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SUBSTANTIATION OF ENVIRONMENT PROTECTION MEASURES OF NATURAL AND MAN-MADE LANDSCAPES IN THE ZONE OF WASTE STORAGE

Показані теоретичні підходи до математичного моделювання процесу перехоплення міграційних речовин з антропогенними фізико-хімічними бар'єрами в природоохоронних меліоративних заходах.

Об'єктом дослідження є меліоративні заходи для захисту від забруднення територій і водних об'єктів у зоні складування відходів, удосконалення підходів до обґрунтування їх виду, складу, конструкції та параметрів.

Одним з найбільш проблемних місць у зоні складування відходів є виникнення непередбачуваних фізичних, хімічних та біологічних процесів, продуктами яких є численні токсичні мігруючі хімічні сполуки в різних агрегатних станах, що негативно впливають на стан довкілля та здоров'я людини.

В ході дослідження використовувалися методи пасивного та активного експерименту. Польові дослідження на діючих виробничих об'єктах складування відходів, а також лабораторні дослідження фільтраційних та сорбційних характеристик меліорант-сорбенту й засипки дренажно-акумулюючих мереж проведені у відповідних атестованих лабораторіях, виконані за діючими стандартними методиками з опрацюванням отриманих результатів за загальноприйнятими статистичними методами.

Розроблено основний конструктивний елемент дренажно-акумулюючих мереж – дренажну траншею-поглинач. Отримано характер і рівень залежностей між параметрами концентрації розчину фільтрату та ємністю меліоранту-сорбенту, за якими може здійснюватись обґрунтування норми його внесення у дренажні траншеї-поглиначі для нейтралізації забруднювачів у фільтраційних водах.

Розроблений комплекс заходів забезпечує необхідний рівень захисту територій та водних об'єктів у зоні складування відходів з дотриманням сучасних економічних, екологічних та соціальних вимог.

Ключові слова: *заходи захисту, природно-техногенні ландшафти, муніципальні тверді відходи, фізико-хімічні бар'єри.*

1. Introduction

Today the problems of water management and environment recovery have become not only of national but also of international significance. Water capacity potential of any territory is a basis for its economic development, social and environmental well-being [1]. The sources of water bodies' pollution are the settlements, big and small enterprises that are not equipped with proper water treatment facilities, surface and underground communications, livestock farms, spent storages and warehouses, sanitary landfills and unauthorized garbage dumps etc. Wastes accumulation in sanitary landfills and dumps cause's unpredictable physical, chemical and biochemical processes [2, 3].

Modern engineered landfills are expected to control fire and spread of litter, limit contact wildlife, minimize or eliminate the release of mobile contaminants to the surrounding environment, and provide acceptable end-of-service land use. From the perspective of environmental protection, release of contaminants to air and groundwater is often considered the most significant issue. If such release occurs, the toxic chemical compounds in various states of aggregation set conditions for air, soil, water bodies and groundwater pollution.

Therefore, studies related to the substantiated of environment protection measures of natural and man-made landscapes in the zone of waste storage are relevant.

2. The object of research and its technological audit

The object of research is ameliorative measures for protection against pollution of territories and water objects in the waste storage zone, improvement of approaches to substantiation of their type, composition, structure and parameters.

One of the most important problems in the waste storage area is the emergence of unpredictable physical, chemical and biological processes, the products of which are numerous toxic migratory chemical compounds in various aggregate states, which adversely affect the state of the environment and human health.

Wastes storage sites, as landscape-geochemical systems, can be characterized as such objects that possess migration ability, i. e. there is a movement and redistribution of chemical elements and their compounds in the solid wastes landfill or dump profile [4].

Into ground water pollutants come mainly because of leachate filtration from solid wastes dumps or infiltration of water from the polluted surface. In such conditions, the migration of toxic compounds is complicated by the fact that along with their basic transportation in the water flow, there is a cross-transportation of compounds in depth profile under the diffusion-convective and convective transportation.

Directional character of migration flows and geo-chemical environment changes on the way of their movement leads to the differentiation of chemical elements and their compounds in vertical and horizontal directions. Thus, the phenomenon of chemical elements accumulation in consequence of migration conditions local changes in a particular part of the landscape-geochemical system is called barrierness [4–6].

According to the theory of environmental and technogenic geochemical barriers such barriers can be presented as a part of the landscape, in which at the relatively short distance there is a reduction of chemical elements migration intensity, thereby increasing their concentration [4].

Containment systems are used at modern landfills to control the movement of liquids and gases into and out of a landfill. Covers and liners used in many modern landfills traditionally have employed low-conductivity materials and resistive barriers (e. g. clays and geomembranes) to impede the movement of water. Typical profile for conventional cover generally consists of compacted fine-textured oil and, depending on the site, may be covered with geomembrane [4].

Environmental conditions common to surficial soils (wet-dry and freeze-thaw cycling and penetration by plants roots and burrowing fauna) can damage both soil barrier layers and geomembranes. These processes form cracks, holes, and other macroscopic features that are collectively referred to as macropores. These features serve as preferential pathways that are reflected as increases in saturated hydraulic conductivity, so distribution of pollutant substances by means of convective or diffusion flow. Thus, convectional covers that are widely used because of their relatively low price and simplicity of design, do not meet up-to-date environment safety requirements.

For territories and water bodies protection from the pollution by means of localization and further neutralization of toxic compounds that are being contained in leachate flow we propose to use the engineering land reclamation measures complex (ELRMC). The ELRMC provides for environment and geochemical conditions improvement based on the use of two types of physicochemical in-ground constructions: vertical and lateral plane technogenic geochemical and hydro-physical barriers [7–9].

Types of physicochemical barriers in ELRMC. The application of two groups of geochemical barriers is caused by existence of different directions of chemical elements flow migration. Vertical geochemical barriers minimize vertical migration of substances and generate differentiation of chemical substances in soil profile.

Lateral geochemical barriers are being applied on the borders of geochemically contrast elements of a landscape when chemicals are being migrating of to adjacent sites that are geochemically integrated with an existing landscape line [5].

The application of hydrophysical barrier is defined by a necessity of flow direction and discharge regulation in half-water-saturated (a zone of aeration) and water-saturated soils within the limits of wastes site. The cases of high water-table standing (0.5…2.0 m) from the bottom of municipal wastes landfill or dump are frequently being observed in practice.

Lowering the level of polluted groundwater, and thus reducing a degree of soil solid phase washing, makes it possible to minimize to the certain measure the convective component of polluting substances carry-out, and thus to reduce an area of soil pollution of in the bottom of municipal wastes site, as well as to protect necessary adjacent water-bearing horizons and water objects.

3. The aim and objectives of research

The aim of research is provision of scientific substantiation of effective environmental and land reclamation measures for the protection of the environment of natural and man-made landscapes in the waste storage area.

To achieve the purpose it is necessary to perform the following tasks:

1. To evaluate the properties of zeolite-smectite as a geochemical barrier.

2. To perform an analysis of the principle of drainage-accumulation systems operating.

3. To describe the mathematical models of the utilization process of migrants in the filtration stream of substances.

4. Research of existing solutions of the problem

It should be noted that today the study of the environmental significance of the use of ameliorants, their influence on the composition and properties of soils is becoming more and more perspective, as shown in the studies of many scientists.

Among modern approaches to solving this problem, the most promising is:

– use of ameliorant-sorbent [6, 8, 10–12];

– creation of drainage facilities to intercept water with pollutants [13–15].

According to research [10–12] ameliorants can perform the function of restoring the natural state of the soil system, affecting the soil reaction, the whole complex of physical and chemical properties of soils, the dosage of chemical elements in the soil solution, migration processes in the soil-groundwater system.

Analysis of literary sources [2, 16] shows that the most rational and perfect from the technical and environmental point of view technical solution of the problem of protecting territories and water objects from pollution is the creation of drainage facilities. According to [13, 15] such drainage structures can act as analogues of trench drainage filters or main and systematic drainage commonly used in reclamation.

Thus, the results of the analysis allow us to conclude that the solution of this scientific problem can be realized on the basis of a complex of amelioration measures, which include the arrangement of drainage-accumulating networks and introduction of reclaimer-sorbent.

5. Methods of research

In practice, these physicochemical barriers can be represented by natural ameliorative sorption materials that work consistently with protective drainage-accumulation system (DAS) or intensive drainage-accumulation system (IDAS).

5.1. The characteristic of zeolite tuff as geochemical barrier. The use of sorption treatment methods is to be promising and the most appropriate for pollutants removal

in solid, liquid and gaseous states of aggregation. The artificial sorption materials, such as activated carbon, synthetic zeolites *NaA*, *CaX*, *CaA* etc. have the limited scope of use basically because of their high price. Thus, relatively inexpensive materials of natural origin, such as peat, clay minerals, lateritic, limestone soils, natural zeolites etc. attract scientists' and manufacturers' attention [7].

It is zeolite tuff, as ameliorative sorption material that is being proposed for resolving of the problem of environment protection. According to scientists' data there are 24 varieties of tuff in the world. However, the necessary adsorption properties have zeolite-smectite tuff, quite common in Rivne region.

Zeolite-smectite tuff has property to adsorb ammonia from the air and it is appropriate to use it for deodorization of a pollutant storing site.

with active sorption and passive filtering materials. The trench contains drainage pipes (tile or plastic) being arranged on its bottom. They receive polluted filtrate water and divert them by means of collectors to the place of utilization (Fig. 1).
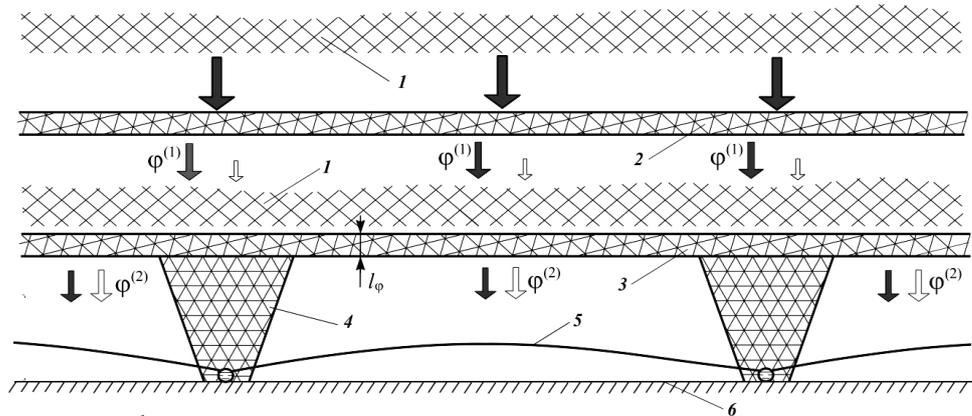
Fig. 1. Scheme and the parameters of technogenic physicochemical and hydro-physical barriers as IDAS (cross-section): 1 — waste dumps; 2, 3, 4 — areas of elements concentration correspondingly in wastes dumps, base of landfill and intensive absorbing drainage trench; 5 — water-table level; 6 — aquifuge; $\varphi^{(1)}$, $\varphi^{(2)}$ — corresponding values (concentrations) of a particular chemical compound $\{\varphi\}$, $\varphi = \overline{1, n_\varphi}$, before and after the barrier; l_φ — the length of the barrier

The research has been confirmed that 1 kg of zeolite can adsorb up to 100 g of ammonia and 400 g of various chemical compounds [7].

Zeolite-smectite tuffs possess high selectivity of absorption and ability to divide the ions and molecules of different substances, high mechanical and chemical resistance. The high intergranular porosity of natural sorbents in comparison with quartz sand provides the increasing of harmful substances accumulation volume. Zeolite-smectite tuffs do not change their physical and chemical properties in the process of operation and maintain high ion exchange selectivity for a variety of chemical elements and compounds.

Zeolite tuff is quite common material in the western and central parts of Ukraine within the geological structure of Ukrainian Crystalline Shield at the depth of 5...200 m. In the quarries contours of Rivne Region, the amount of raw zeolite tuff, as a by-product of basalt mining, could be $2 \cdot 10^7$ tons by approximate estimation [7]. For this reason, it can be effectively used for nature conservation activities within the application of the ELRMC.

5.2. The principle of drainage-accumulation systems operating. The DAS operates as an anthropogenic geochemical barrier, in which at the relatively short distance the concentration of toxic chemical compounds increases. Constructionally, it is a hookup of consecutive connected elements – absorbing drainage trenches (ADT). ADT are filled with active sorption and passive filtering materials to provide localization and further neutralization of leachate flow that is moving to the environment.

To intensify the groundwater table decreasing with the simultaneous possibility of safe water diversion from solid wastes dumps, it is advisable to apply IDAS, which combines the technogenic geochemical (sorption ameliorant) and hydrophysical (drainage system) barriers. The main structural element of IDAS is intensive absorbing drainage trench (IADT) – water diversion device filled

5.3. The criterion of drainage-accumulation systems operating. In accordance with physicochemical barriers principle of operation, the DAS is designed to perform two main functions – filtration (water diversion) and sorption (extraction of pollutants from the leachate) with simultaneous agreement of filtration and sorption velocity.

Thus, clarification of a ground-water flow from polluting substance $\{\varphi\}$, $\varphi = \overline{1, n_\varphi}$ on its passage through the technogenic physicochemical barrier with length l_φ that is being presented with a backfill of adsorbing drainage trench, is carried out under condition:

$$t_\varphi = \frac{l_\varphi}{k_1} > t_r = 2\tau_{1/2\varphi}, \qquad (1)$$

where t_φ is a time of ground-water passage that is being polluted by substance $\{\varphi\}$, $\varphi = \overline{1, n_\varphi}$, through the technogenic physicochemical barrier; k_1 – hydraulic conductivity coefficient of adsorbing drainage trench backfill; t_r – time of «zeolite tuff – leacheate» system reaction relative to adsorption the specific substance $\{\varphi\}$, $\varphi = \overline{1, n_\varphi}$; $\tau_{1/2\varphi}$ – time of half-reaction in «zeolite tuff – leacheate» system.

6. Research results

On a site-specific basis, the vadose zone affects the movement of water, nutrients, chemicals, pathogens, and contaminants to the water table zone where the porous media is saturated. Of special importance from a vadose zone perspective are different types of contaminants (e. g., low-level, mixed, radioactive) that have been buried in or released to the vadose zone, or the contaminants that have been or will be disposed in special vadose zone facilities (e. g., lined landfills, vaults).

In most cases, the dominant mechanism for movement is the liquid water flux, and to some extent in drier regions, the vapor flux (exceptions include non-aqueous phase

liquids and gases). Thus, the successful assessment of the quantity and quality of groundwater resources depends, in part, on the ability to predict the flux of water that moves into and through the:

1) vadose zone;
2) groundwater zone.

Moreover, the fluxes in the vadoze zone are the primary mechanism for transporting the contaminants to the groundwater zone.

Numerical modeling is one of the methods used to estimate the flux of water moving through the vadose zone as well as in saturated porous media.

Unsaturated Liquid Water Flow. The differential equation for liquid water flow is a modified form of Richards' equation [17]. This equation describes the change in water storage, redistribution, and plant water uptake at every point within the soil profile. The flow of water across either boundary of the profile is represented by:

– specifying a flux (e. g., precipitation, evaporation, or drainage);

– calculating a flux either directly (e. g., evaporation as a diffusive flux);

– indirectly (e. g., holding the value of the boundary-node head constant for such boundary conditions as a ponded surface, evaporation, or a water table).

The development of the modified Richards' equation begins with Darcy's law. In its original form, Darcy's law represented an empirical relationship between the rate of flow in saturated sand and the hydraulic head gradient. The one-dimensional differential form of Darcy's law is:

$$q_L = -K_S \frac{\partial H}{\partial z}, \qquad (2)$$

where q_L – flux density of water, cm hr^{-1}; K_S – saturated hydraulic conductivity, cm hr^{-1}; z – depth below the soil surface, cm.

Darcy's law can be extended to unsaturated flow by replacing the saturated conductivity term with liquid conductivity, K_L as a function of matric head, yielding:

$$q_L = -K_L(\psi) \frac{\partial H}{\partial z}. \qquad (3)$$

Equation (3) must be combined with the continuity equation to describe transient flow. The continuity equation states that the change in water content of a volume of soil must equal the difference between flux into and out of the soil volume. For one-dimensional flow, the continuity equation is:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_L}{\partial z}, \qquad (4)$$

where θ – the volumetric water content, $\text{cm}^3\ \text{cm}^{-3}$; t – time, hr.

Combining Equations (3) and (4) yields:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K_L(\psi) \frac{\partial H}{\partial z} \right]. \qquad (5)$$

With the soil surface as the reference elevation, the gravitational head at a point in the soil is the elevation of the point with respect to the soil surface and thus is negative. Because depth measured from the surface is positive, the gravitational head equals the negative of soil depth.

Therefore, z is replaced with $-z$. The second convention concerns matric head, which is a negative number for unsaturated soil conditions. Matric head is replaced with suction head, h, which is the negative of matric head. Thus, a positive suction head represents a matric head, and a negative suction head represents a pressure head. The calculation of hydraulic head then changes from $H = \psi + Z$ to the:

$$H = -(h + z). \qquad (6)$$

Using the chain rule of differentiation, $\frac{\partial \theta}{\partial t}$ in Equation (4) can be replaced by $C(h)\frac{\partial h}{\partial t}$, where $C(h)$ represents $\frac{\partial \theta}{\partial h}$ (i. e., the negative of the specific moisture capacity). With this manipulation and the incorporation of the identity $h = -\psi$, Equation (5) becomes:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K_L(h) \frac{\partial H}{\partial z} \right]. \qquad (7)$$

Combining Equations (5) and (6) and adding a sink term, S, for water uptake by plants gives:

$$C(h)\frac{\partial h}{\partial t} = -\frac{\partial}{\partial z}\left[K_L(h)\left(\frac{\partial h}{\partial z} + 1 \right) \right] - S(z,t), \qquad (8)$$

where $S(z,t)$ indicates that the sink term is a function of depth and time.

The assumptions that led to Equation (8) are:
– fluid is incompressible;
– air phase is continuous;
– air phase is at constant pressure;
– flow is one-dimensional;
– liquid water flow is isothermal;
– vapor flow is negligible.

To solve the flow equation for liquid water, model must be supplied with relationships for both water content and hydraulic conductivity as functions of suction head. The water content relationship is known as the soil water retention function (its derivative is the capacity term in Equation (7). The hydraulic conductivity relationship is known as the hydraulic conductivity function.

The soil hydraulic properties, i. e. generally Soil Water Characteristic Curve (SWCC) can be described using different methodological approaches, such as polynomials, Haverkamp functions, Brooks-Corey functions, van Genuchten functions, modified Brooks-Corey and van Genuchten functions. In our opinion it is advisable to use Genuchten functions that describe soil water retention as follows:

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha h)^n \right]^{-m}, \qquad (9)$$

where α, m, n – curve fitting parameters; θ_s – saturated volumetric water content; θ_r – residual volumetric water content; and

$$K_L = K_S \frac{\left\{ 1 - (\alpha h)^{n-2}\left[1 + (\alpha h)^n \right]^{-m} \right\}}{\left[1 + (\alpha h)^n \right]^{lm}}, \qquad (10)$$

where m is usually assumed $m = \dfrac{1-1}{n}$; l – fitting parameter.

In addition, van Genuchten functions allow to describe effect of hysteresis on Water Retention during drying and wetting periods.

Saturated Liquid Water Flow. Utilization with the system of filters (barriers) in one-dimensional non-stationary case. For resolving the problem of contaminants migration in the soil profile within the subject area of fluid mechanics, as well as for drainage accumulation systems substantiation as physicochemical barriers. The mathematical model of leachate flow migrating substances utilization by the system of filters in one-dimensional non-stationary case can be used (Fig. 2). Usually the process of polluting substances migration is being caused and tracked along with the phenomenon of mass transfer, sorption kinetics and filtration.

According to [16], the boundary value problem of such model is being described with the following system of the equations:
– for concentrations $c_i(x,t)$, $i = \overline{1,n}$:

$$\frac{\partial}{\partial x}\left(D_i(c)\frac{\partial c}{\partial x}\right) -$$
$$-V_i(c)\frac{\partial c_i}{\partial x} - \frac{\partial N}{\partial t} = \sigma_i \frac{\partial c_i}{\partial t},$$
$$i = \overline{1,n}; \qquad (11)$$

– sorption kinetics:

$$\frac{\partial N}{\partial t} = \gamma(c_i - C_*), \; i = \overline{1,n}; \qquad (12)$$

– ground-water filtration:
a) according to Darcy's law:

$$V_2 = -k_i \frac{\partial h_i}{\partial x} + \nu_i \frac{\partial c_i}{\partial x}, \; i = \overline{1,n}; \qquad (13)$$

b) and to the equation of flow continuity:

$$\frac{\partial V_i}{\partial x} = 0, \; i = \overline{1,n}. \qquad (14)$$

Under following boundary conditions for concentration c_i and a pressure h:
– the initial condition for concentrations:

$$c_i(x,0) = \tilde{C}_0^i(x), \; i = \overline{1,n}; \qquad (15)$$

– boundary conditions for concentrations:

$$c_1(0,t) = \tilde{C}_1(t); \qquad (16)$$

– conditions of conjunction for concentrations:

$$c_i(l_i,t) = c_{i+1}(l_i,t), \; i = \overline{1,n-1}; \qquad (17)$$

– boundary conditions for pressure:

$$h(0) = H_1, \; h(l) = H_2; \qquad (18)$$

– conditions of conjunction:

$$V_i(l_i) = V_{i+1}(l_i), \quad i = \overline{1,n-1}, \qquad (19)$$

where D_i – convective diffusion coefficient; V_i – filtration velocity; γ – mass exchange coefficient; $\sigma(x)$ – soil profile tension; $\tilde{C}_0^i(x)$ – distribution of concentrations in the soil profile in initial time point; $\tilde{C}_1(t)$ – concentration of dissolved substances before the filter; $\tilde{C}_2(t)$ – concentration of dissolved substances after passage of the filter; C_* – concentration of limiting saturation; H_1, H_2 – piezometric pressures correspondingly in the upper and lower pools; t – time.
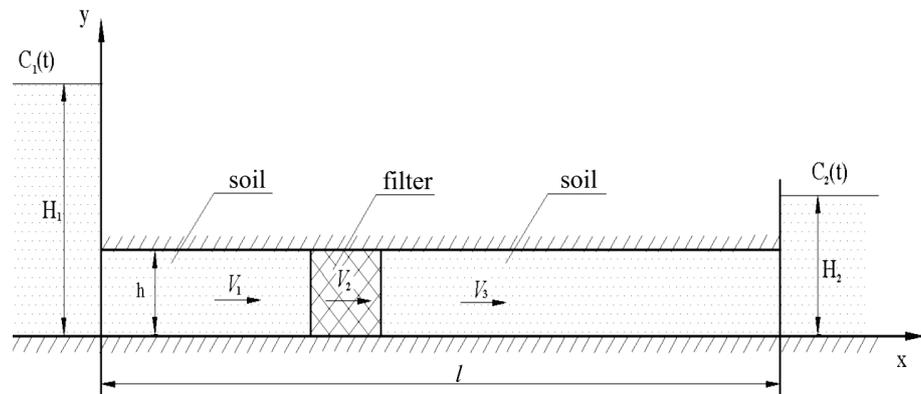
Fig. 2. The scheme of migrating utilization by physicochemical barrier

Realization of the given mathematical model in the medium of visual programming (for example Delphi 7.0) provides the opportunity to carry out the significant amount of numerical experiments and to analyze them.

Such kind of approach consists in search of numerical solutions of differential equations that characterize the process of pollution substances migration with use of appropriate models.

This approach is based on a principle of the fullest account of the mechanism of substances movement in the structure of soil profile in time, thus from the theoretical point of view is the most substantiated.

7. SWOT analysis of research results

Strengths. Application of the above-mentioned approach provides simultaneous protection of soil, safe removal of moisture from the pollutant by cleaning of filtrate, improvement of the territory in the zone of location of the source of pollution by 60...80 % and reduction of the risk of the disease of the population in the adjacent zone by 40...60 %.

Weaknesses. The study has no practical confirmation.

Opportunities. The issue of territories and water bodies protection from pollution in the location area of solid wastes dumps and landfills is relevant and has a complex integrated character. One of the possible approaches to solve this problem is the creation of artificial physicochemical barriers on the trajectory of technogenic flows movement. The barriers can be represented as DAS (or IDAS) in combination with natural (or artificial) sorption materials as ameliorants with simultaneous agreement of filtration and sorption processes.

The proposed approach may be interesting not only for Ukraine, since the issue of environmentally safe waste disposal is an actual and important issue at the global level.

Threats. The implementation of the proposed approach requires the reconstruction of dumps or landfill.

8. Conclusions

1. During the evaluation of the properties of zeolite-smectite as a geochemical barrier was founded that: zeolite-smectite tuff has property to adsorb ammonia from the air and it is appropriate to use it for deodorization of a pollutant storing site; zeolite-smectite tuffs possess high selectivity of absorption and ability to divide the ions and molecules of different substances, high mechanical and chemical resistance. zeolite-smectite tuffs do not change their physical and chemical properties in the process of operation and maintain high ion exchange selectivity for a variety of chemical elements and compounds.

2. During the analysis of the principle of drainage-accumulation systems operating was founded that:
– the drainage-accumulation systems operates as an anthropogenic geochemical barrier, in which at the relatively short distance the concentration of toxic chemical compounds increases;
– constructionally, it is a hookup of consecutive connected elements – absorbing drainage trenches, which are filled with active sorption and passive filtering materials to provide localization and further neutralization of leachate flow that is moving to the environment;
– to intensify the groundwater table decreasing with the simultaneous possibility of safe water diversion from solid wastes dumps, it is advisable to apply intensive drainage-accumulation system, which combines the technogenic geochemical (sorption ameliorant) and hydrophysical (drainage system) barriers.

3. Realization of the described mathematical models in the medium of visual programming provides the opportunity to carry out the significant amount of numerical experiments and to analyze them. Such approach consists in search of numerical solutions of differential equations that characterize the process of pollution substances migration with use of appropriate models. It is a differential form of presentation of the migration of pollutants; this approach is based on the principle of the most complete consideration of the mechanism of the pollutants transfer on the profile of the soil and in time, therefore, from the theoretical point of view, it is the most justified.

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