RUDN Journal of Ecology and Life Safety
Вестник РУДН. Серия: Экология и безопасность жизнедеятельности
ISSN 2313-2310 (Print); ISSN 2408-8919 (Online)
2023 Vol. 31 No. 3 359–367
http://journals.rudn.ru/ecology

ENVIRONMENTAL MONITORING

ЭКОЛОГИЧЕСКИЙ МОНИТОРИНГ

DOI: 10.22363/2313-2310-2023-31-3-359-367
EDN: UZMUSO
УДК 504.064.3

Research article / Научная статья

Analysis of the spatiotemporal fields of chemical soil pollution as a basic component of urban ecosystems

Inna Z. Kamanina[1,2]✉, Svetlana P. Kaplina[1,2], Anna V. Lyubimova[1,3]

[1] Federal State Budgetary Educational Institution of Higher Education "Dubna State University", Moscow region, Dubna, Russian Federation
[2] Joint Institute for Nuclear Research, Moscow region, Dubna, Russian Federation
[3] All-Russian Research Geological Petroleum Institute, Moscow, Russian Federation
✉kamanima@uni-dubna.ru

Abstract. The soil is a depositing medium and an indicator of geochemical load. The fulfillment of important ecosystem functions by urban soils ensures the ecological safety of urban ecosystems as a whole. The purpose of the work is to forecast soil pollution as a basic component of the urban ecosystem with a high level of technogenic load. The calculation of the spatio-temporal fields of chemical pollution of soils in the city of Kolchugino, Vladimir region, was carried out using a balance model based on ecological and analytical data utilizing the results of area surveys of soils and snow cover. The content of heavy metals of hazard classes 1 and 2 in soil and snow samples (solid and liquid phases) was determined by atomic absorption method according to standard methods. The analysis of spatio-temporal fields of soil contamination for each heavy metal is performed on the basis of map diagrams constructed using the INTEGRO GIS software-technological complex. Taking into account aerotechnogenic intake, an assessment of the degree of accumulation of heavy metals in soils and their time to reach the critical level is given. In the soils of Kolchugino, an excess of sanitary and hygienic standards (gross forms) is revealed for all the metals studied. Analysis of the data of spatio-temporal fields of soil pollution with heavy metals in the city of Kolchugino showed that the established level of soil pollution exceeding the MPC is primarily associated with the past economic activity of non-ferrous metallurgy enterprises and will remain at the same level in the near future.

Keywords: heavy metals, environment, pollution, soil, city, ecosystem, balance approach

Information on financing. The work was carried out as part of the research work of the priority level of support for the University "Dubna" (Order No. 21 of 01/22/2021).

Acknowledgments: S.L. Baybakova for assistance in the collection and analysis of soil and sample of snow cover.

Authors' contributions: *I.Z. Kamanina* – the concept of the study, data analysis, interpretation of the results, formulation of conclusions, writing the text of the article; *S.P. Kaplina* – carrying out calculations, formulating conclusions, writing the text article, *A.V. Lyubimova* – carrying out calculations, data processing, the formation of GIS, the construction of cartographic schemes of the study area.

Article history: received 25.01.2023; revised 25.03.2023; accepted 25.05.2023.

For citation: Kamanina IZ, Kaplina SP, Lyubimova AV. Analysis of the spatiotemporal fields of chemical soil pollution as a basic component of urban ecosystems. *RUDN Journal of Ecology and Life Safety.* 2023;31(3):359–367. http://doi.org/10.22363/2313-2310-2023-31-3-359-367

Анализ пространственно-временной картины полей химического загрязнения почв как базового компонента городских экосистем

И.З. Каманина[1,2]✉, **С.П. Каплина**[1,2], **А.В. Любимова**[1,3]

[1] *Федеральное государственное бюджетное образовательное учреждение высшего образования «Университет «Дубна», Московская область, г. Дубна, Российская Федерация*

[2] *Международная межправительственная организация Объединенный институт ядерных исследований, Московская область, г. Дубна, Российская Федерация*

[3] *Всероссийский научно-исследовательский геологический нефтяной институт, г. Москва, Российская Федерация*

✉kamanima@uni-dubna.ru

Аннотация. Почва является депонирующей средой и индикатором геохимической нагрузки. Выполнение важных экосистемных функций городскими почвами обеспечивает экологическую безопасность урбоэкосистем в целом. Цель работы – прогноз загрязнения почв как базового компонента урбоэкосистемы с высоким уровнем техногенной нагрузки. Расчет пространственно-временных полей химического загрязнения почв г. Кольчугино Владимирской обл. выполнен с помощью балансовой модели на основе эколого-аналитических данных по результатам площадных съемок почв и снежного покрова. Содержание тяжелых металлов 1 и 2 классов опасности в пробах почв и снега (твердая и жидкая фазы) определяли атомно-абсорбционным методом по стандартным методикам. Анализ пространственно-временных полей загрязнения почв для каждого тяжелого металла выполнен на основе карт-схем, построенных при помощи программно-технологического комплекса ГИС INTEGRO. Дана оценка степени накопления тяжелых металлов в почвах и времени достижения критического уровня с учетом аэротехногенного поступления. В почвах г. Кольчугино выявлено превышение санитарно-гигиенических нормативов (валовых форм) для всех исследованных металлов. Анализ данных пространственно-временных полей загрязнения почв тяжелыми металлами г. Кольчугино показал, что установленный уровень загрязнения почв, превышающий ПДК, связан в первую очередь с прошлой хозяйственной деятельностью предприятий цветной металлургии и в ближайшей перспективе останется на том же уровне.

Ключевые слова: тяжелые металлы, окружающая среда, загрязнение, почва, город, экосистема, балансовый подход

Информация о финансировании. Работа выполнена в рамках НИР приоритетного уровня поддержки университета «Дубна» (Приказ № 21 от 22.01.2021).

Благодарности: С.Л. Байбаковой за помощь в сборе и анализе образцов почв и снежного покрова.

Вклад авторов: *И.З. Каманина* – концепция исследования, анализ данных, интерпретация результатов, формулирование выводов, написание текста статьи; *С.П. Каплин*а – проведение расчетов, формулирование выводов, написание теста статьи; *А.В. Любимова* – проведение расчетов, обработка данных, формирование ГИС, построение картографических схем исследуемой территории.

История статьи: поступила в редакцию 25.01.2023; доработана после рецензирования 25.03.2023; принята к публикации 25.05.2023.

Для цитирования: *Каманина И.З., Каплина С.П., Любимова А.В.* Анализ пространственно-временной картины полей химического загрязнения почв как базового компонента городских экосистем // Вестник Российского университета дружбы народов. Серия: Экология и безопасность жизнедеятельности. 2023. Т. 31. № 3. С. 359–367. http://doi.org/10.22363/2313-2310-2023-31-3-359-367

Urbanization process is one of the main contemporary challenges accompanied by a constant increase in the load on the natural environment components [1–3]. Small and medium-sized towns play a specific role in the system of cities, they make up 85% of Russian urban dwellings nowadays. Such towns differ in their identity and the degree of study of the anthropogenic load and its impact on various components of the environment. Among them there are single-industry towns in which industrial facilities of ferrous and non-ferrous metallurgy, chemical industry with a high level of localization of pollution are located [4]. At present, the task of sustainable urban development, taking into account environmental safety, is coming to the fore. In this regard, the need to study modern processes taking place in urbanized territories is steadily increasing. The forecast of the ecological state of urban ecosystems will allow addressing environmental challenges of small and medium-sized towns more efficiently.

Urban soils perform important ecosystem functions that often remain undervalued. At the same time, soil is a depositing medium and an indicator of geochemical load. The main source of pollutants entering urban soils is atmospheric precipitation both from local stationary sources of industrial enterprises and motor vehicles, secondary pollution as a result of denudation processes in urbanized landscapes, and due to the transfer over considerable distances from external objects of technogenic impact. The analysis of the spatio-temporal picture of the fields of soils chemical contamination allows us to assess the degree of accumulation of heavy metals in urban soils and the time to reach a critical level.

The research objective: the forecast of soil contamination as a basic component of the urban ecosystem of Kolchugino, Vladimir region, using a balance approach.

Research object and methodology

The town of Kolchugino is located in the northwestern part of the Vladimir region (56°17'; 39°22' on the right bank of the Peksha River, which is a tributary of the Klyazma River. The city is 74 km from Vladimir and 131 km from Moscow. The area of the city is 31 km2, the population is 41,953 (small town). This is a single-industry town. There are 19 large, medium and small industrial enterprises operating in the town. The main city-forming enterprises are non-ferrous metals processing plants: JSC “Electric Cable Kolchuginsky Plant”, LLC “Kolchuginsky Melchior”, JSC “Intersilverline”, LLC “MTK “ZiO-Met”, “Kolchuginsky Non-ferrous Metals Plant” (in 2017 became part of JSC “Electric Cable Kolchuginsky Plant”). The Kolchuginsky Non-ferrous Metals plant produced about 30% of the total volume of rolled non-ferrous metals in Russia. Part of the residential buildings are located within the sanitary protection zone of enterprises and are experiencing a high level of pollution.

The calculation of spatio-temporal fields of chemical contamination of urban soils was performed using the balance model of T.N. Lubkova [5] on the basis of ecological and analytical data obtained by the authors as a result of longitudinal study of various environmental components of the Central Russian small and medium-sized towns. The data of area surveys of soils and snow cover of the city of Kolchugino were used, taking into account its functional zoning. Soil and snow cover samples were taken in accordance with generally accepted requirements[1] on a randomly ordered grid, considering functional zoning at the rate of 1 sample per 1 sq. km.[2] A total of 20 soil samples and 20 snow samples were obtained. In soil and snow samples (separate solid and liquid phases), the content of heavy metals of hazard classes 1 and 2 was determined by standard methods using the QUANTUM-2A atomic absorption spectrophotometer by LLC Cortec. The data obtained as a result of quantitative chemical analysis of the studied samples were

[1] MG 2.1.7.730-99. Methodological guidelines “Hygienic assessment of the soil quality of populated areas”. Moscow: Federal Center of State Sanitary and Epidemiological Supervision of the Ministry of Health of Russia, 1999. 38 p.

[2] GOST 17.4.4.02-84. Nature conservation. Soil. Methods of sampling and preparation of samples for chemical bacteriological, helminthological analysis. Moscow: Publishing House of Standards, 1985. 12 p.

processed by methods of mathematical statistics using software packages Statistica 6.0 and Microsoft Excel. Further, on the basis of the calculated data obtained, a schematic map of the spatial and temporal fields of soil contamination for each heavy metal was constructed using the INTEGRO GIS software and technology complex (included in the Unified Register of the Russian Ministry of Communications Software under number 4302), developed in the Geoinformatics Laboratory of the VNIIGEOSYSTEMS Research Institute (1998–2015). The function "Multilevel basis spline" is used as an interpolation algorithm.

Results and discussion

Based on data on the content of heavy metals in the soils of the city of Kolchugino, the territory was ranked according to the level of soil contamination with chemicals[3], where the first level of contamination refers to the "permissible", and the content of TM does not exceed the maximum permissible values. Excess of sanitary and hygienic standards (gross forms) are noted for all metals studied. The average content of lead, cadmium, zinc and copper exceeds the UEC by 1.5 to 2.8 times. Areas with an "average" level of contamination were identified on the territory of the city, the area of such territories was 13% of the city's territory in lead (3.9 sq. km), 17% in copper (5.2 sq. km).

This level of contamination is recorded for two metals at once (lead and copper), the areoles of contamination are located on the territory of the residential part of the city. The "low" level of contamination was detected by the content of all the studied metals. The area of such territories was: for cadmium on 75% of the city's territory (23.4 sq. km), for zinc – 71% (22.1 sq. km), for copper – 69% (13 sq. km), for lead 34% (6.5 sq. km).

In the assessment and prediction of pollution of local ecosystems by chemical elements, it is possible to use a balance model that allows describing the dynamics of individual geochemical indicators in a certain volume of the natural environment, determining the relationship between the rates of change in migration flows in space and the rates of change in the status of the system over time [6].

To calculate the load of heavy metals with atmospheric precipitation, the results on the content of suspended and dissolved forms of heavy metals in snow samples were used. The entry of heavy metals into soils with dust deposition during the calculation period is characterized by the accumulation of pollutants in the upper soil horizon, directly in contact with the surface layer of the atmosphere during this period. Calculations were carried out in accordance with MG 2.1.7.730-99. Methodological guidelines "Hygienic assessment of the soil

[3] Methodological recommendations for assessing the degree of atmospheric air pollution of settlements with metals based on their content in snow cover and soil. Moscow: IMGRE, 1990. 16 p.; The procedure for determining the amount of damage from land pollution with chemicals. Moscow: Roskomzem, Ministry of Natural Resources of Russia. 1993. 29 p.

quality of populated areas". Moscow: Federal Center of State Sanitary and Epidemiological Supervision of the Ministry of Health of the Russian Federation 4 according to the following formula:

$$\Delta Q_{HM} = \left[(1 - f^{ss})\left(1 - \frac{\tau^{P} P_3^{P} C_f}{\tau^{HM} P_3^{HM\ ss}}\right) + (1 - f^{cv})\frac{1}{Kcv}\right] \times \tau^{HM} P_3^{HMss} ST. \quad (1)$$

Statistical characteristics of the load of heavy metals with atmospheric precipitation according to snow survey data are presented in Table 1.

Statistical characteristics of the load of heavy metals with atmospheric fallout according to snow survey data

Characteristic	ΔQ tm, g/sq.km per year			
	1 hazard class			2 hazard class
	lead	zinc	cadmium	copper
Minimum	525	3 089	41	178
Maximum	4 099	30 421	440	2 833
Average	1 227	12 011	182	1 302
Median	751	11 374	175	1 252
Standard deviation	984	7 264	126	785
Mean error	220	1 624	28	176
Dispersion	968 173	52 761 825	15 924	616 092

Analysis of the data obtained showed that the intake of heavy metals with atmospheric precipitation in Kolchugino is uneven and characterized by extremely pronounced spatial heterogeneity. A higher load of heavy metals is typical for the eastern and southeastern parts of the city. The intensity of precipitation of copper and zinc decreases with distance from the territory of the industrial site, where the main city-forming enterprises of non-ferrous metallurgy are concentrated. For lead and cadmium, the dependence is less pronounced.

Based on the data on the content of heavy metals in the soil and the calculated load with atmospheric precipitation, the spatio-temporal fields of urban soil pollution for the medium and long term were calculated. The calculation of the predicted (at the end of the calculation period n) concentrations of heavy metals in soils was carried out according to the formula:

$$C(n) = C(0) + \frac{1}{hd}\sum_{i=1}^{n}\frac{\Delta Q\text{тм}}{S}, \quad (2)$$

where $C(n)$ and $C(0)$ – predicted and current concentrations of heavy metals in soils ($C(0) = C_{ф}$); d – soil density, h – the height of the soil layer.

Based on the results of forecast calculations, a series of map-scheme of the spatial distribution of heavy metals on the territory of Kolchugino was constructed.

[4] MG 2.1.7.730-99. Methodological guidelines "Hygienic assessment of the soil quality of populated areas". Moscow: Federal Center of State Sanitary and Epidemiological Supervision of the Ministry of Health of Russia, 1999. 38 p.

The analysis of the data of the spatio-temporal fields of soil contamination with heavy metals in Kolchugino showed that the lead content in soils for 100 years remains within the limits of the already existing contamination, namely 66% of the city's territory has an *"acceptable" level, 21*% – "*low*" and 13% – "*average*" *contamination levels*. In 1000 years, at the current rate of lead intake with atmospheric precipitation, the area with an "*acceptable*" *level* of contamination will decrease by 2.6 sq. km and will make up 57% of the city's territory. At the same time, the area with a "*low*" *level of contamination* will increase to 22% of the territory. According to calculations, the zinc content will reach a *"low" level of contamination* in 75% of the city's territory within 50 years. In 100 years, a *"low" level of zinc contamination* will be observed in soils on an area of 83% of the city's territory. In 1000 years, the entire territory of the city will move into the category with a *"low" level* of soil contamination with zinc. In terms of cadmium content, the soils of Kolchugino remain at the same level of contamination after 50 years. After 100 years, with the existing load of the city territory of 2.6 sq. km with a *"low" level of contamination,* deterioration will occur and the second "permissible" level of contamination will be reached. In 1000 years, cadmium contamination in 9% of urban soils will reach the third *"average" level of contamination*. Within 100 years, the levels of soil contamination in terms of the content of gross forms of copper will not change and will amount to: "high" contamination level on 4% of the city territory, *"average" level* – 17%, *"low" level* – 42% and *"acceptable" level* – 37%. After 1000 years, soils on an area of 3.9 sq. km will move from the first *"acceptable" level* to the second *"low" level of contamination*.

In addition, based on the data on the content of heavy metals in soils obtained using the balance model, a forecast calculation was carried out to achieve various levels of soil contamination in Kolchugino (the lower limits of the ranges of values characterizing each level of contamination) in accordance with [6]. Data analysis showed that the average time to reach the *second "low" level of soil contamination* in Kolchugino (if this level is not reached) will be 3074 years for lead, the minimum is 286 years. A similar pattern is observed for copper, the average time will be 2686 years, the minimum is an order of magnitude less – 262 years. The average time to reach the 2nd level of cadmium contamination will be 228 years, the minimum – 77. The most unfavorable forecast is noted for zinc – the minimum time to reach the 2nd level of contamination is 2 years, the average time to reach 126 years.

The third "average" level of soil contamination will be reached on average: for lead in 17131 years, for zinc – 6392, for cadmium – 2687, for copper – 42584. The time to reach the *fourth "high" level of contamination* will be: for lead – 35001, for zinc – 21621, for cadmium – 5441, for copper – 42799. The average time to reach the fifth *"extremely high" level* of soil contamination in Kolchugino will be tens of thousands of years: for lead – 93286, for zinc – 44465, for cadmium – 26095, for copper – 77177.

Probably, the established level of soil contamination with heavy metals, which exceeds the MPC in most of the city, is primarily associated with the past economic activity of non-ferrous metallurgy enterprises that have existed in the city since 1871. Currently, the enterprises have undergone significant modernization, including systems for cleaning atmospheric emissions, which has led to a significant reduction in emissions. Nevertheless, as already noted, the intensity of precipitation of copper and zinc depends on the distance to the industrial site where non-ferrous metallurgy enterprises are concentrated and decreases with distance from the industrial site. For lead and cadmium, the dependence is less pronounced, which indicates the arrival of heavy metals, including from other sources, such as urban boilers, road and rail transport, etc.

Conclusion

Small towns are an integral component in the structure of the Russian Federation, which concentrate domestic history and culture as well as science and industry. Recently, the state has been paying great attention to the economic and social development of small towns. At the same time, the further development of those will inevitably lead to an increase in anthropogenic load. In order to preserve environmental safety and sustainable development of towns, it is necessary to focus on the environment. Implementation of a balanced approach to predict the spatio-temporal picture of urban soil contamination makes it possible to assess trends in urban ecosystem pollution. The results obtained are of interest for making timely management decisions aimed at creating a safe, comfortable environment for living and economic activity on the territory of Kolchugino.

References

[1] Bityukova VR. The integral estimation of ecological situation of Russian cities and towns. *Regional Studies.* 2014;4:49–57. (In Russ.).

[2] Meisner TN. Safety of a modern city as a subject of interdisciplinary research. *Humanitarians of the South of Russia*. 2020;9(1):131–140. (In Russ.).

[3] Rogozhina NG. Environmental Challenges of Urbanization in Southeast Asia.*Outlines of global transformations: politics, economics, law*. 2020;13(1):102–118. (In Russ.). http://doi.org/10.23932/2542-0240-2020-13-1-6

[4] Bityukova VR. Environmental problems of small towns of Russia. *Bulletin of Moscow University. Series 5: Geography.* 2007;(1):13–21. (In Russ.).

[5] Lubkova TN. *Assessment and forecast of technogenic pollution of local ecosystems by chemical elements on the basis of balance calculations: abstract of the thesis of a candidate of geological and mineralogical sciences*. 25.00.09. Moscow State University. M.V. Lomonosov. Moscow; 2007. 29 p. (In Russ.).

[6] Makarov OA, Makarov AA. Prediction of chemical pollution of soils with heavy metals using the balance sheet method (for example local sites in Moscow and Podolsk). *Ecology of urban areas*. 2016;(1):50–58. (In Russ.).

Bio notes:

Inna Z. Kamanina, Candidate of Sciences in Biology, Assistant professor, Department of Ecology and Earth Sciences, Faculty of Natural and Engineering Sciences, Dubna State University, 19 Universitetskaya St, Dubna, Moscow region, 141982, Russian Federation. ORCID: 0000-0001-9186-8689. E-mail: kamanina@uni-dubna.ru.

Svetlana P. Kaplina, Candidate of Sciences in Biology, Assistant professor, Department of Ecology and Earth Sciences, Faculty of Natural and Engineering Sciences, Dubna State University, 19 Universitetskaya St, Dubna, Moscow region, 141982, Russian Federation. ORCID: 0000-0003-1323-6349. E-mail: sv_kap@mail.ru

Anna V. Lyubimova, Candidate of Sciences in Technology, Head of the Department of GIS and Digital Cartography of the Federal State Budgetary Institution of Geoinformatics Department “VNIGNI”, 8 Varshavskoe shosse, Moscow, 117105, Russian Federation. ORCID: 0000-0002-8075-937X. E-mail: anna_lioubimova@mail.ru.