Досліджено та проаналізовано гідрохімічний склад стічних фільтраційних вод (фільтрату) на прикладі полігону твердих побутових відходів м. Житомира (Україна). Отримані експериментальні дані та виявлені їх особливості узагальнено у вигляді математичних моделей динаміки змін кількості хімічних компонентів у пробах фільтрату. Ці моделі дозволяють прогнозувати склад фільтрату та розробляти заходи щодо його знезараження

Ключові слова: тверді побутові відходи, стічні фільтраційні води, сезонна динаміка, математична модель моделювання гідрохімічного складу фільтрату

Исследован и проанализирован гидрохимический состав сточных фильтрационных вод (фильтрата) на примере полигона твердых бытовых отходов г. Житомира (Украина). Полученные экспериментальные данные и выявленные их особенности обобщены в виде математических моделей динамики изменений количества химических компонентов в пробах фильтрата. Эти модели позволяют прогнозировать состав фильтрата и разрабатывать мероприятия по его обеззараживанию

Ключевые слова: твердые бытовые отходы, сточные фильтрационные воды, сезонная динамика, математическая модель моделирование гидрохимического состава фильтрата

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MATH MODELING AND ANALYSIS OF THE IMPACT OF MUNICIPAL SOLID WASTE LANDFILL LEACHATE ON THE ENVIRONMENT

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1. Introduction

Municipal waste accumulation, recycling and disposal remain a difficult problem in Ukraine due to the lack of evidence-based solutions regarding environmental engineering protection. One of the key municipal waste disposal measures is a modern construction of municipal solid waste dumps.

The current crisis with the provision of public services has not bypassed the municipal solid waste management. The companies working in the field of waste management are unable to provide the population with quality public services. Their equipment is mostly outdated and worn out. Only a small part of municipal solid waste from households is collected separately and recycled. There are special entities. However, the market for these services is underdeveloped, and information on the possibility of recycling can hardly be obtained. Municipalities do not develop selective waste collection systems because of insufficient demand for secondary resources and the lack of information on the possibility of recycling. A small quantity and poor quality of collected waste along with inadequate marketing do not make profits because the cost of collection is higher. So, valuable secondary resources are dumped instead of being reused in economic activities.

An essential element of municipal solid waste (MSW) management is the management of solid waste provided for recycling, which will reduce the amount of waste at dumps and give financial support for waste collection. Such activities require also the support of a local community, which needs the introduction of environmental education.

MSW dumps are a significant source of water pollution. As a result of infiltration of atmospheric precipitation, percolating wastewater (leachate) is generated at dumps. The MSW disposal also causes environmental problems such as methane generation and soil subsidence at dumps. However, leaching and groundwater contamination are the most dangerous. Rain (melt) water, seeping through the landfilled waste layers is saturated with chemicals that are formed in the waste decomposition process. Such water with dissolved contaminants is called leachate and is a particularly toxic (poisonous) substance, which, along with organic residues, contains iron, mercury, zinc, lead and other metals, dyes, pesticides, detergents and other chemicals.

All municipal waste of the city of Zhytomyr (Ukraine) without pre-sorting is stored in the landfill, which became a source of heavy pollution of the atmosphere and groundwater. It should be noted that no regulatory document for maintenance and operation of MSW landfills prohibits accumulation of leachate. Only the fact of toxic substances ingress into the environment outside the landfill is considered a violation of environmental legislation.

Therefore, to prevent ingress of toxic substances into the environment, measures should be developed for reducing the amount of leachate through proper MSW landfilling and decontamination of leachate that is accumulated in the landfill sumps.

To address these two urgent problems, information on the hydrochemical composition of leachate on the example of MSW landfill sumps in Zhytomyr (Ukraine) was analyzed and mathematical models of the dynamics of the hydrochemical composition of leachate were developed in the paper. This has allowed predicting the amount and composition of leachate for the next year and developing recommendations on the MSW landfill operation and measures for leachate decontamination in sumps.

2. Literature review and problem statement

Municipal waste accumulation, recycling and disposal remain a difficult problem due to the lack of evidence-based conceptual solutions regarding environment engineering protection. One of the key municipal waste disposal measures is a civilized construction of municipal solid waste (MSW) dumps. The experience of Ukraine and Western Europe shows that the MSW landfill construction is much cheaper than the construction of waste incineration plants [1, 2].

Distinctive features of MSW from other waste are [2]:

1) localized spacing;

2) genetically inherent chemical heterogeneity.

The more complex is the chemical nature of waste, the more dangerous they are to people and the environment [3]. Waste management has been and remains one of the priorities of the developed countries in two main contexts: environmental protection and resource recycling implementation. MSW management is covered in works of many scientists who have made an essential contribution to a research on methods of waste management, provision of environmental safety of the sites and aspects of the impact of municipal solid waste of different morphological structure on the environment [2, 3].

At present, the amount of MSW that is generated and released annually into the biosphere is overwhelming and makes up about 400 million tons a year, which negatively affects the sanitary and epidemiological welfare of settlements [2, 4–7]. According to the Ministry of Regional Development, Construction, and Communal Living of Ukraine, specific waste generation indicators average 250 kg/year per capita, while in large cities they reach 330–380 kg/year, increasing annually by 3.5 % [3]. The vast amount of MSW is stored at garbage dumps, illegal or "landfills". This is the least effective method of MSW management as garbage dumps often occupy huge areas of fertile land (storage of 1 ton of waste requires 3 m^2 area). The majority of dumps (80 to 90 %) are overloaded, have long-term violations in design parameters on the amount of waste. However, until the early 90s, the waste situation in most countries was the same as it is today in Ukraine. Waste was generally transported to landfills or dumps to be disposed or incinerated. Thus, in the mid 90s in Sweden 40 % of waste, in the UK – 90 %, in the US – 80 %, in Canada – about 95 %, in Europe – on average 60 % (after removing the glass, paper, metals) came to dumps or landfills for disposal [2]. The morphological composition of MSW in Ukraine, especially in large cities, is rapidly becoming similar to the composition of MSW in Western countries with a considerable part of waste paper and plastic, which are also subject to storage. According to the National Ecological Centre of Ukraine [3], more than 1 billion m^3 of human waste have been accumulated in Ukrainian landfills and dumps. According to the official data of the State Statistics Service of Ukraine, 3.5 % of them undergo recycling. This waste occupies more than 7 thousand hectares of land.

The main method of sanitation of urban areas from MSW is disposal in landfills and dumps, where physicochemical and biochemical processes of waste decomposition, accompanied by pollutants emissions into the environment have been occurring for decades. The main source of the negative impact of MSW landfills on the hydrosphere is percolating water [8–10].

The volume of percolating water depends on environmental factors, waste humidity, landfill engineering infrastructure, waste pre-treatment. PW volume calculation is based on the MSW landfill water balance. Depending on climatic conditions and landfill capacity, the leachate volume averages from 2000 to 4000 m^3/(ha per year). A significant difference of leachate from other types of wastewater is uneven accumulation within a year due to seasonal fluctuations in precipitation [3].

The composition of leachate depends on the stage of the landfill life cycle: active operation, reclamation, post operation and assimilation. The final stages of the landfill life cycle include the period of operation, exceeding the design lifetime (after 20 years of waste deposition), reclamation and post operation stages [11]. Analysis of the processes of degradation of the MSW various factions allows determining the chemical composition of leachate at each stage of the landfill life cycle.

Biochemical processes, occurring in anaerobic conditions are essential in waste decomposition. The main phases of anaerobic waste biodegradation are hydrolysis, acetogenesis, active methanogenesis, stable methanogenesis, full assimilation. MSW also contains ferrous and nonferrous metals, which are capable of being corroded, participating in redox reactions, forming complex compounds with organic ligands – products of biochemical decomposition of an organic part of MSW, forming sparingly soluble hydroxides, carbonates, phosphates, sulfides [2].

Thus, it was found that the negative impact of MSW landfills on water resources is a worldwide problem. But the development of specific recommendations on preventive measures and methods of environmental protection greatly depends on the location of each of the landfills and local hydrogeological and meteorological conditions, as well as the composition of MSW coming to garbage dumps. Therefore, the development of effective measures that will improve the environmental safety of our country requires the analysis and mathematical modeling of the dynamics of the properties of leachate from landfills in the city of Zhytomyr.

3. Goals and objectives

The goal of the paper is a pilot study, analysis and modeling of the hydrochemical composition of MSW landfill leachate for further development of the chemical decontamination technology.

The objectives that were accomplished in the work include:

– synthesis of existing research on the impact of MSW landfill leachate on the environment;

– collection of data on the chemical composition of Zhytomyr MSW landfill leachate;

– analysis of the data and development of mathematical models representing the dynamics of hydrochemical parameters of MSW landfill leachate.

4. Materials and methods of research of structural and functional characteristics of leachate

The research was conducted in the local MSW landfill in Zhytomyr, Ukraine. All municipal waste of Zhytomyr is stored without pre-sorting in this landfill, which has become a source of heavy pollution of the atmosphere and groundwater (and a threat to the epidemic status in general) and requires improvement of the waste disposal process. According to the data presented at the 12th session of the VI convocation of the Zhytomyr City Council, about 12–15 million m^3 of various waste have been accumulated since the beginning of operation of the municipal landfill (since 1957). In 1957, it was enough to choose a place, to make a fence and start waste disposal. The environmental problem, posed by this huge chemical bomb cannot be overemphasized.

Over the years of operation the dump heap has grown up to 30 meters, its area is 21.6 hectares (according to the state act on land the total area is 21.5670 hectares); disposal area is 18.7 hectares, and the rest is divided into 6 cards that continue to operate. Bunding was performed along the landfill perimeter. In late 1998, 10 hectares of lands of PJSC "Kroshenskiy brick yard" were withdrawn and transferred to the Department of Housing and Communal Services for the city dump expansion. Every year about 300 thousand m^3 of waste come to the city dump. The driveway to the landfill was paved, the permit system was organized. The landfill is located in the northern part of the city on Andriivska street. The distance from the landfill site to residential one-storey detached houses is 500 m.

Garbage from houses is transported by KATP-0628. The companies and organizations, which transport waste themselves are allowed to the landfill with badges, issued by the company. A cursory examination of waste is performed before going to the card to prevent toxic waste storage. Up to 30 million tons of waste of various hazard classes are disposed at the city dump.

The stated morphological composition of municipal waste coming to the landfill: food waste – 33.1 %; paper – 5.9 %; metal – 3.3 %; polymer packaging – 13.2 %; wood – 4.1 %; glass – 13.5 %; rags – 2 %; leather, rubber – 1.4 %; construction waste – 3.7 %; road sweepings – 11 %; other waste – 8.8 %.

Every spring, after snow melting or heavy rains, the amount of liquid leachate that flows into reservoirs, located in the lowest point of the dump dramatically increases and threatens to leak to the Kroshenka river breaking through an artificial dam. The object is under constant control of the City State Ecological Inspection. The average annual amount of MSW coming to the Zhytomyr landfill is 162.2 thousand m^3, or 54 thousand tons with a specific weight of 0.333 t/m^3, estimated humidity – 60 %. That is, about 32.4 thousand m^3 of free water gets to the landfill for one year. Given the average area of the landfill body (18.7 hectares), the average annual precipitation in the landfill body is 105.094 thousand m^3/year. Evaporation from the landfill surface, which depends on the amount of precipitation and radiation balance of the evaporation surface (40.3 kcal/cm^2 per year) is 460 mm/year (86.02 thousand m^3/year. Thus, the amount of leachate formed in the landfill is 51.47 thousand m^3/year, or 141 m^3/day.

Leachate sampling to assess the impact on ground and surface water was carried in this landfill in places of constant hydrobiological observations in parallel with hydrochemical sampling. Sump 1 and sump 2 are two places of leachate accumulation. Observations covered all biological seasons. Obtaining representative data to assess the structural and functional characteristics, as well as the dynamics of the leachate required sampling twice a quarter. Sampling was conducted in a clearly set time. The time interval from 10 to 12 am was the most optimum.

The samples, starting from the surface, were taken in each meter of the water layer to account for leachate vertical dynamics and minimize errors caused by its movement deep in the soil. The samples were poured into one container (a 10.0–12.0 dm^3 plastic bucket), from which the integrated samples of 0.5–1.0 dm^3 were then taken. The integrated sample volume of 0.5 or 1.0 dm^3 was determined by a preliminary visual examination of the leachate:

a) under intense leachate change, a 0.5 dm^3 sample was enough;

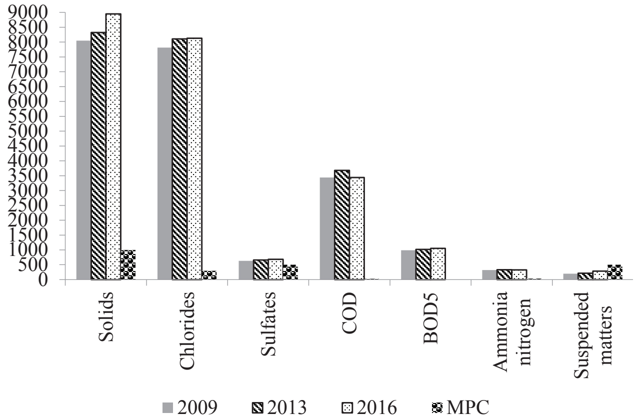
b) under little change and influence, especially in winter or early spring and late autumn periods, 1.0 dm^3 were taken.

One sample was fixed, and the other was used to study the landfill leachate condition. This was extremely necessary, since the fixation may damage some morphological properties of leachate that are characteristic systematic features.

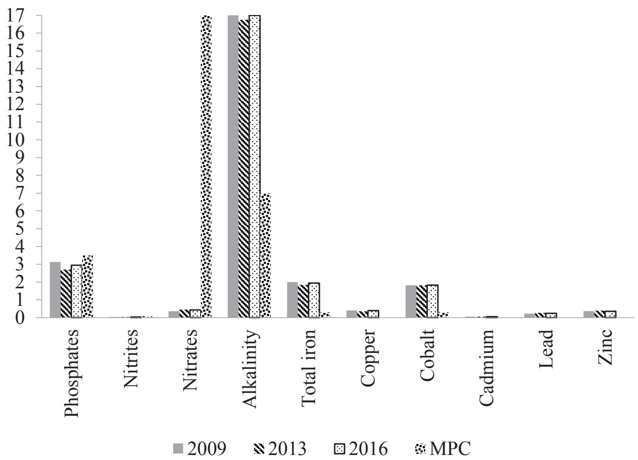
Sampling to quantify the leachate was conducted with a Ruttner water sampler. Given that hydrochemical, microbiological, toxicological samples were taken in parallel with the leachate sampling, 3–5 dm^3 water sampler volume is the most appropriate. Leachate samples were taken and stored in glass bottles or plastic flasks, calibrated accordingly to 0.5 and 1.0 dm^3, tightly covered with lids. The label on the flask with the sample was filled in. All necessary sampling data (the name of the reservoir, site, section line, sampling date, day, month, year, time of sampling, transparency, sample volume, water and air temperature, amount of oxygen, hydrometeorological data – weather conditions and sampling time, different kinds of garbage, etc.) were noted in a mandatory data journal. As the works at the reservoir were finished, all notes of the mandatory data card were recorded in a bound and numbered laboratory notebook.

5. The results of research of percolating water properties and their discussion

In order to determine the chemical composition and organoleptic properties of wastewater, sampling points were identified and samples from two reservoirs were taken: one from a large and deep reservoir (reservoir 1), the second – from the most remote reservoir from the landfill area (reservoir 2). The study of physicochemical properties of the samples was performed at the laboratory of the State Ecological Inspection in the Zhytomyr region. The analysis of the chemical composition and organoleptic properties are presented in Fig. 1, 2.



a



b

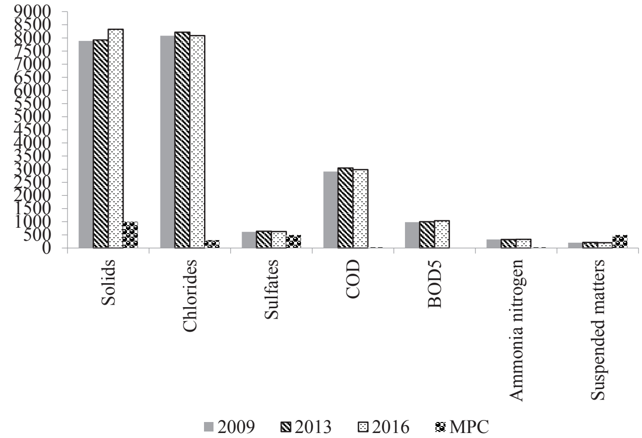
Fig. 1. The comparative analysis of the 2009–2016 indicators of the leachate from the sump 1 and the maximum permissible standards of percolating water: *a* — solids, chlorides, sulfates, COD, BOD_5, ammonia nitrogen and suspended matter; *b* — phosphates, nitrites, nitrates, alkalinity, iron, copper, cobalt, cadmium, lead and zinc

The research shows that percolating water has a slightly acidic medium reaction, the pH is 6.0–6.5. Threshold dilution by color in the water of the first reservoir is 1:5400, the second – 1:250. The initial wastewater chromaticity, determined by a chromaticity scale, is 1500 and 800 respectively in the 1st and 2nd sources.

The analysis of the leachate samples from the sumps for the period 2009–2016 shows that chemicals such as phosphates, iron, cobalt, cadmium, lead, chemical oxygen demand (COD) and biochemical oxygen demand (BOD), alkalinity and hardness indicators at MSW dumps in Zhytomyr are excessive. Therefore, it is needed to pay special attention to these figures and develop a set of measures for their control and forecast for the future.

To build the model, the statistics on the impact of Zhytomyr landfill leachate, which would characterize the pollution processes of percolating water of the city MSW landfill was used. These indicators are changes in the concentrations of the chemical composition of wastewater within a year.

The experimental data were obtained, and their features, summarized in the form of linear and nonlinear statistical mathematical models of the processes of changes in the quantitative composition of chemical indicators of the leachate samples from the sumps were identified. These models are the basis for forecasting the pollution processes of percolating water of Zhytomyr MSW landfill, development and implementation of practical measures aimed at minimizing the impact of MSW landfills on the hydrosphere in the final stages of the life cycle.



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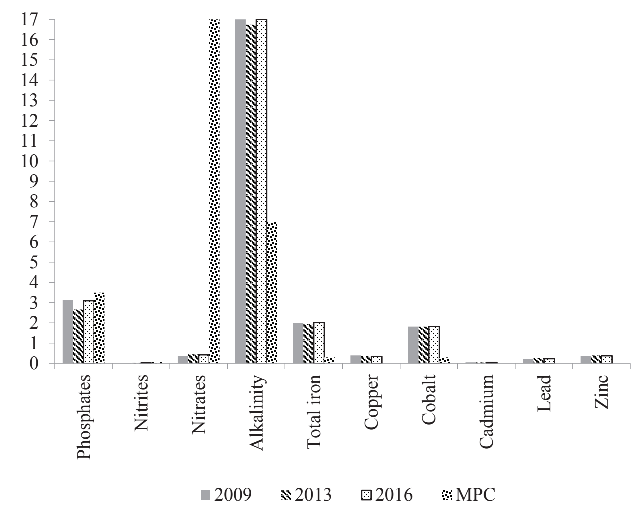

b

Fig. 2. The comparative analysis of the 2009–2016 indicators of the leachate from the sump 2 and the maximum permissible standards of percolating water: *a* — solids, chlorides, sulfates, COD, BOD_5, ammonia nitrogen and suspended matter; *b* — phosphates, nitrites, nitrates, alkalinity, iron, copper, cobalt, cadmium, lead and zinc

The method of statistical modeling of changes in the quantitative composition of chemical properties of the leachate samples of the sumps 1 and 2 on average over the analyzed years for two sumps was to choose the type of approximating curve so that the approximating curve was the most consistent with long-term experimental data. To investigate the changes in concentrations of solids and sulfates, the 3rd-degree polynomial approximation of their number was performed, and the polynomial coefficients that approximate the experimental data were determined.

The results show that the 3rd-degree polynomial reasonably well represents the dynamics of the concentration of these indicators for 2009–2016. Fig. 3–4 show the results of mathematical modeling and approximation of the dynamics of the above-mentioned parameters. The function (1) describes the general behavior of the indicators, the 3rd degree polynomial approximation of their number was performed.

$$C = a_0 + \sum_{i=1}^{n} a_i \times x^i, \quad (1)$$

where C – the chemical concentration, $a_{0,}$ a_i – the polynomial coefficients, n – the number of experimental data points used for approximation, x – the number of the year since 2009.

The results of approximation of the chloride concentration dynamics revealed that the polynomial has the form of the exponent and is described by the regression equation:

$$C_{solids}=2.4489x^3-14769x^2+3\cdot10^7x-2\cdot10^{10}, \quad (2)$$

where x – the number of the year, approximation reliability R^2=0.9604.

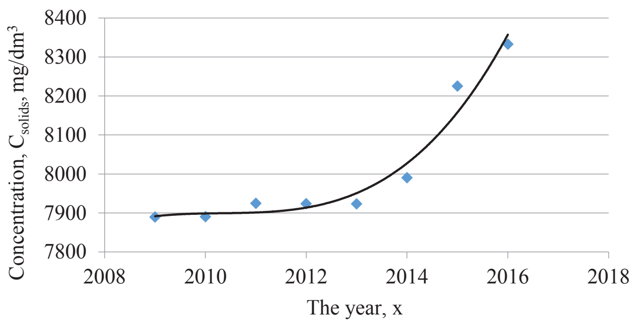

Fig. 3. The results of mathematical modeling of the solids concentration dynamics: ■ — experimental leachate research data; solid line — approximation results

The results of approximation of the sulfate concentration dynamics revealed that the polynomial has the form of a cubic parabola and is described by the regression equation:

$$C_{sulfate}=-1.2098x^2+12.993x+604.29, \quad (3)$$

correlation reliability R^2=0.8868.

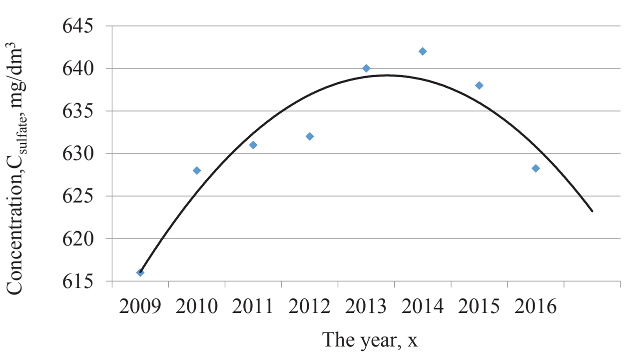

Fig. 4. The results of mathematical modeling of the sulfates concentration dynamics: ■ — experimental leachate research data; solid line — approximation results

To investigate the changes in concentrations of chlorides, total iron, COD and BOD_5, the 4th-degree polynomial approximation of their number was performed, and the polynomial coefficients that approximate the experimental data were determined.

The results of approximation revealed the regression equation that describes the dynamics of the quantitative composition of chlorides (4) and the approximating curve that has the form of the 4th-degree parabola (Fig. 5).

$$C_{chl}=1.7363x^4-30.373x^3+168.06x^2-308.61x+8250.8, \quad (4)$$

correlation reliability R^2=0.8846.

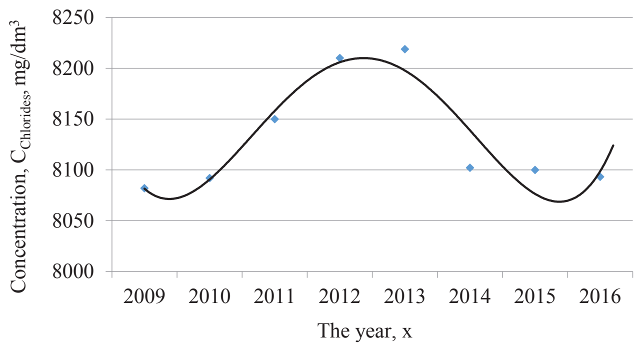

Fig. 5. The results of mathematical modeling of the chlorides concentration dynamics: ■ — experimental leachate research data; solid line — approximation results

The results of approximation of the COD concentration dynamics revealed that the polynomial has the form of the 4th degree parabola and is described by the equation:

$$C_{COD}=0.585x^4-4711.3x^3+1\cdot10^7x^2-2\cdot10^{10}x+1\cdot10^{13}, \quad (5)$$

correlation reliability R^2=0.9309.

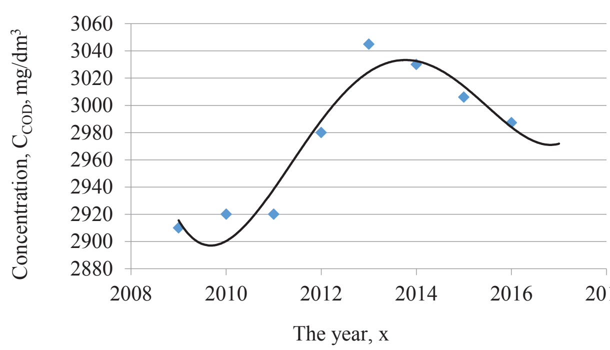

Fig. 6. The results of mathematical modeling of the COD concentration dynamics: ■ — experimental leachate research data; solid line — approximation results

The results of approximation of the total iron concentration dynamics revealed that the polynomial has the form of a growing curve (Fig. 7) and is described by the equation (6):

$$C_{total\ Fe}=0.0015x^4-0.03x^3+0.2125x^2-0.594x+2.4058, \quad (6)$$

correlation reliability R^2=0.8661.

To investigate the changes in concentrations of ammonia nitrogen and BOD_5, approximation of their number by linear dependence was performed (Fig. 8, 9). The function (7) describes the general behavior of the concentrations of these substances.

$$C_i=kx+b, \quad (7)$$

where C_i – the concentration of the ith chemical, k – the parameter (proportionality factor) depends on the concentration of the studied substance and is determined according to field observations, b – time-dependent proportionality factor.

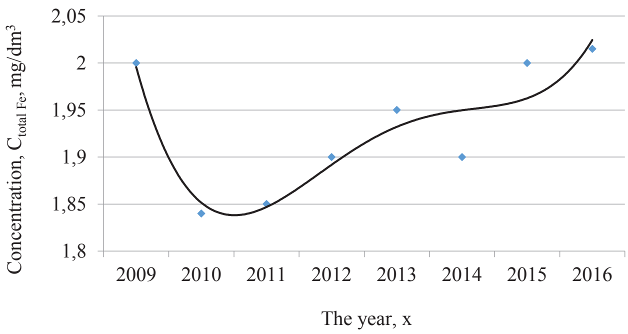

Fig. 7. The results of mathematical modeling of the total iron concentration dynamics: ■ — experimental leachate research data; solid line — approximation results

Thus, the results of the research and mathematical modeling of the BOD_5 concentration dynamics revealed that the amount of oxygen (mg/dm³), which was spent for a specified period of time for oxidation of the reservoir pollutants, contained in 1 liter of water at 20 °C has the form of linear dependence (Fig. 8) and is described by the equation (8):

$$C_{BOD5}=6.0324x+978.86, \quad (8)$$

correlation reliability R^2=0.8717.

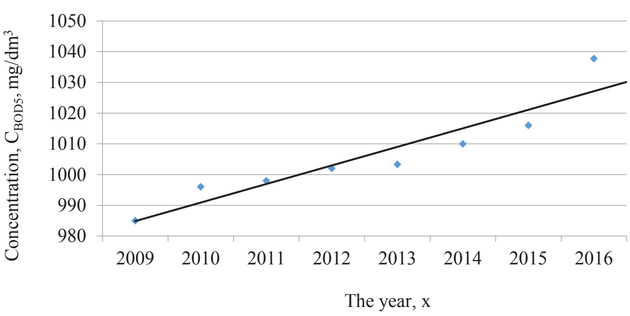

Fig. 8. The results of mathematical modeling of the BOD_5 concentration dynamics: ■ — experimental leachate research data; solid line — approximation results

The results of the research and mathematical modeling of the ammonia nitrogen concentration dynamics revealed that the dynamics of this indicator over the analyzed years has the form of a straight line and is described by the equation (11):

$$C_{amonia\ N}=0.9676x+322.14, \quad (9)$$

reliability coefficient R^2 = 0.9531.

All the mathematical models and the results of approximation well represent the dynamics and trends in hydrochemical parameters of leachate from the MSW landfill in the city of Zhytomyr (Ukraine) for 2009–2016. Modeling of the processes that characterize trends in hydrochemical indicators over the analyzed period, determining the patterns of changes in the concentrations of chemicals allow making predictions about the future use of the local MSW landfill and assessing its impact on surface and ground water. Also, the research makes it possible to promptly develop and implement measures aimed at minimizing the harmful effects of MSW landfills on the hydrosphere.

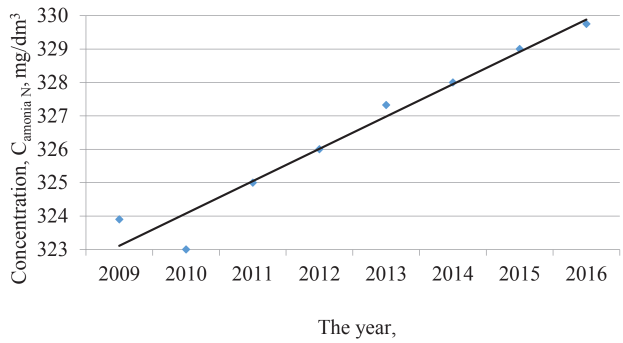

Fig. 9. The results of mathematical modeling of the ammonia nitrogen concentration dynamics: ■ — experimental leachate research data; solid line — approximation results

6. Discussion of the results of the research on the impact of MSW landfill leachate on water bodies

The main advantage and practical importance of the research is the possibility of using the results in the design of new MSW landfills, improvement of existing landfills and increasing the environmental security of Ukraine on this basis. The paper presents the results of the research that is a continuation of the authors' research in previous years [12, 13]. The leachate from MSW landfills is one factor that causes pollution of reservoirs for household purposes, promotes excessive phytoplankton development and affects drinking water quality.

The analysis of the leachate composition indicates the presence of a wide variety of chemical elements and their concentrations in the leachate. Data on the hydrochemical composition of leachate is the determining factor in selecting the treatment technique. For example, it may be physical and chemical, biological treatment or a combination thereof. Also, membrane treatment is becoming more common.

The priority is to reduce the amount and toxicity of leachate, increase the leachate processability by changing the ultimate morphological composition of waste in landfills. This requires intensifying public outreach activities, ensuring effective waste sorting and extraction of valuable components at early stages of formation, receiving thus considerable profit and protecting the environment from negative impacts, since legal framework governs effective waste management.

The research results the can be used as a basis for constructing a general mathematical model of the landfill leachate formation, considering weather and geographical conditions of the landfill area, specific features of water balance.

Future research may be aimed at acquiring data on the leachate composition over a longer period of time and determining the relationship between the characteristics of the waste coming to the landfill and indicators of environmental pollution.

7. Conclusions

1. It was found that the negative impact of MSW landfills on water resources is a worldwide problem. Herewith,

many researchers consider the geochemical composition of leachate from those landfills, analyze the impact of individual elements on the environment and the factors that influence the leachate composition. However, the development of specific recommendations on preventive measures and environmental protection methods greatly depends on the location of each of the landfills and local hydrogeological and meteorological conditions, as well as the composition of MSW coming to landfills in Ukraine. Therefore, the development of effective measures that will improve the environmental safety of Ukraine requires the analysis and mathematical modeling of the dynamics of the properties of leachate from MSW landfills in the city of Zhytomyr.

2. To address these pressing problems, data on the hydrochemical composition of leachate from MSW landfill for the period 2009–2016 were collected. The analysis of the leachate revealed the component percentage. It was found that chemicals such as phosphates, iron, cobalt, cadmium, lead, COD and BOD, alkalinity and hardness indicators of solid waste in Zhytomyr MSW landfill exceed the maximum permissible concentrations.

3. The experimental data were obtained, and their features, summarized in the form of linear and nonlinear statistical mathematical models of the processes of changes in the quantitative composition of chemical characteristics of the leachate samples of the sumps were identified. These models are the basis for forecasting the pollution processes of percolating water of Zhytomyr MSW landfill, development and implementation of practical measures aimed at minimizing the impact of MSW landfills on water resources.

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