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Alla Bevza[1]
Yuri Kutlakhmedov[2]
Maria Kravets[3]

ENVIRONMENT RADIOCAPACITY THEORY APPLICATION FOR THE ASSESSMENT OF HEAVY METALS MIGRATION IN ECOSYSTEMS

[1,2,3]National Aviation University
1, Kosmonavta Komarova prospect, 03680, Kyiv, Ukraine
E-mails: bevza_a_g@ukr.net[1]; ecoetic@yandex.ru[2]; maria050690@ukr.net[3]

Abstract. *The article describes the usage of the theory of the environment capacity for assessment of heavy metals migration in ecosystem. Possibility of adaptation of the ecosystem boxes model for investigation of heavy metals migration in biotic and abiotic components of ecosystem based on radionuclide ^{114}Cd usage as tracer, which is radioactive analog of heavy metal Cd is demonstrated. Using of indicator - factor of the environment capacity on artificial tracer - ^{114}Cd for the assessment of the system holding ability, which is under technogenic loading caused by heavy metals, is demonstrated.*

Keywords: boxes model; capacity of the environment; capacity factor; heavy metals; tracer.

1. Introduction

Heavy metals (HM) relate to priority pollutant substances. Observation of the substances concentration is obligatory in all environments. The peculiarity of HM is the fact that they do not decay and do not depredate with time, as chemical pollutant substances of organic origin, do not disappear, and only change form of existence, redistribute and gradually accumulate in different biotic and abiotic components of ecosystem.

Monitoring and assessment of possible HM impacts on the environment and on human organism are necessary, and relevance of this problem is obvious, because a mechanism of natural self-purification from intake HM is absent in reality, and their excessive supplying into living organisms violates metabolic processes, slows the growth and development.

Studying the consequences of chemical pollution actively conducts during last decades in many countries. In the Soviet Union ecological and geochemical investigations have been started in the eighties by J. E. Sayet and have been developed in works of A. Perelman, M. A Glazovskaya, N.S Kasimova, E. P Yanina and others. There are amount of data about soil pollution by HM in the works of Ilyin V. B, Alexeeva Y. V, Kabata-Pendyas A. and other. In Ukraine at the present time D. V. Ahtyrskyy and A. H. Nekos, the scientists from Kharkiv national university named by V. N Karazin, investigate HM content in soil and plants. As follows, during last years significant amount of factual material from ecological geochemistry is accumulated. However, nowadays the possibility to receive fundamentally new results with the help of empirical generalization to a large extent is exhausted. So, there is a necessity of development of the methods of modeling and prognoses of HM migration in the environment. These methods should be based on accumulated data base and should be used for prediction of harm for human and for prevention the irreversible changes in ecosystems.

In radioecology for description of transfer and migration of radionuclides in ecosystem methods of boxes model are successfully used. It is based on the theory of radiocapacity (propoused by Agre and Korogodin in 1960 at first). According to the theory of radiocapacity, ecosystems have fundamental property, which allows to accumulate and firmly hold radionuclides coming to them. A measure of this property can be the factor of radiocapacity - relation of radionuclide activity, which firmly sorbed by components of ecosystems, to the hole radioactivity of the ecosystem. It is established that decreasing the indicator of ecosystem radiocapacity clearly reflects the decreasing in well-being and reliability of its biota. Radiocapacity and factor of radiocapacity can act as the measure of the ecosystem and its components reliability. Radiocapacity determines as available amount of radionuclides, that can be accumulate in ecosystem without changes of its basic functions. Factor of radiocapacity determines as a part of radionuclides (pollutants), which accumulates in ecosystem [1].

Radionuclides, as biogenic analogs, can be widely used as tracers – witnesses of fundamental physiological process. For example, Cs – analog of important chemical elements, which used for biota nutrition – K, and Sr – analog Ca. So, higher speed and volume of accumulation of ^{137}Cs in biota indicate better state of ecosystem biota. It can be prognosed. Ideology of tracers can be used in radioecological and ecological investigations of the state and well-being of ecosystem biota. Method of radioactive tracers are perspective, because such tracers we “generously” scattered on all territory of Ukraine. Effectiveness of such methods conforms by simplicity and accuracy of determination of radionuclides, fundamentality of the physiological process in plants which consume such tracers, presence in literature data about speed parameters of radionuclide transfer, and also simplicity in evaluation of radiocapacity factors.

So, based on this theory, assumption, that there is possibility of comparing HM behavior with behavior of their radioactive analogs, is made. For example, migration of divalent metals can be modulate by the behavior of responsible radionuclides – their radioactive analogs. Numerous data about accumulation of radiactivity by different elements of ecosystems are present in many experiments - particularly in the works of O. O. Timofeeva-Resovska [2].

So, using the theory of radiocapacity and considering ecosystem as transportation system of pollutants from environment to humans, as **object of research** was taken migration process of HM (salts of cadmium) as chemical analog of radionuclide ^{114}Cd among the ecosystem components.

2. The aim of the research

The aim of the research is to investigate the possibility of using the radiocapacity theory to study the processes of migration of HM in a model ecosystem

3. Methods of the research

a) method of mathematical modeling of HM and radionuclide's migration process in ecosystem,

b) method of statistical analysis.

The method of boxes model is the simplest and the most adequate mathematical method which is used for description of ecological process in ecosystems of different complexity. In boxes models all chain of pollutant transferring for simplicity divides on boxes. Interaction between boxes set with the help of accumulation and transfer, which characterize transformation and migration of pollutants in ecosystem. These coefficients demonstrate in how many times more (or less) activity of certain pollutants in elements of ecosystem can be in comparison with environment. At the same time assumption that radionuclide which entered in boxes, immediately mixed in all parts of boxes equally in any moment of time, and coefficient of radionuclide transferring between boxes are constant, is made. Number of boxes mathematical models has been tested already and used by scientist and research institutions [3, 4].

4. Materials and methods

Mathematical dynamical model of HM (salts of Cd) transferring in water ecosystem, caused by emergency discharge of metal content water, into water bodies, was developed by the help of boxes models method (fig. 1).

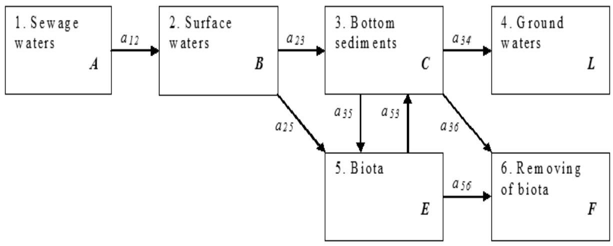

Fig. 1. Boxes model of HM transferring in water ecosystem, caused by emergency discharge

Box Bottom sediments represents a silt and sand of the reservoir, and box Biota includes such plants as Lemna minor, Elodea canadensis, Stratiotes aloides, Carex, Phragmites communis and animals Limnaea stagnalis (shellfish), Perca.

Model is based on conceptual block-scheme of radionuclide transferring in ecosystem components. Values of coefficient are showed in table 1 and based on real literature data about average speeds of distribution and redistribution of radionuclides in ecosystems [5, 6], and about coefficients of radioactivity accumulation [2]. The plants with especially higher coefficients of accumulation are *Lemna minor* (0,55) and *Elodea canadensis* (0,37), the animals – *Limnaea stagnalis* (0,22). Coefficient of accumulation in sand changes from 0,01 to 0,03, and in silt 0,25-2,3 only on 2-3 years in connection with gradual withering away and subsidence of detritus [2].

Mathematical model of HM transferring in water ecosystem with one-time emergency discharge of sewage water, describe as system of differential equation of first order (1) with constant coefficient of radionuclide transferring between boxes a_{ij}, where variables *a, b, c, l, e, f* – are dynamical specific activities of pollutants in boxes: *sewage waters, surface waters, Bottom sediments, grounwaters, biota, removing of biota and bottom sediments for their utilization,* t – time (in mounths).

Table 1. Average value of radionuclide's transferring coefficient from box to box

Environment	a_{ij}	Value
Sewage waters → Surface waters	a_{12}	0,5
Surface waters → Bottom sediments	a_{23}	0,15
Surface waters → Biota	a_{25}	0,3
Bottom sediments → Ground waters	a_{34}	0,05
Bottom sediments → Biota	a_{35}	0,2
Bottom sediments → Removing of bottom sediments	a_{36}	0,2
Biota → Bottom sediments	a_{53}	0,01
Biota → Removing of biota	a_{56}	0,4

$$\begin{cases} \dfrac{da(t)}{dt} = -a_{12}a(t); \\ \dfrac{db(t)}{dt} = a_{12}a(t) - a_{23}b(t) - a_{25}b(t); \\ \dfrac{dc(t)}{dt} = a_{23}b(t) + a_{53}e(t) - a_{35}c(t) - a_{34}c(t); \\ \dfrac{dl(t)}{dt} = a_{34}c(t); \\ \dfrac{de(t)}{dt} = a_{25}b(t) + a_{35}c(t) - a_{53}e(t) - a_{56}e(t); \\ \dfrac{df(t)}{dt} = a_{36}c(t) + a_{56}e(t). \end{cases}$$

Calculation of the system of differential equations is performed by the help of computer program MAPLE 6.

5. Graphical models and their results

The solution of system in graphical form is presented on fig. 2–4.

Received model suggests about the process of water self purification finish after emergency discharge of metal contain sewage water after 18 months. Peak of water pollution will be observed after 2 months and equal to the 4 % of HM from their total content in runoff. Accumulation of HM in other component of ecosystem has exponential character. Thus biota will be most active absorb pollutants (during 4 months). It is necessary to remove biota on the 5-th month for its future utilization.

By increasing the content of biota in reservoir we can intensify the process of water purification. So, enriching biocenose by plants with higher coefficient of accumulation - *Lemna minor* and *Elodea canadensis* (average coefficient of accumulation has become C_{ac} = 0,5), we received graphical model (fig. 3), which shows decreasing of maximal content of HM in water on 1% and reduction of time which need for accumulation of HM by biota – on 0,5 months.

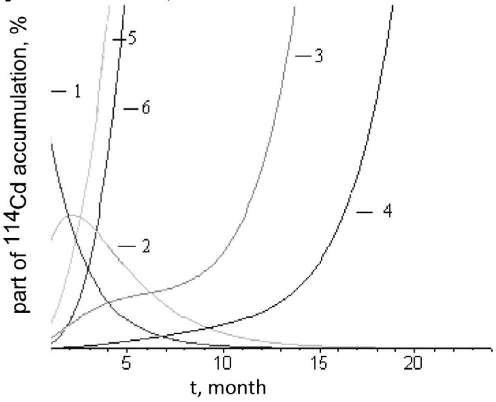

Fig. 2. Graphic of radioisotope ^{114}Cd accumulation in the components of water:
1 – accumulation of ^{114}Cd in box sewage waters $a(t)$, 2 – accumulation of ^{114}Cd in box *surface waters* $b(t)$,
3 – accumulation of ^{114}Cd in box bottom sediments $c(t)$,
4 – accumulation of ^{114}Cd in chamber ground waters $l(t)$,
5 – accumulation of ^{114}Cd in chamber biota $e(t)$,
6 – accumulation of ^{114}Cd in chamber removing $f(t)$

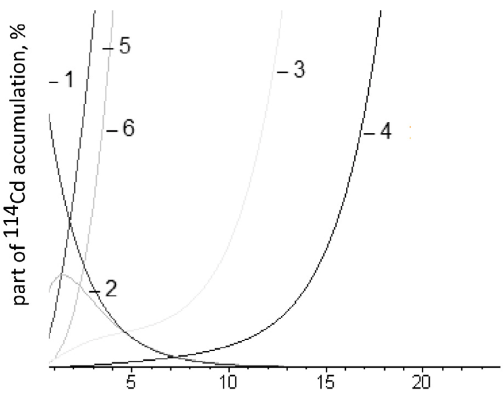

Fig. 3. Graphic of radioisotope ^{114}Cd accumulation in components of water ecosystems at $C_{ac\ biota}$ = 0,5:
1 – accumulation of ^{114}Cd in box sewage waters $a(t)$,
2 – accumulation of ^{114}Cd in box *surface waters* $b(t)$,
3 – accumulation of ^{114}Cd in box *bottom sediments* $c(t)$,
4 – accumulation of ^{114}Cd in box ground waters $l(t)$,
5 – accumulation of ^{114}Cd in box biota $e(t)$,
6 – accumulation of ^{114}Cd in box *removing* $f(t)$

Graphical model of accumulation of radioisotope ^{114}Cd in the components of water ecosystem with higher content of biota C_{ac} = 0,8 (fig. 4.) confirms efficiency of HM sorbtion by reservoir biota. Maximal content of HM in water will be 2,5 % at the 2 months after discharge. And time of accumulation of HM by biota will decrease to the 3-th months.

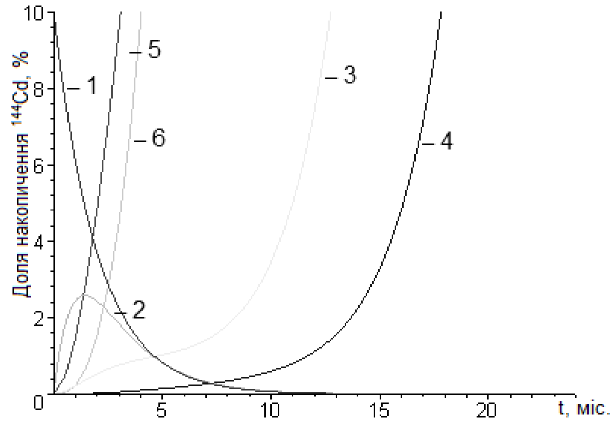

Fig. 4. Graphic of radioisotope ^{114}Cd accumulation in components of water ecosystems at $C_{ac\ biota} = 0{,}8$:
1 – accumulation of ^{114}Cd in box sewage waters $a(t)$,
2 – accumulation of ^{114}Cd in box *surface waters* $b(t)$,
3 – accumulation of ^{114}Cd in box *bottom sediments* $c(t)$,
4 – accumulation of ^{114}Cd in box *ground waters* $l(t)$,
5 – accumulation of ^{114}Cd in box *biota* $e(t)$,
6 – accumulation of ^{114}Cd in box *removing* $f(t)$

So, changing species diversity and increasing content of biota in ecosystem, can perform management of pollutants flows in ecosystem - regulate revenues of pollutant substances to different components of ecosystems.

If make assumption that concentration of Cd in sewage waters, which was discharged into reservoirs due to emergency situations, equaled 0,05 mg/l at MPC_{Cd} = 0,005 mg/l (for reservoirs of domestic using), then according the model with increased content of biota and with the coefficient of accumulation - 0,5, can predict decreasing of Cd concentration in surface waters up to 0,0014 mg/l.

6. Holding ecosystem ability

Based on given model holding ability of individual component, and system in whole, been calculated by formulas [3]:

$$R_i = \frac{\sum a_{ij}}{\sum a_{ij} + \sum a_{ji}}, \qquad (1)$$

where R_i – holding ability of box; a_{ij} – specific activity of pollutants that coming in box; a_{ji} – specific activity of pollutants that incoming from box.

$$R_{cons} = \prod_{i=1}^{n} R_i, \qquad (2)$$

where $R_{consistently}$ – holding ability of consistently connected boxes; R_i – holding possibility of box.

$$R_{par} = 1 - \prod_{i=1}^{n} (1 - R_i), \qquad (3)$$

where $R_{parallel}$ – holding ability of parallel-connected boxes; R_i – holding possibility of box.

Phased assessment of HM transferring from box to box of research model allowed to determine four main probable ways of the ecosystem pollution (fig 5):

– first (*a*), when pollutant go through the boxes 1, 2, 5, 6;

– csecond (*b*), when pollutant go through the boxes 1, 3, 4, 5, 6;

– third (*c*) when pollutant go through the boxes 1, 3, 5, 6;

– fourths (*d*), when pollutant go through the boxes 1, 3, 6.

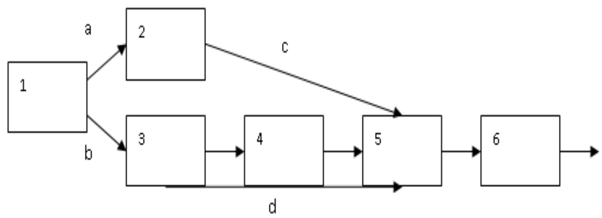

Fig. 5. Scheme of the main probable ways of the ecosystem pollution

The results of calculations by the scheme are showed in table 2. They show the ability of ecosystem at different content of biota to keep pollutants in ground water and bottom sediments.

Table 2. Results of calculations of holding ecosystem ability

R_i	$C_{ac\ biota} = 0{,}3$	$C_{ac\ biota} = 0{,}5$	$C_{ac\ biota} = 0{,}8$
R_a	0,318	0,303	0,289
R_b	0,107	0,113	0,119
R_c	0,324	0,343	0,360
R_d	0,54	0,54	0,54
R_{total}	0,810	0,813	0,816

7. Conclusions

1. It is substantiated the possibility of using of the radiocapacity theory for studying process of HM migration in the environment.

2. Possibility of investigation of the ecosystem components pollution dynamic by HM is proven. Possibility of this process management using developed boxes model of ^{114}Cd transition in water ecosystem caused by emergency discharge of metal content sewage waters is proven.

3. It is calculated holding ability of the investigated modeled ecosystem.

4. It is possible significantly reduce the receipt of pollutants due to increased supply of biomass in the reservoir.

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А.Г. Бевза[1], Ю.О. Кутлахмедов[2], М.О. Кравець[3].
[1,2,3]Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: bevza_a_g@ukr.net[1]; ecoetic@yandex.ru[2]; maria050690@ukr.net[3]

У роботі обгрунтовано застосування теорії ємності середовища для оцінки міграції важких металів в екосистемі. Показано можливість адаптації камерної моделі екосистеми для дослідження міграції важких металів у абіотичних та біотичних компонентах екосистеми на основі використання в якості трасеру радіонукліду ^{114}Cd, який є радіоактивним аналогом важкого металу Cd. Показано використання показника – фактору ємності середовища по штучному трасеру – ^{114}Cd для оцінки утримуючої здатності екосистеми, яка зазнає техногенного навантаження важкими металами.

Ключові слова: важкий метал; камерна модель; трасер; ємність середовища; фактор ємності

А.Г. Бевза[1], Ю.А. Кутлахмедов[2], М.А. Кравец[3].
[1,2,3]Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680
E-mails: bevza_a_g@ukr.net[1]; ecoetic@yandex.ru[2]; maria050690@ukr.net[3]

В работе обосновано применение теории емкости среды для оценки миграции тяжелых металлов в экосистеме. Показана возможность адаптации камерной модели экосистемы для исследования миграции тяжелых металлов в абиотических и биотических компонентах экосистемы на основе использования в качестве трассера радионуклида ^{114}Cd, который является радиоактивным аналогом тяжелого металла Cd. Показано использование показателя – фактора емкости среды по искусственному трассеру – ^{114}Cd для оценки удерживающей способности экосистемы, которая испытывает техногенной нагрузки тяжелыми металлами.

Ключевые слова: емкость среды; камерная модель; трассер; тяжелый металл; фактор емкости

Bevza Alla. Assistant of Professor of Ecology Department, Institute of Environmental Safety, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kiev, Ukraine, specialty "Ecology and environmental protection" (2004).
Publications: 27.
Research area: ecology, radioecology, modeling of ecological processes.
E-mail: bevza_a_g@ukr.net.

Kutlakhmedov Yuri. Doctor of Biology.
Head of Laboratory of Biosystems Radioecological Reliability, Institute of Cell Biology and Genetic Engineering, National Academy of Sciences of Ukraine, Kyiv.
Publications: 256.
Education: Kyiv State University of T. G. Shevchenko, Kyiv, Ukraine (1967).
Research area: ecology, radioecology, ecological processes modelling.
E-mail: ecoetic@yandex.ru.

Kravets Maria. Postgraduate student of the Institute of Ecological Safety, National Aviation University, Kyiv, Ukraine (master on Ecology, graduated in 2013).
Education: National Aviation University, Kyiv, Ukraine, major “Ecology and Environment Protection”.
Publications: 2.
Research area: radioecology, ecological processes modelling, ecology.
E-mail: maria050690@ukr.net.