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SPATIAL PATTERNS OF THE FORMATION OF DRINKING WATER QUALITY WITHIN THE ODESA URBAN SYSTEM

Breus D. S. *– PhD in agriculture,*
Associate Professor at the Department of Ecology and Sustainable Development named by prof. Yu.V. Pylypenko,
Kherson State Agrarian and Economic University
breusd87@gmail.com

The article is devoted to the study of spatial patterns of the formation of drinking water quality within the Odesa urban system. The analysis was carried out taking into account the interaction of natural, anthropogenic and technogenic factors that affect the state of the water supply system, pump stations and water intake sources. It was found that the key factors of water quality deterioration are local sources of pollution, such as unauthorized discharges, deterioration of communications, proximity to sources of salt water, high level of urbanization, etc. The study focuses on the territorial differentiation of water quality, in particular the level of technical condition of water supply networks and hydrological features of the area. The aim of the article is to determine the quality of drinking water in water supply system and pump stations of the city of Odessa, as well as to model the spatial distribution of the main macrocomponents in water and its toxic pollution on the territory of the urban system of the city. For this purpose, the content of the main chemical elements in drinking water sampled at control points located throughout the city was determined. The samples were examined using portable testers with ion-selective electrodes. An experimental study was also conducted to determine the general toxicity of drinking water using the method of dividing water samples into toxicity classes based on the experiment with onion (*Allium Cepa L.*). The obtained data were interpreted using the ArcGIS program and spatial models of the patterns of formation of drinking water quality within the Odessa urban system were created. It was established that the content of the main macrocomponents in the drinking water of Odessa does not exceed the maximum permissible concentrations (MPC) established by the Ukrainian (State Sanitary Norms and Rules 2.2.4-171-10) standard for the quality of surface water intended for drinking needs. It was established that the general toxicity of drinking water in the city is mainly of medium and high levels. The obtained data have applied value for the formation of strategies for sustainable water use, optimization of water supply systems and minimization of environmental risks for the population of Odessa.

Keywords: urban system, water quality, GIS-technologies, general toxicity, spatial distribution, macrocomponents.

Statement of the task. The aim of an article is to study and to analyze the spatial heterogeneity of distribution of main macrocomponents in drinking water of Odesa and to determine the level of its toxic pollution using GIS technologies.

Analysis of recent research and publications. In present almost all large cities experience water shortages. Water consumption here is 10 times higher than in rural areas, in addition, water in cities is of worse quality, and sometimes does not meet sanitary standards, due to the lack of appropriate technologies, equipment and funds. Water is a fundamental natural resource that sustains life, ecosystems and human society. Thus, the study of the qualitative composition and toxic pollution of drinking water in the water supply systems of large cities is an important issue for the sustainable development of urbanized systems (Pichura et al., 2020). Article 4 of the Law of Ukraine "On Ensuring Sanitary and Epidemic Welfare of the Population" states that citizens have the right to drinking water that is safe for health and life.

According to article 7 of the Law of Ukraine "On drinking water and drinking water supply", the state guarantees the protection of the rights of consumers in the field of drinking water and drinking water supply by providing every person with drinking water of normative quality within the limits of scientifically based norms of drinking water supply depending on the district and living conditions and by implementing measures of organizational, scientific-technical, sanitary-epidemiological, environmental, economic and legal nature regarding the improvement of the quality of drinking water, the development of drinking water supply, the protection of sources and drinking water supply systems (Pichura et al., 2023).

Odesa is one of the major consumers of water resources in Ukraine. Here the drinking water comes from city's centralized water supply system. Its length from the source – the Dniester River, to the city is 350 km. The river flows through the territories of Ukraine and Moldova, where there are many large industrial and economic enterprises that discharge large quantities of wastewater into the river. Pump stations – is the water pumps, which are located in all districts of the city, and where people can take drinking water free of charge, is also play a significant role in the city's drinking water supply. There are 16 pumping stations in Odesa, and they have different aquifers – from 120 to 350 meters. All pumps are maintained by the utility company, according to the calculations of which, an average of 45,000 Odesa residents use the services of pumping stations every day. Water consumption on one pump is 18-20 m^3 per day (Kutishchev et al., 2021).

In recent years, relevant bodies register a non-compliance of the quality of drinking water of the Dniester River with the requirements of the State Standard of Ukraine 4808:2007 "Sources of centralized drinking water supply.

Hygienic and ecological requirements for water quality and sampling rules" as for the source of drinking water supply (according to bacteriological and chemical indicators), mainly because of the discharges of wastewater upstream the water intake. Total mineralization, hardness, and chloride content increased. Bacteriological indicators in the area of the water intake, exceeds the permissible values by ten times. These changes are especially acute in winter, when the river is covered with ice, and in summer due to intense evaporation processes and low water level, which reduces its ability to self-clean (Pichura et al., 2018).

Water purification and water preparation of Dniester water for its further use for drinking purposes is carried out at the "Dniester" water station, built in 1873 in the village Bilyaivka which is 33 km from Odesa. The average daily drinking water supply today is about 700.000 m^3/day. Drinking water is supplied to Odesa (75 %) and to about 50 settlements of the region, including the cities Pivdennyi, Bilhorod-Dnistrovskyi, Illichivsk, Bilyaivka, and Ovidiopil. The number of water consumers is over a million people. The main consumers of water are the households (69 %), state enterprises (15.9 %), private enterprises (15.1 %).

The "Dniester" station carries out lighting, decolorization and disinfection of water. After that the water flows through water pipes to the city. The distribution network of the city (1,293 km long) consists of 45 % of cast iron pipes, 26 % of steel pipes, and 29 % plastic pipes. The main number of water pipes with a significantly exceeded service life. The accident rate on the pipelines is extrimly high, this leads to water losses, interruptions in normal water supply to consumers, an increase in labor costs associated with repair and reconstruction works, and most importantly, contributes to the worsening of the epidemic situation in the city. The long-term transportation of water through main water pipes and the unsatisfactory technical condition of the distribution network creates favorable conditions for the development and accumulation of microflora, the formation of biological fouling and sediments which lead to the increasing of general toxicity of water. This is also facilitated by the presence of organic substances and biogenic elements in water, that are the substrate for microflora (Fatma et al., 2018).

As a result of the vital activity and death of microorganisms, the quality of drinking water deteriorates: unpleasant odor appears, turbidity and color are increasing and sanitary and biological indicators are decreasing. According to all stated above the control under the quality of drinking water is the major question of the sustainable development of the society which has a great influence on health of the population (Pichura et al., 2022).

Materials and methods. To study the content of the main macro-components present in the water, samples were taken at control points located throughout the city (Figure 1). Samples were taken both from the centralized water supply system (6 control points) and from the pump stations used by the population for drinking needs (16 control points).

Fig. 1. **Control points of water sampling**

The hardness of water is one of the most important quality indicators, it negatively affects human health and has a detrimental effect on pipelines, leading to the formation of scale (Boiko et al., 2018). This indicator depends on the presence of soluble and sparingly soluble mineral salts, mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}).

The water sampling was carried out in February 2024. Analysis of samples of Odesa drinking water was conducted using Horiba LAQUAtwin portable testers with ion-selective electrodes. Within the study the following parameters were measured: cations (Na^{+}, K^{+}, Ca^{2+}), nitrogen compound (NO_3^{-}), salt (NaCl), electro conductivity (Cond), pH and hardness of water. Resulting the tests performed, cartographic material of spatial heterogeneity of studied elements' distribution in water was designed (Breus et al., 2022). The maximum permissible concentrations of studied elements in drinking water according to State sanitary and chemical standards are presented in Table 1.

Table 1. **Sanitary and chemical indicators of safety and quality of drinking water (MPC)**

Name of indicator	Standards for drinking water according to State Sanitary Norms and Rules 2.2.4-171-10	
	Water supply system	Pump stations
Na^+, mg/dm^3	≤200	≤200
K^+, mg/dm^3	2 – 20	2 – 20
Ca^{2+}, mg/dm^3	≤130	25 – 75
NO_3^-, mg/dm^3	≤50	≤10
NaCl, g/dm^3	0.1 – 0.6	0.1 – 0.6
Cond, µS/cm	<800	<1500
pH	6.5 – 8.5	6.5 – 8.5

The measurement of water hardness has different standards; the correspondence of units is presented in Table 2.

Table 2. **Correspondence of water hardness units**

Hardness, mg-eq/dm^3	Calcium hardness, mg [Ca^{2+}]	Hardness, °dH	Hardness, °FH
1	20.04	2.8	5
2	40.08	5.6	10
4	80.16	11.2	20
6	120.24	16.8	30
8	160.32	22.4	40

The division of water on types according to German degrees of hardness is presented in Table 3.

Table 3. **Typification of drinking water according its hardness**

Water type	Hardness, °dH
Soft	0 – 3.37
Moderately hard	3.38 – 6.74
Hard	6.75 – 10.11
Very hard	≥10.12

To determine the general toxicity of the samples of drinking water, a generally accepted test method on onion (*Allium Cepa* L.) was used (Fiskesjo, 2023). For this purpose, bulbs of different sizes (n=200) were kept in a dry place in transparent glass containers (0.5 dm^3) under temperature stimulation (20 ±2.5 °C) and natural light until the leaves grew, during 14 days. Bulbs with leaves 3 ±0.5 cm long were selected from them to form three experimental groups depending on size (d=40, 50, 60 cm). Bulbs (n=30) of each group were grown in water sampled from each test point (Tkachuk et al., 2022). Bottled purified water

"Morshinska" was used as a control. Directly before biotesting, leaves that had grown were cut to the base of the bulbs, as well as individual dry roots, young roots did not appear on the onions during leaf germination.

Germination period was 144 hours (6 days). The data collected on the fourth day was considered for the experiment; further period was not taken into account, as starting from the fifth day the length of roots and leaves and their quantity of the studied onions started to level off in almost all variants of the experiment. The length and number of roots and leaves of each bulb were measured every 24 hours. Data were entered into a table for further processing using software ArcGIS Pro (Breus et al., 2023).

During the study phytotoxic effect of solutions was calculated according to an effect of the water on the growth ability of roots and leaves (Calvelo et al., 2010):

$$PE_{(r,\ l)} = ((L_c - L_t) \times 100\%) / L_c, \quad (1)$$

where $PE_{(r,\ l)}$ – phytotoxic effect of solutions on roots and leaves respectively;
L_t – the average value of the indicator in test variant;
L_c – the average value of the indicator in control variant.

According to the obtained data, the average value of the toxicity index for each variant of tested water was calculated according to the formula:

$$TI = (PE_{(1)} + PE_{(2)} + PE_{(i)}) / n, \quad (2)$$

where TI – toxicity index for each variant of water,
$PE_{(1,2,i)}$ – phytotoxic effect calculated for each test function (length, number),
n – number of test responses involved for the water variant.

Based on obtained data resulting map with levels of toxic pollution of drinking water and its distribution throughout the city was built. The level of contamination of drinking water with toxicants is classified into 5 levels, which are presented in Table 4.

Table 4. **Classification of the level of toxicity of drinking water**

Water class	Value
Low toxicity	0 – 20.0
Weak toxicity	20.1 – 40.0
Average toxicity	40.1 – 60.0
High toxicity	60.1 – 80.0
Maximum toxicity	80.1– 100

Built-in ArcGIS Pro software tools were used for mapping and geostatistical processing of the data obtained during the experiment. For the prediction of spatial distribution of the main macrocompanents in sampled water Kernel Interpolation with Barriers was used, this is a predictor that allows supplying feature barriers.

The distance between two locations is defined as the shortest sequence of straight lines that connect the two locations but do not cross a barrier. To build the resulting map of toxic pollution the deterministic interpolator "Radial Basis Function" with multiquadric kernel function was used (Skok et al., 2023).

Result and discussion. Conducted research of selected samples of drinking water in Odesa showed compliance of the water with sanitary and chemical indicators of safety and quality of drinking water, i.e. maximum permissible concentrations of elements for almost all studied indicators. The results of the tests are presented in Table 5.

Table 5. **Indicators of drinking water quality in Odesa**

Point	Na^+, mg/dm^3	K^+, mg/dm^3	NO_3^-, mg/dm^{3-}	Ca^{2+}, mg/dm^3	Hardness, mg-eq/dm^3	pH	Cond, µS/cm	NaCl, g/dm^3
Pump stations								
1	110	4	24	41	2	7.6	1020	0.5
2	170	5	24	50	2	6.5	1200	0.6
3	25	4	15	100	5	7.5	520	0.3
4	70	3	14	12	1	7.5	440	0.2
5	130	4	22	25	1	7.5	810	0.4
6	24	2	9	21	1	6.4	290	0.2
7	76	3	14	12	1	7.6	475	0.2
8	91	3	16	24	1	6.7	540	0.3
9	98	3	17	21	1	6.8	630	0.3
10	100	3	18	27	1	7.0	650	0.3
11	110	3	17	16	1	6.6	635	0.3
12	150	4	22	47	2	7.4	985	0.5
13	200	5	22	23	1	7.8	1080	0.5
14	150	4	21	18	1	7.5	860	0.5
15	180	5	24	120	6	7.5	1400	0.7
16	75	4	15	50	2	6.5	520	0.3
Water supply system								
1	23	4	14	89	4	7.7	550	0.3
2	27	4	15	91	5	6.9	520	0.3
3	30	4	15	110	5	7.5	520	0.3
4	39	4	14	96	5	7,6	540	0.3
5	23	4	15	99	5	7.5	530	0.4
6	25	4	15	100	5	6.3	550	0.3
Control	25	2	12	37	2	7.1	212	0.1

Analyzing the table with data on the quality of drinking water, it is clear that according to the indicators Na^+ and K^+ there is no excess of the maximum permissible concentration in accordance with the State Sanitary Norms and Rules 2.2.4-171-10. Figure 2 presents the spatial models of distribution of these two macroelements within the territory of Odesa.

On the other hand, according to the indicator of the nitrate content in the water sampled from the pump stations, there is a two-fold excess of the maximum permissible concentrations at almost all sampling points. Most recent studies shows that when analyzing water for nitrates, their level is often higher in water from wells. This explained by the fact that nitrates enter the aquifer with the runoff of fertilizers from agricultural lands, and water that comes from wells directly from natural sources is not additionally purified, like water in the city's water supply system. The content of nitrates in the water sampled from water supply system is within the permissible limits which apply for drinking needs water.

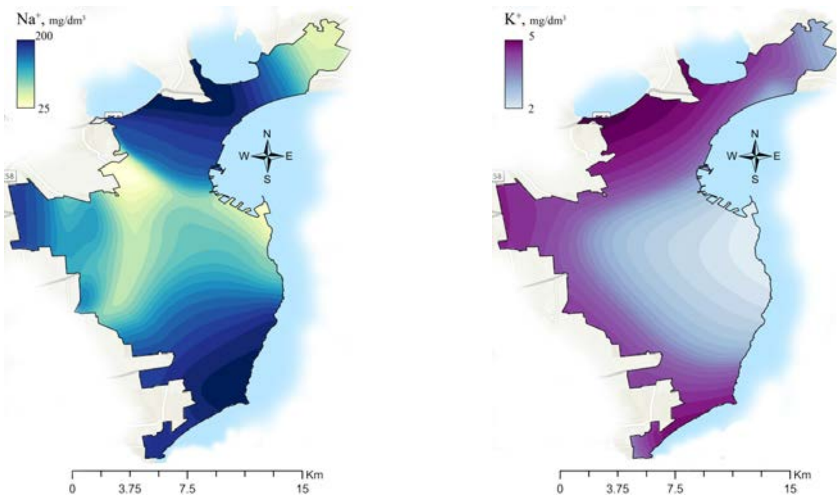


Fig. 2. **Spatial models of Na^+ and K^+ distribution in drinking water, mg/l**

The calcium content in the city's water supply system does not exceed the MPC. The limit concentration of this element according to norms and rules is set at the level of 130 mg/dm^3. But its content in water is significantly high, which is explained by calcium deposits on the inner walls of the pipes, which depends on exceeding of the service life of most of the city's water supply system.

In the samples of water taken from pump stations, there was an excess of the established norms in only two variants, these pumps are located on Starokinny Market and on Lymanska Street, the last one is located in close proximity to two estuaries, Kuyalnytskyi and Khadzhibeyskyi, this leads to the possibility of estuary water get into the aquifer from which pumping station taking the water. The spatial distribution of NO_3^- and Ca^{2+} are presented on Figure 3.

The calcium content in water directly affects its hardness. According the tables of correspondence of different units of water hardness and of classification of drinking water according its hardness most of water samples taken from pump stations are assigned to "soft" and "moderately hard" type of water, and only two samples showed “very hard” type of water.

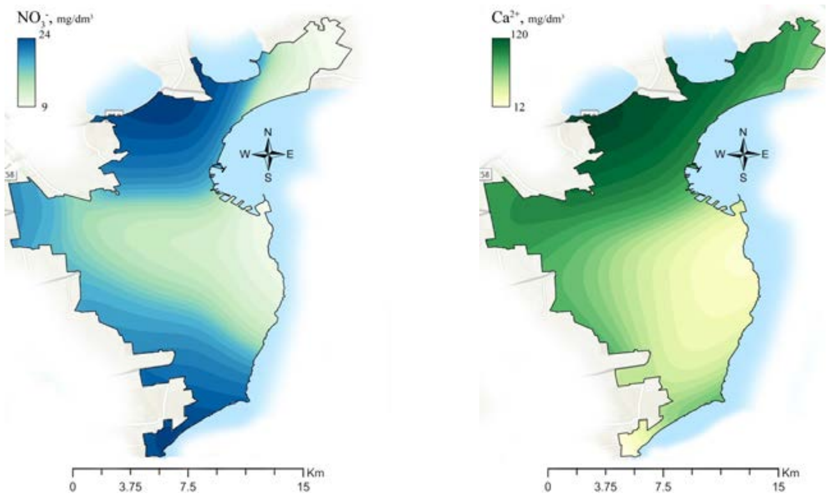


Fig. 3. **Spatial models of NO_3^- and Ca^{2+} distribution in drinking water, mg/l**

Analyzing the table with data on water hardness it is clear that all samples of water taken from supply system has “very hard” type. The reasons of this are an old system of water supply and poor equipment of water purification. The spatial models of the water hardness and characteristics of water pH within the territory of the city is presented on Figure 4.

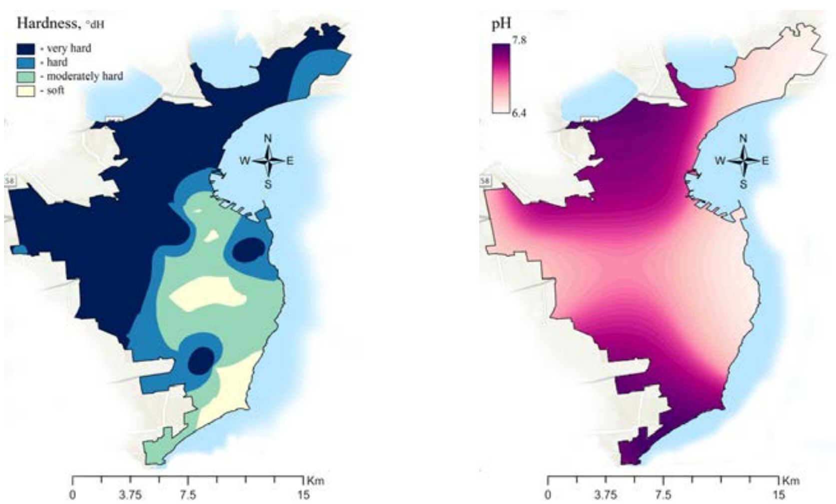
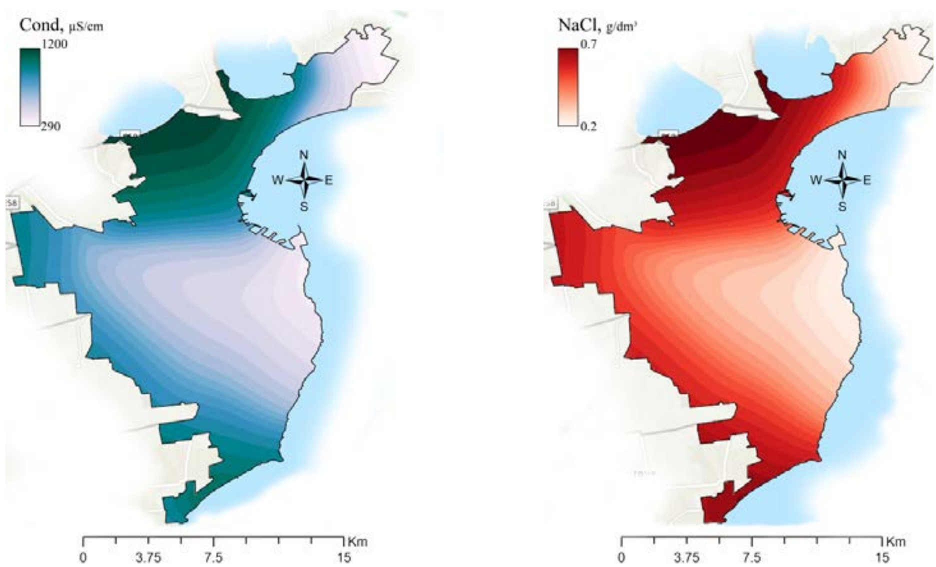


Fig. 4. **Spatial model of hardness of drinking water in Odesa, dH**

Water best meets the body's needs and blood pH. Blood pH norms shows that its value should range from 7.35 to 7.45, ideally the acidity of the water consumed by a person every day should be the same. As it can be seeing from the model the pH of the sampled water varies from 6.4 to 7.8. This result is within the standards established for drinking water. That is, all the water that was selected for analysis is neutral according to this indicator.

Electrical conductivity (EC) is a measurement of water's ability to conduct electricity, because dissolved salts and other inorganic chemicals conduct electricity, conductivity increases with increasing salinity. That is why these two parameters are depending on each other. According to the standards for drinking water (State Sanitary Norms and Rules 2.2.4-171-10), the water sampled both from water supply system and pump stations corresponds to the maximum permissible concentrations in drinking water. Models of spatial distribution of salt content in water and its conductivity are presented on Figure 5.



a b

Fig. 5. **Spatial models of Conductivity, µS/cm (a) and Salt content, mg/l (b)**

Analyzing models on Figure 5 the dependence between these two parameters is visually followed. Two points of water sampling from pump station has an increased concentration of salt and as a result the increased conductivity. In first case the reason of higher content of salt depends on close location of pump station to estuaries, the same as in variant with calcium content. In second case the higher level of NaCl depends on the depth of the aquifer because this pump station has the deepest well in Odesa. Considering this fact and taking to account the geology of groundwater in the South of Ukraine it is concluded that the water for this pump station is going from Black Sea artesian basin. In the vertical section of this basin, the upper horizons of groundwater up to a depth of 100-300 m are fresh, and the deeper horizons have brackish or salt water.

The general toxicity of water sampled in the water supply system and pumping stations of Odesa was conducted on the basis of the method based on the growth properties of onion roots and leaves in water samples. The obtained results of the experiments are presented in Table 6.

Table 6. **The results of toxicological testing of drinking water**

Point	Average roots length, cm (96 hr)			Roots quantity, n (96 hr)			Average leaves length, cm (96 hr)			Leaves quantity, n (96 hr)			TI
	d=40	d=50	d=60	d=40	d=50	d=60	d=40	d=50	d=60	d=40	d=50	d=60	
Pump stations													
1	2,4	2,9	0,5	12	2	1	2,1	-	-	7	-	-	68
2	3,2	4,3	5,0	30	11	20	8,0	-	2,5	6	-	3	10
3	4,3	2,2	-	30	3	-	-	-	-	-	-	-	79
4	4,5	3,8	4,8	10	2	4	4,1	-	-	6	-	-	48
5	4,5	-	4,1	5	-	25	-	-	-	-	-	-	74
6	2,5	2,6	2,2	21	10	18	4,0	-	-	5	-	-	51
7	4,5	-	2,2	5	-	1	0,5	-	-	1	-	-	83
8	5,3	1,6	1,6	1	4	2	-	-	-	-	-	-	83
9	5,9	5,0	0,9	1	8	3	5,3	-	-	7	-	-	50
10	2,3	6,2	3,3	1	30	13	4,6	-	-	5	-	-	43
11	4,3	-	-	17	-	-	9,0	-	-	7	-	-	63
12	6,1	3,5	-	30	14	-	6,7	-	-	9	-	-	46
13	4,5	-	-	11	-	-	2,9	-	-	5	-	-	72
14	5,5	4,6	1,6	16	16	4	7,3	-	3,7	3	-	7	25
15	4.3	-	-	10	-	-	2.5	-	-	6	-	-	69
16	2,5	6,5	3,5	1	30	15	5	-	-	6	-	-	35
Water supply system													
1	6,1	-	4,0	30	-	15	0,4	-	-	2	-	-	63
2	4,7	4,1	1,0	30	30	1	-	0.7	-	-	1	-	65
3	5,0	3,6	1,3	18	30	2	5,3	-	-	9	-	-	43
4	2,8	2,7	4,1	4	5	8	1,0	-	-	2	-	-	70
5	-	5,0	5,9	-	30	30	-	-	-	-	-	-	60
6	4.3	-	-	10	-	-	2.5	-	-	4	-	-	74
Contr.	4.9	4.5	4.2	30	30	24	5.0	1.0	3.0	6	2	3	-

During the onion germination experiment, in all variants of the selected water samples, a regularity of suppressed growth of the root system in larger bulbs was observed. In variants with bulbs of a diameter 50 and 60 millimeters a complete absence of leaves was observed, with the exception of some variants of the test.

As a resulting of the experiment, development of the root system during germination was conditionally divided into three groups: well-developed, poorly developed and underdeveloped. Examples of formed roots are presented in Figure 6. To calculate the toxicity index the number and average length of roots and leaves were taken into account, the third group was not counted.

a) b) c)

Fig. 6. **Examples of the development of root system: *a* – well-developed; *b* – poorly developed; c – underdeveloped**

The spatial model of the distribution of toxic pollution of drinking water in Odessa was built on the basis of the calculated toxicity index. The results are presented on Figure 7.

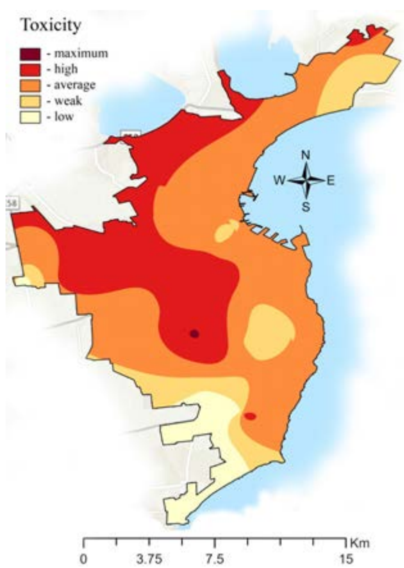


Fig. 7. **Spatial distribution of toxic pollution of drinking water**

The analysis of the obtained model shows that on the most cities' territory drinking water from the water supply system and pump stations belongs to the high and average class of toxic pollution.

Conclusions. As a result of spatial modeling of the formation of the drinking water quality in Odesa it was determined that the indicators of the content of the main macroelements in water which is going from water supply system are within the range of maximum permissible concentrations. Only the calcium content can cause concern, because without timely renewal of the pipes of the city's water supply system, in the future this indicator may significantly exceed regulatory standards.

The NO_3^- concentration in waters supplied by pumping stations of the city is within 15-24 mg/dm^3 while the permissible concentration of nitrate in ground waters for drinking purposes according the Ukrainian standard State Sanitary Norms and Rules 2.2.4-171-10 is on the level of 10 mg/dm^3.

In terms of electrical conductivity and mineralization, the water that was taken from the pumping stations in most cases does not exceed the established limit values – 1500 µS/cm and 0.6 g/l, respectively. The worst according to these indicators was the water sampled from the pump located on the border of two estuaries (1400 µS/cm and 0.7 g/l). Water from the city water supply system according to these two indicators was within the range of 520-550 µS/cm and 0.3 – 0.4 g/dm^3, which is the average value of the standards for drinking water (800 µS/cm and 0.1 – 0.6 g/dm^3 respectively).

The last stage of the research was to determine the level of general water toxicity in the city. Analyzing the obtained data, it was concluded that the water sampled in most of the studied area has a toxicity index from 40 to 60, which corresponds to average toxic pollution. Also, a significant area of the city has this indicator at the level of 60-80, which is a high level of toxic pollution.

ПРОСТОРОВІ ЗАКОНОМІРНОСТІ ФОРМУВАННЯ ЯКОСТІ ПИТНОЇ ВОДИ В МЕЖАХ УРБОСИСТЕМИ МІСТА ОДЕСА

Бреус Д. С. *– к.с.-г.н., доцент кафедри екології та сталого розвитку імені професора Ю.В. Пилипенка,*
Херсонський державний аграрно-економічний університет
breusd87@gmail.com

Стаття присвячена дослідженню просторових закономірностей формування якості питної води в межах урбанізованої системи міста Одеса. Аналіз проводився з урахуванням взаємодії природних, антропогенних та техногенних чинників, що впливають на стан водопровідної мережі, бюветних комплексів та джерел водозабору. Виявлено, що ключовими факторами погіршення якості води є локальні джерела забруднення, такі як несанкціоновані скиди, зношеність комунікацій, близькість до джерел соленої води, високий рівень урбанізації та інше. Дослідження акцентує увагу на територіальній диференціації якості води, зокрема рівня технічного стану водопровідних мереж та гідрологічних особливостей місцевості. Метою статті є визначення якості питної води в системах водопостачання та насосних станцій м. Одеси, а також моделювання просторового розподілу основних макрокомпонентів хімічного складу води та її токсичного забруднення на території урбосистеми міста. Для цього було проведено визначення вмісту основних хімічних елементів у питній воді, відібраній на контрольних пунктах, розташованих по всьому місту. Зразки досліджували за допомогою портативних тестерів з іоноселективними електродами. Також було проведено експериментальне дослідження з визначення загальної токсичності питної води за методикою розподілу проб води на класи токсичності на основі досліду з цибулею (*Allium Cepa L.*). Отримані дані були інтерпретовані з використанням програми ArcGIS та створено просторові моделі закономірностей формування якості питної води в межах урбосистеми Одеси. Встановлено, що вміст основних макрокомпонентів у питній воді м. Одеси не перевищує гранично допустимих концентрацій (ГДК), встановлених українським (Державні санітарні норми і правила 2.2.4-171-10) стандартом якості поверхневих вод, призначених для питних потреб. Встановлено, що загальна токсичність питної води на території міста переважно середнього та високого рівнів. Одержані дані мають прикладне значення для формування стратегій сталого водокористування, оптимізації систем водопостачання та мінімізації екологічних ризиків для населення Одеси.

Ключові слова: урбосистема, якість води, ГІС-технології, загальна токсичність, просторовий розподіл, макрокомпоненти.

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