate emission from the WDF body, surface runoff (SO 2)	– Pollution of ground and surface waters. – Pollution of soils of adjacent areas.	– Water permeability of relief-forming rocks. – Depth and protection of groundwater, presence of water intakes. – Location of surface water bodies in the adjacent area, groundwater flow vector.
Formation of technogenic relief (SO 3)	– Influence on the stability of natural landforms. – Influence on the dynamics of exogenous relief formation. – Manifestations of unfavorable and dangerous geomorphological processes. – Changes in solar insolation and advection parameters.	– Geomorphological parameters of the territory. – Parameters of exogenous geodynamics
Formation of pathogenic microflora (SO 4)	– Microbiological contamination of the underlying soil. – Microbiological contamination of soils in the surrounding area. – Microbiological contamination of ground and surface waters. – Distribution of pathogenic microflora by representatives of fauna.	– Water permeability of relief-forming rocks. – Depth and protection of groundwater, presence of water intakes. – Location of surface water bodies in the adjacent area, groundwater flow vector. – Parameters of biological and microbiological activity of soils on adjacent territories. – Quantitative and species composition of fauna.
Formation of technogenic soil (SO 5)	– Replacement of natural soil by technogenic one with a high concentration of technogenic elements. – Restrictions on the use of territories after the assimilation of waste by the environment.	– The structure of the soil cover of the territory. – Characteristics of soil productivity.

Source: developed by the author.

A comprehensive geoecological study of the AGS "Waste Disposal Facility" allows ranking the components of the environment and zoning the territory on the priority hazard of the impact of the object [33]. The next stage is to determine the output of the AGS "Waste Disposal Facility", the most hazardous in these conditions, as well as the most significant for it, are inputs of the system (assessment of the input-output relationship), which will eventually make it possible to develop solutions to minimize this hazard.

CONCLUSION

Adaptation of methodologies of geoecological, system analysis, information modeling and risk-oriented approach to anthropogenic geoecological system "Waste disposal facility" allows to develop an algorithm for estimation of dynamic stability and, hence, ecological safety of this system.

The first stage of such algorithm is identification and analysis of inputs and outputs of the system at different stages of the object life cycle, as a result of which a conceptual model of AGS "Waste Disposal Facility" is developed. Then, on the basis of geoecological analysis, it is necessary to carry out a qualitative and the object's quantitative assessment of environmental risks and the territory of its disposal. Having chosen the most significant (dangerous for the environment) output of the system in the current natural, climatic and geoecological conditions, to analyze its relationship with the parameters of the inputs by assessing the density of the connection and choose the input(s) of the system, which have a significant impact on the output parameters. The conducted research makes it possible to develop recommendations for minimizing the negative environmental impact of the AGS "Waste Disposal Facility" at any stage of its existence.

Thus, modeling of AGS "Waste Disposal Facility" and assessment of interrelation of inputs (essential factors) and outputs (indicators of system state) on the basis of determination of priority ecological risks of the object and its territory allows to optimize management process of such system, defining priority directions of development of organizational and technical measures on providing its ecological safety.

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СИСТЕМНЫЙ ПОДХОД К МОДЕЛИРОВАНИЮ СЛОЖНЫХ ПРОЦЕССОВ ВЗАИМОДЕЙСТВИЯ ОБЪЕКТОВ РАЗМЕЩЕНИЯ ОТХОДОВ С ОКРУЖАЮЩЕЙ СРЕДОЙ В УПРАВЛЕНИИ ЭКОЛОГИЧЕСКОЙ БЕЗОПАСНОСТЬЮ АНТРОПОГЕННЫХ ГЕОЭКОЛОГИЧЕСКИХ СИСТЕМ

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Длительная локализация отходов производства и потребления на объектах размещения отходов (ОРО) формирует антропогенные геоэкологические системы (АГС), находящиеся в постоянной вещественно-энергетической взаимосвязи с внешней средой и оказывающие разностороннее негативное воздействие на нее. Настоящее исследование посвящено разработке методологических аспектов адаптации системного подхода к изучению и моделированию сложных процессов АГС для создания алгоритма оценки и управления их экологической безопасностью. Объектом исследования является сооружение для локального складирования отходов — полигон твердых коммунальных отходов (ТКО). Использованы авторские методические разработки комплексной геоэкологической оценки территорий расположения полигонов ТКО в Воронежской области, основанные на геоэкологическом анализе и районировании площади региона по условиям размещения таких объектов, статистические данные по организации ОРО, методы системного, экосистемного, геоэкологического анализа, информационного моделирования, анализа экологических рисков. Использование системного подхода с дифференциацией входов (существенных факторов) и выходов (показателей состояния) системы для анализа ее взаимодействия с внешней средой позволило разработать концептуальную модель АГС «Полигон ТКО» применительно к различным ее состояниям. Алгоритм оценки экологической безопасности системы, включает этапы: идентификация и анализ показателей входов и выходов системы на разных этапах жизненного цикла объекта; разработка концептуальной модели АГС «объект размещения отходов»; качественная и количественная оценка экологических рисков объекта и территории его размещения с целью выбора наиболее значимого (опасного для окружающей среды) выхода системы; анализ его взаимосвязи с параметрами входов с помощью оценки плотности связи; выбор входов системы, оказывающих значимое воздействие на формирование выхода. Результаты оценки экологической устойчивости АГС «полигон ТКО» позволяют определить приоритетные направления минимизации негативного воздействия объекта на окружающую среду на любых этапах его жизненного цикла.

Ключевые слова: антропогенная геоэкологическая система, объект размещения отходов, системный анализ, информационное моделирование, оценка экологической устойчивости, экологическая безопасность.

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