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GIS-BASED ASSESSMENT OF RISK FOR DRINKING WATER CONTAMINATION TO CHILDREN'S HEALTH IN RURAL SETTLEMENTS

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Abstract

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Nitrates and heavy metals are two of the most significant groundwater pollutants that have an impact on people's health all around the world. In order to assess their risk to children's health, this study aims to determine the total iron, manganese, and nitrate content in drinking water sources of non-centralized water supply of the educational institutions in the rural settlements of Zhytomyr region. A total of 114 water samples from wells and bores used by the educational institutions to supply domestic and drinking water to rural residential areas were collected. The Measurement Laboratory of Polissia National University conducted analytical studies. The danger to children's health was evaluated using the hazard quotient and following the methodology recommended by the US Environmental Protection Agency. The software ArcGIS Pro was used to identify risk zones.
The average total iron content in the drinking water of the Berdichev, Zhytomyr, and Novohrad-Volinsky districts was 1.5–2.8 times higher. In all regions, the average manganese concentration did not go above the allowable level. On average, the nitrate content was also below the threshold, but in 22.6–42.9% of the samples, it exceeded the allowable level. Children aged 6–12 years were at the highest risk, and children living in Berdichev district had the highest hazard quotient at 1.972. The fact that nitrates accounted for 67–84% of the total risk indicates the danger associated with the intake of nitrates, even in amounts below the allowable concentration.

Key words: drinking water, children, risk, nitrates, total iron, manganese, hazard quotient, GIS.

Introduction

Groundwater is a valuable natural resource, as it is a significant source of fresh water, and for the majority of rural residential areas, it is the primary source of drinking water supply and irrigation of agricultural crops (Bujnovský, 2018). Although the quality of groundwater is typically better than that of surface water, it is nonetheless affected by a variety of anthropogenic and natural processes, including pollution from urbanization, industry, agriculture, sanitation, waste, and so on.

For rural residential areas, heavy metal and nitrate contamination of drinking water coming from noncentralized water supply sources is a problem. Since the health of the population depends on the quality of the water, it is becoming more and more relevant to examine the risks to human health posed by the continual intake of poor-quality water. Numerous Ukrainian studies currently discuss the assessment of drinking water quality from noncentralized water supply sources and its effects on public health (Herasymchuk et al., 2022; Romanchuk et al., 2021; Huschuk et al., 2018; Lototska, Prokopov, 2018, etc.). Foreign scientists from many countries of the world also have investigated this issue, particularly in India (Giri, Singh, 2015; Karunanidhi et al., 2021), Bangladesh (Ghosh et al., 2020), Iran (Parvizishad et al., 2017; Qasemi et al., 2018; Aghapour et al., 2021), China (Yu et al., 2020), Indonesia (Sadler et al., 2016), Pakistan (Khalid et al., 2018), the USA (Wheeler et al., 2015; Rogan et al., 2009), Spain (Zufiaurre et al., 2020), Kenya (Nyambura et al., 2020), Bulgaria (Vladeva et al., 2000), Romania (Moldovan et al., 2020), and others, including the use of geographic information system (GIS) technologies (Ni et al., 2009; Shalyari et al., 2019). However, in our opinion, not enough consideration has been given to the assessment of the health risk to children living in rural residential areas, who are the most susceptible group to the impacts of contaminants that can infiltrate drinking water and food products (Ford et al., 2017), particularly in Zhytomyr region (Valerko et al., 2021).

Among the wide range of groundwater pollutants, heavy metal contamination is of serious concern. Most heavy metals are toxic to human health, especially when their concentrations exceed the standards and accumulate over a long period of time (Maksimović et al., 2019). The most common heavy metals that can harm people even at low concentrations are iron and manganese. Dangerous conditions like Parkinson's disease, Huntington's disease, Alzheimer's disease, cardiovascular diseases, hyperkeratosis, diabetes, pigmentation changes, kidney diseases, liver diseases, respiratory diseases, and neurological disorders can all be caused by an excess

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Table 1. Standard exposure factors, (US EPA, 2012).

Exposure factors	Segments of population			
	Infants, up to 2 years of age	Children, aged 2–6	Teenagers, aged 6–16	Adults, aged 16–18
Drinking water intake, dm^3/day	0.08	0.85	2	2.5
Body weight, kg	10	15	50	70
Threshold (reference) dose, mg/kg × day (nitrates)	1.6			
Threshold (reference) dose, mg/kg × day (iron)	0.3			
Threshold (reference) dose, mg/kg × day (manganese)	0.14			

Note: US EPA – US Environmental Protection Agency.

of iron and manganese in drinking water (Powers et al., 2003; Kell, 2010; Farina et al., 2013). Manganese is the most significant water contaminant (Giri et al., 2015). Its presence in drinking water has been linked to neurotoxicity (Merrill et al., 2011) and gastrointestinal issues. Drinking water with increased iron content can cause dysfunction in many organs (Heming et al., 2011).

Due to farming practices and the disregard for sanitary rules within private households, nitrates are one of the most prevalent pollutants of drinking water, particularly in rural areas. High nitrate exposure can result in methemoglobinemia in infants and cancer in adults (Deepanjau, Navindu, 2000). Constant consumption of excessive amounts of nitrates results in respiratory tract infections and changes in the immune system (Sadler et al., 2016), goiter in children (Vladeva et al., 2000), and congenital defects of the central nervous system (Ward et al., 2018). It has been proven that there is a strong link between nitrates in drinking water and colorectal cancer in men. The carcinogenic risk to humans depends on the nitrate concentration and increases significantly when the nitrate content in drinking water exceeds 3.87 mg/dm^3, which is significantly below the current standard (the safe level of nitrates is set at 50 mg/dm^3) (Schullehner et al., 2018). In addition, drinking nitrate-contaminated water during the first trimester of pregnancy has been linked to an increased risk of congenital abnormalities (Sadler et al., 2016).

Ninety percent of the population in the European Union (EU) countries has access to centralized water supply and wastewater disposal. Only 58.7% of people in Ukraine presently have access to centralized water supply, while only 37.6% have access to centralized wastewater disposal. Only 29% of rural residents in Ukraine have access to the water distribution network, compared to 87.2% of urban residents. In this regard, Zhytomyr region is not an exception. It is ranked 17th among other regions of Ukraine in providing the centralized water supply to rural residents and ranks 20th in providing it to the residents in urban-type settlements in Ukraine (Ministry of Development of Communities and Territories of Ukraine, 2020).

Rural areas are not equipped with centralized water supply and drainage systems. As a result, residents of households use untreated groundwater of unknown quality without understanding the possible consequences for their health. Therefore, it is an acute and urgent matter to assess the risk to human health, especially that of children, from drinking water that has been contaminated with heavy metals and nitrates.

Thus, the purpose of our study is to determine the content of nitrates, iron, and manganese in drinking water sources of the noncentralized water supply of educational institutions in rural residential areas of Zhytomyr region, as well as to assess the risks to the children's health posed by the influence of these pollutants. All interested parties can use the study findings to prevent potential risks to children's health in rural areas.

Material and methods

The study was carried out within Zhytomyr region in the rural settlements of Berdichev, Zhytomyr, Korosten, and Novohrad-Volinsky districts. Water samples were taken from wells and bores located on the territory of preschool educational institutions and schools. A total of 114 drinking water samples were collected. The Measurement Laboratory of Polissia National University conducted analytical studies of water for the content of iron, manganese, and nitrates.

The risk to children's health of various age groups was evaluated using the risk assessment methodology developed by the US Environmental Protection Agency (US EPA). In order to estimate the possible noncarcinogenic risks to human health, estimated daily intake (EDI) indicators and hazard quotient (HQ) were used.

The average EDI of a chemical substance during a person's lifetime with drinking water was calculated according to Equation 1:

$$EDI = C \times IR/BW, \quad (1)$$

where EDI is the average EDI of a chemical substance during a person's lifetime (mg/kg × day), C is the concentration of the substance in drinking water (mg/dm^3), IR is the water intake rate, and BW is the human body weight in kg.

The risk of the potential noncarcinogenic effects was assessed using the HQ, which is the ratio of the average EDI of a chemical substance to its safe (reference) level of influence, and was calculated according to Equation 2:

$$HQ = EDI/RfD, \quad (2)$$

where EDI is the average EDI of a chemical substance during a person's lifetime (mg/kg × day) and RfD is the threshold (reference) dose (mg/kg × day).

Values of exposure factors that are recommended as standard were taken according to the following methodology (Table 1).

ArcGIS is a powerful platform used to create, analyze, edit, import, and publish geographic data. ArcGIS provides means of

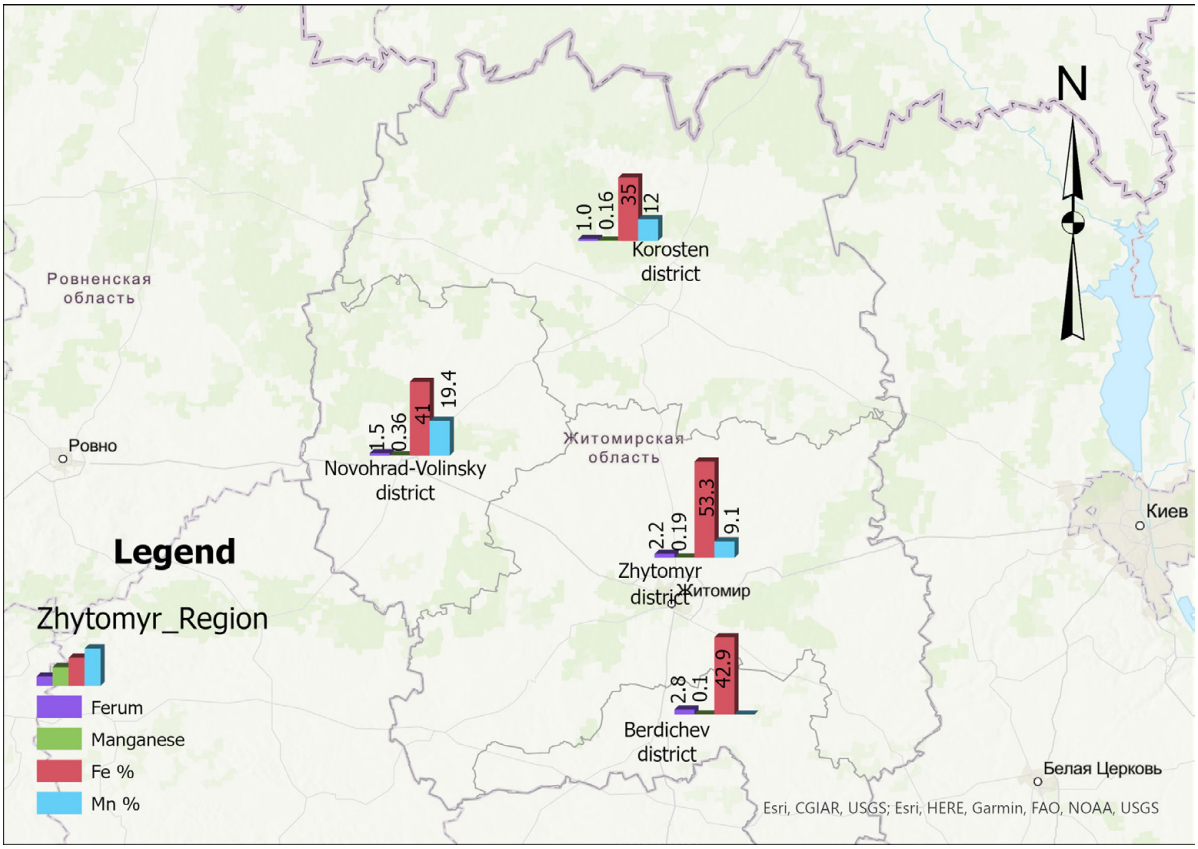

Fig. 1. Average content of total iron and manganese in the drinking water of educational institutions in Zhytomyr region (mg/dm³) and the percentage of samples that exceeded the standard (%).

displaying results on professional quality maps. In this study, the ArcGIS Pro software was used to provide graphical representation of the content of the water quality indicators under investigation, to single out the most critical zones in terms of districts and to ensure that risk zones can be seen more clearly.

Results

The study findings showed that the average total iron content in drinking water sampled from educational institutions in the Zhytomyr region ranged from 1.0 to 2.8 mg/dm³, and that in 41–53.3% of samples, the content was higher than the allowable level. The average manganese content was within the standard, although occasionally, it concentration in excess was recorded in Zhytomyr, Korosten, and Novohrad-Volinsky districts.

In Berdichev district, the average total iron content in the drinking water of educational institutions was 2.8 mg/dm³, which exceeded the allowable level by almost three times. Its maximum content of 10.6 mg/dm³ was found in the dug well of the secondary school in the village Mala Piatyhirka. Nearly 43% of the samples overall contained an excessive amount of iron. As for manganese, its content was within the allowable level, and its average content was 0.1 mg/dm³ (Fig. 1).

The average total iron content in the drinking water of educational institutions located in Zhytomyr district was 2.2 mg/dm³. Its maximum concentration at the level of 9.8 mg/dm³ was recorded in the well of Vertokyivka secondary school. Also, 53% of samples were characterized by excessive iron content. The average manganese content was at the level of 0.2 mg/dm³. However, 9% of the selected samples exceeded the standard. Its maximum content was found in the well of Sadky secondary school at the level of 1.61 mg/dm³, which exceeded the standard by 3.2 times (Fig. 1).

In Korosten district, the total iron content in the drinking water of educational institutions in rural settlements was at the level of 1 mg/dm³, which was within the acceptable range. Overall, 35% of the samples had an excessive amount of iron. Its maximum concentration at the level of 5.5 mg/dm³ was recorded in the village water supply line of Ignatpil preschool educational institution. The average manganese content was 0.16 mg/dm³, which was within the allowable range. Also, 12% of the selected samples were characterized by excessive manganese content, and its highest concentration at the level of 0.84 mg/dm³ was found in the well of a preschool educational institution in the rural settlement of Radovel (Fig. 1).

In Novohrad-Volinsky district, the average total iron content was 1.5 mg/dm³. The maximum iron content at the level of 10.6 mg/dm³ was found in the well of the food block of the secondary school in the village of Nesolon. In general, 41% of the samples had an excessive iron concentration. The average manganese level was 0.36 mg/dm³, which was within the acceptable range. However, in 19% of the samples, it exceeded the allowable level.

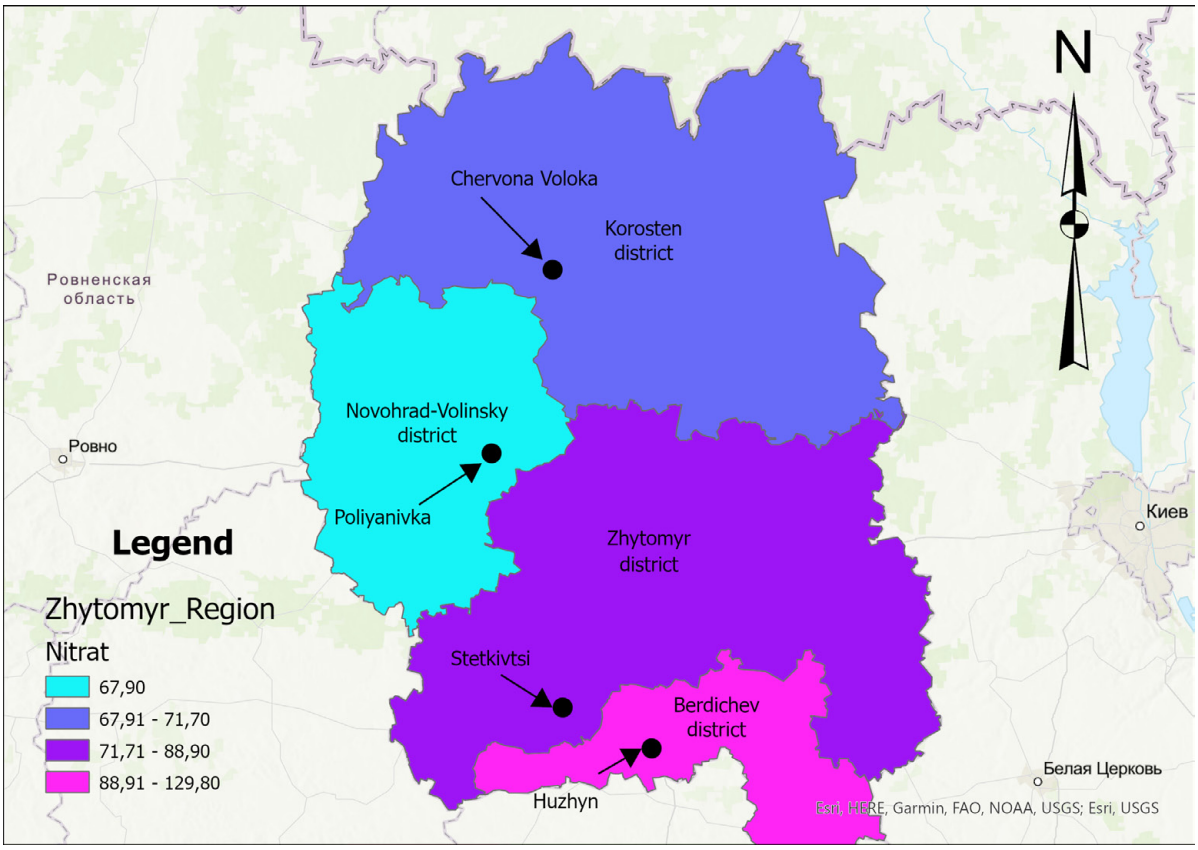

Fig. 2. Average and maximum nitrate content in the drinking water of educational institutions in Zhytomyr region (mg/dm^3).

Table 2. Results of assessment of the intake of iron and manganese with drinking water by children in Zhytomyr region.

Districts	Total iron				Manganese			
	Infants, up to 2 years of age	Children, aged 2–6	Teenagers, aged 6–16	Adults, aged 16–18	Infants, up to 2 years of age	Children, aged 2–6	Teenagers, aged 6–16	Adults, aged 16–18
Berdichev	0.02	0.16	0.11	0.1	0.001	0.006	0.004	0.003
Zhytomyr	0.02	0.12	0.09	0.08	0.002	0.01	0.008	0.007
Korosten	0.01	0.06	0.04	0.04	0.001	0.009	0.006	0.006
Novohrad-Volinsky	0.01	0.09	0.06	0.05	0.003	0.02	0.01	0.02

Its maximum content at the level of 1.95 mg/dm^3, which exceeded the standard by almost four times, was found in the drinking water of Novohrad-Volinsky gymnasium (Fig. 1).

In all districts of the Zhytomyr region that were analyzed, the average nitrate content in drinking water at the educational institutions was 50 mg/dm^3, which did not go above the allowable level. Berdichev district had the highest average nitrate concentration of 39.2 mg/dm^3 (Fig. 2).

The maximum nitrate concentration of 96 mg/dm^3 was recorded in the well of the secondary school in the village Khazhyn in Berdichev district. Its excessive content was found in almost 43% of the selected water samples. In Zhytomyr district, 22.7% of the selected samples were characterized by excessive nitrate concentration. Its maximum content of 151.4 mg/dm^3 was found in the well of the secondary school in the village of Stetkivtsi. The nitrate content in the well of a preschool educational institution, which was located in the village of Red Voloka in Korosten district, was nearly six times higher than the allowable level. In Korosten district, 22.6% of water samples were found to have nitrate levels that exceeded the allowable level. Also, 34% of the samples in Novohrad-Volinsky district had excessive nitrate content. Its highest concentration, 104.8 mg/dm^3, was found in the general secondary school in the village of Poliianivka (Fig. 2).

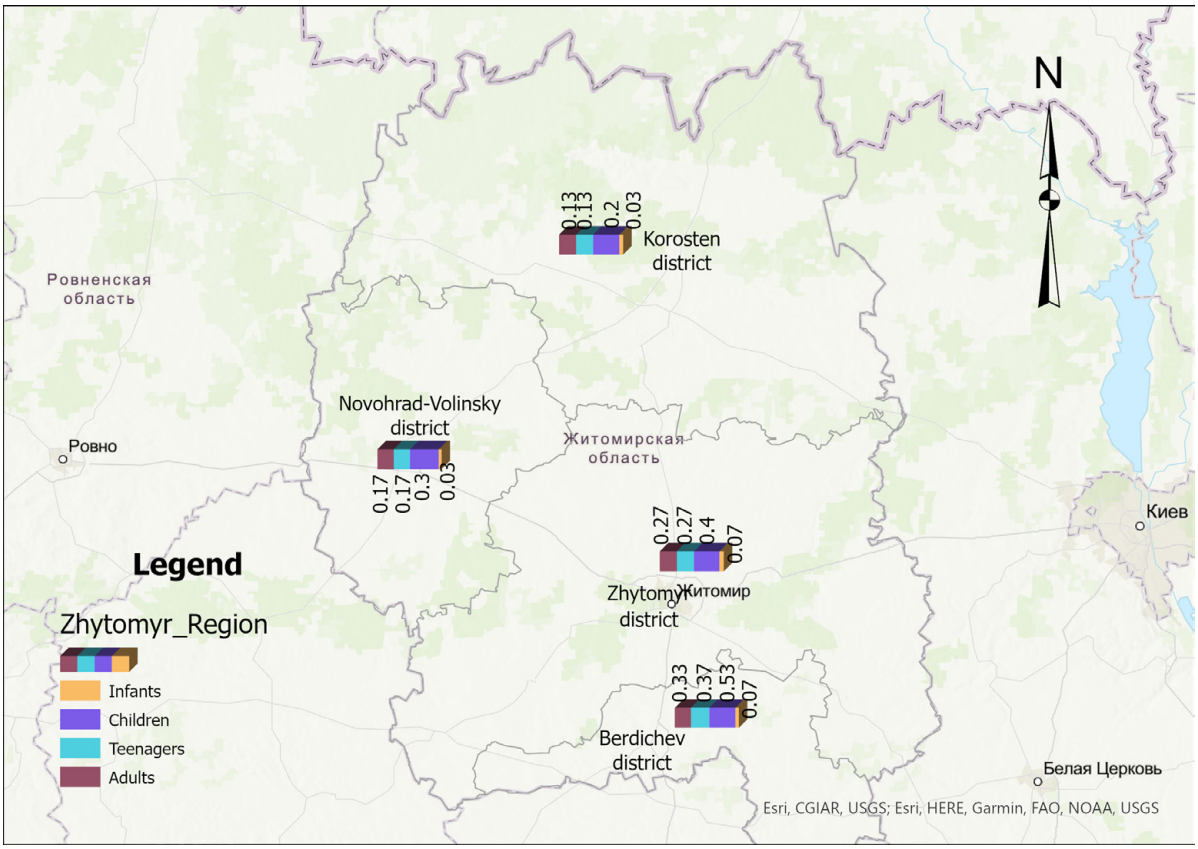

Fig. 3. Magnitude of the risk to children depending on the iron content in the drinking water.

Table 3. Results of assessment of the intake of nitrates with drinking water by children in Zhytomyr region.

Districts	Infants, up to 2 years of age		Children, aged 2–6		Teenagers, aged 6–16		Adults, aged 16–18	
	Avg. conc.	Max conc.	Avg. conc.	Max conc.	Avg. conc.	Max conc.	Avg. conc.	Max conc.
Berdichev	0.3	0.8	2.2	5.44	1.6	3.84	1.4	3.4
Zhytomyr	0.22	1.21	1.55	8.58	1.1	6.06	0.98	5.41
Korosten	0.31	2.3	2.17	16.32	1.53	11.52	1.37	10.29
Novohrad-Volinsky	0.21	0.84	1.49	5.94	1.05	4.19	0.94	3.74

Based on the obtained data on the content of iron, manganese, and nitrates in water, we calculated the values of average daily intake doses of iron, manganese (Table 2), and nitrates (Table 3).

Based on the average and maximum values, we calculated the average daily intake doses of nitrates by children through drinking water. It was determined that teenagers and children aged 2–6 typically had the highest values of the average daily intake dose (Table 3).

Using the HQ, the risk to human health posed by iron and manganese contamination of drinking water was evaluated. Even with iron content above the allowable level, the magnitude of the risk to children from constant water consumption did not surpass unity, indicating a negligibly low level of risk. Additionally, it has been proven that children face a risk that is much higher than that of teenagers (Fig. 3).

The situation with manganese is similar because even at its highest concentrations, the calculated HQ due to the manganese content did not surpass unity, indicating a low risk of negative effects (Fig. 4).

The magnitude of the risk of adverse effects on children's health from drinking water with a nitrate content that did not exceed the standard was greater than unity only for children aged 2–6 in Berdichev and Korosten districts. In other cases, the risk was low, but only at average nitrate content. At the highest nitrate concentrations in water, the risk mainly ranged from 1 to 5, indicating an average level of danger. In Korosten district, at the maximum nitrate content, the level of danger was high because the value of the HQ ranged from 5 to 10. Additionally, the critical level of danger was recorded for children aged 2–6 in Korosten district (Fig. 5).

It has been established that children aged 2–6 are the most susceptible category of the population to the nitrate content in water.

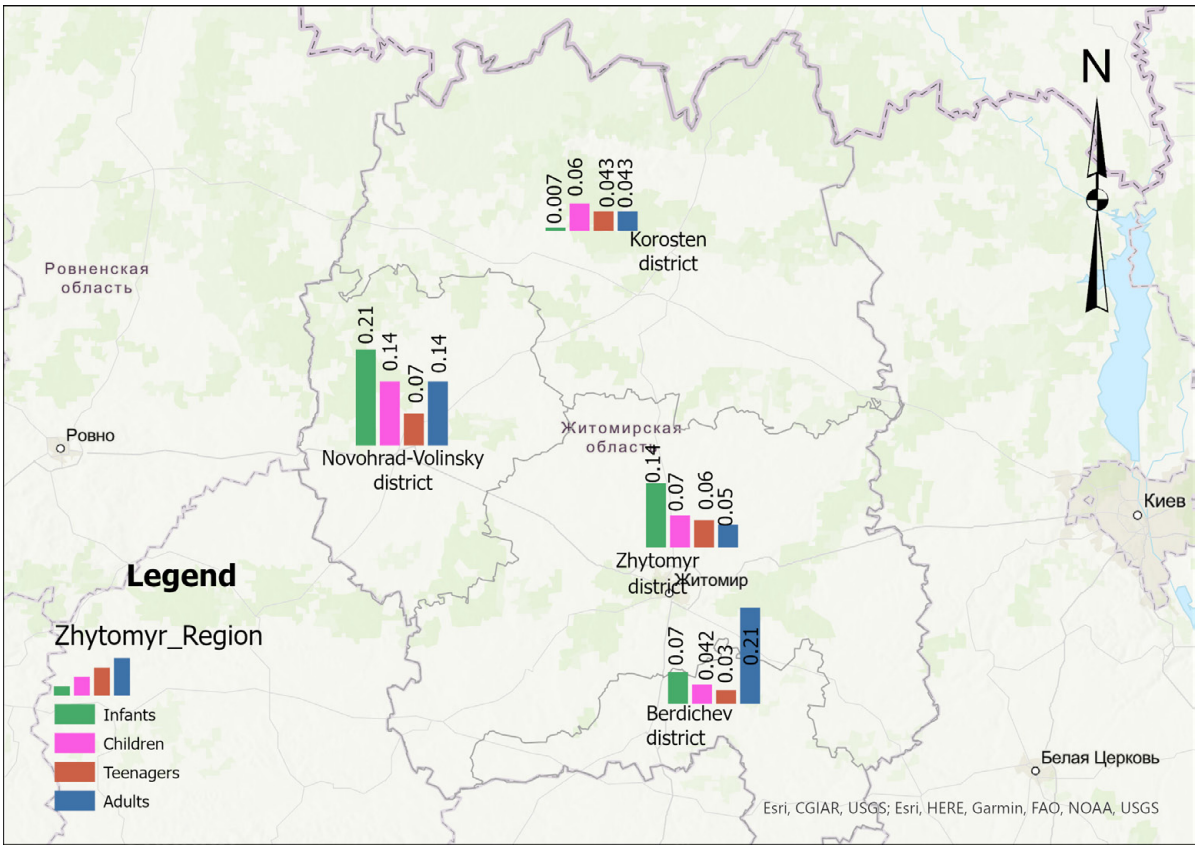

Fig. 4. Magnitude of the risk to children depending on the manganese content in the drinking water.

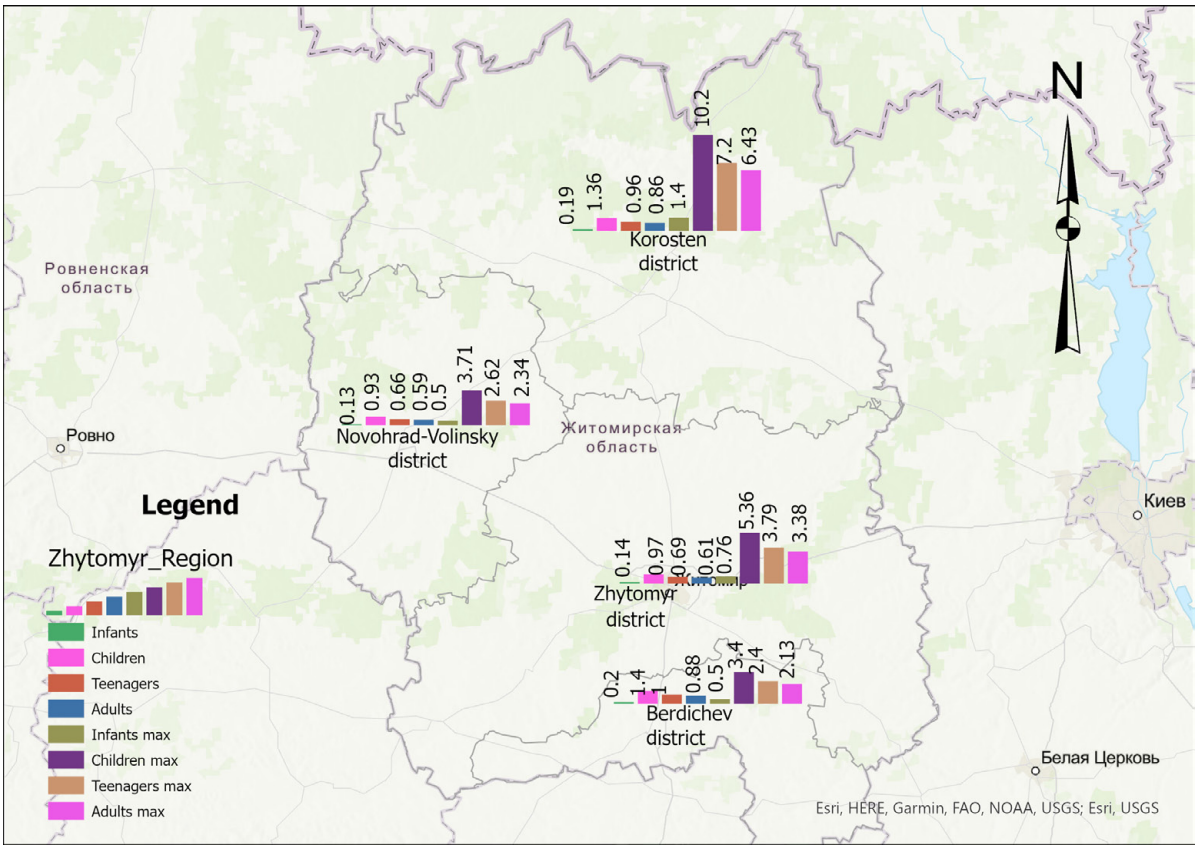

Fig. 5. Magnitude of the risk to children depending on the nitrate content in drinking water.

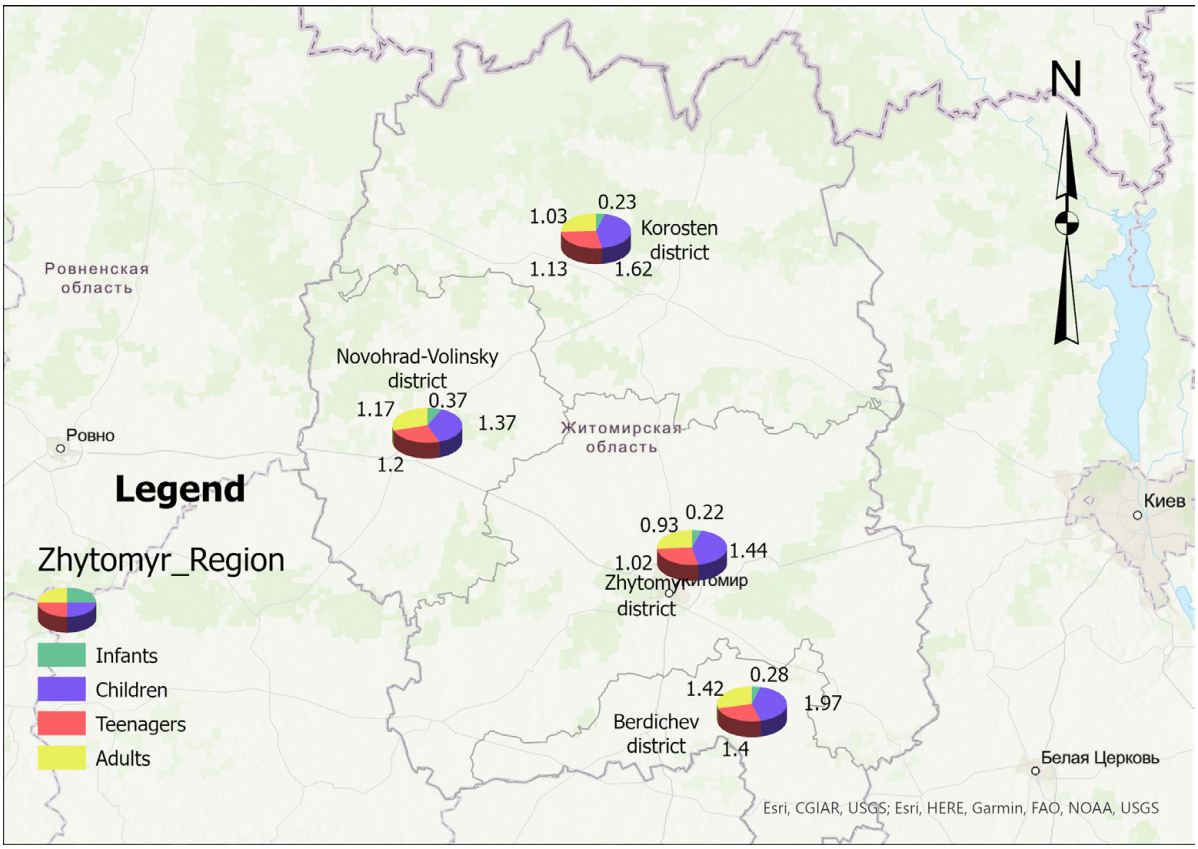

Fig. 6. Total risk to children's health.

Children aged 6–12 had the highest magnitude of the total risk to their health from drinking water that contained nitrates, iron, and manganese. The highest HQ of 1.972 was recorded for children living in Berdichev district, which indicates an average degree of risk. Infants were found to be at the lowest risk level, which is related to minimal water intake. However, given that infants may be on artificial feeding, which may result in increased water consumption and the possibility that adverse effects for the child may occur even with the nitrate content in water exceeding 10.0 mg/dm^3, the level of hazard for this category of the population may be significantly higher (Aghapour, 2021). The magnitude of risk for teenagers was approximately 30% lower than that of children, and it remained practically at the same level as that of adults aged 16–18 (Fig. 6).

Nitrates was the highest contributor to the total magnitude of risk to children's health in rural settlements of Zhytomyr region. Their share varied from 67% in Zhytomyr district to 84% in Korosten district. Total iron, whose contribution to the total risk ranged between 12 and 28%, took the second place. Manganese is distinguished by having the least contribution, ranging from 2% in Berdichev district to 10% in Novohrad-Volinsky district (Fig. 7).

Discussion

The risk of negative impact on human health is closely correlated with the quality of drinking water from sources of noncentralized water supply in rural residential areas. Quite frequently, high levels of nitrates, iron, and manganese in such water are the reason for its poor quality. Therefore, it is crucial to estimate the noncarcinogenic danger that drinking low-quality water poses to the health of the rural population, particularly children.

Iron and manganese are naturally occurring metals that coexist in groundwater because they have many similar chemical properties, including the same univalent charge under physiological conditions, the same ionic radius, and similar human intake mechanisms. Important minerals like iron and manganese are required for the body to function properly. The recommended levels of iron and manganese in drinking water are 0.3 and 0.4 mg/dm^3, respectively, according to the World Health Organization. The standard content of iron and manganese in water sources of noncentralized water supply in Ukraine must not be higher than 1.0 and 0.5 mg/dm^3, respectively, in accordance with State Sanitary Rules and Regulations (DSanPiN) 2.2.4-171-10 "Hygienic Requirements for Drinking Water Intended for Human Consumption." Manganese is a mineral that is commonly found in food, and its deficiency in humans is very rare. Manganese intake through food is typically significantly higher than from drinking water.

The use of the HQ to assess the risk to human health associated with the intake of drinking water containing heavy metals makes it possible to establish their noncarcinogenic effects. Giri and Singh (2015) discovered, in particular, that manganese contamination of water poses a noncarcinogenic risk to

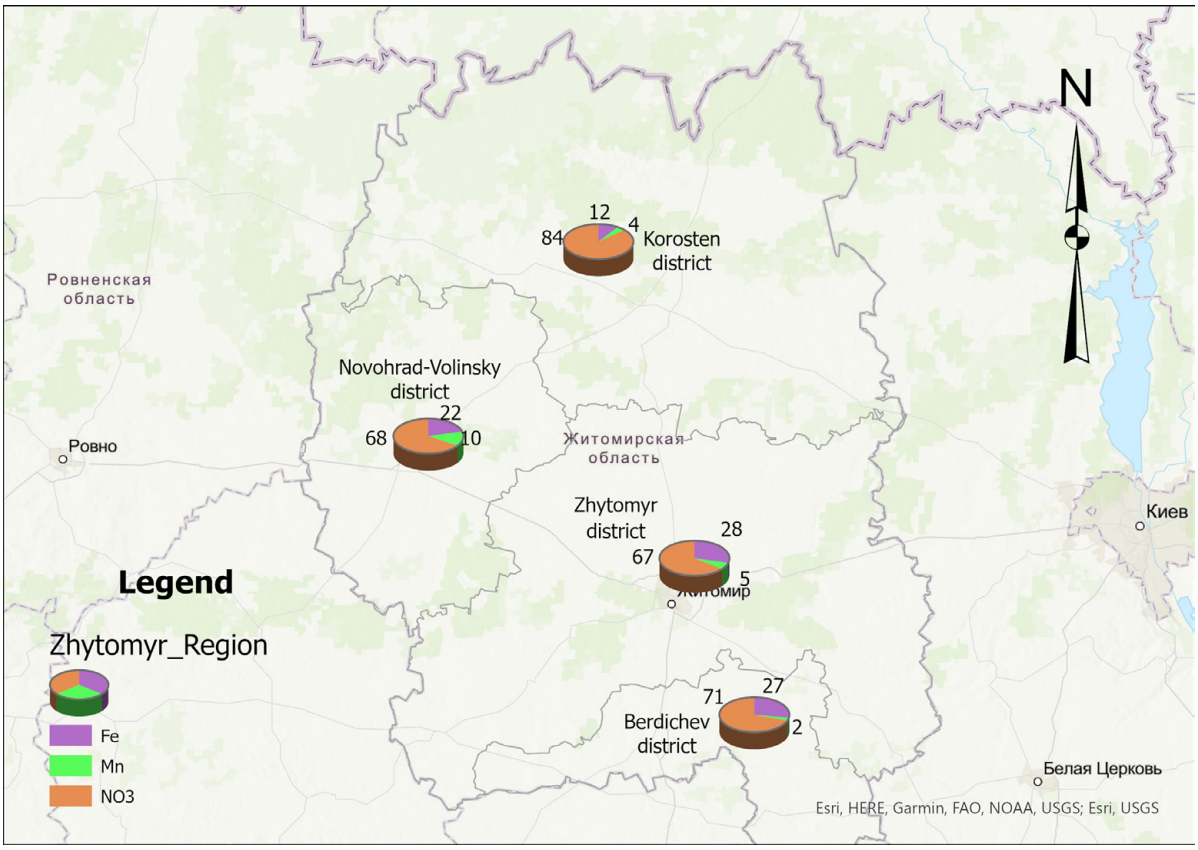

Fig. 7. Shares of iron, manganese, and nitrates in the total magnitude of risk to children aged 2–6 (%).

human health, with children being noticeably more at risk than adults. Similar were the study findings obtained by Polyakov et al. (2018), and our studies also supported these results (Valerko, Herasymchuk, 2021), which showed that children under the age of 6 had the highest HQ values when it came to water intake (Valerko, Herasymchuk, 2021). Additionally, our earlier study demonstrated that the risk is greater than unity only when the iron concentration reaches 10 mg/dm^3 or above (Valerko et al., 2021). In contrast, Ghosh et al. (2020) studied iron and manganese content in drinking water from noncentralized water supply sources in Bangladesh and found that adults had much higher noncarcinogenic health risks from iron and manganese intake than children. In our opinion, the use of different adult body weight (50 kg) and water intake rates (3.53 l/day) in this study may be the reason for the contrary results. According to Prybylova and Kachan (2017), drinking water with a high iron and manganese content increases the risk of kidney, gastrointestinal, central nervous system, and cardiovascular system disorders. They also advise against drinking such water without preliminary water treatment.

Many contemporary researchers are concerned about the issue of nitrate contamination of drinking water from sources of noncentralized water supply in rural settlements, since high nitrate content in well water is currently being observed all over the world.

In many parts of the world, the nitrate concentration in drinking water is rising, primarily as a result of the use of inorganic fertilizers and livestock manure in agricultural areas (Ward et al., 2018). The primary anthropogenic source of nitrogen in the environment is nitrogenous fertilizers (Wheeler et al., 2015). Following the invention of the Haber–Bosch process in the 1920s, their use increased exponentially. After 1980, synthetic fertilizers have been used extensively on agricultural land. As a result of nearly half of all nitrogen runoff from agricultural areas entering surface water and groundwater, the quantity of nitrates in water resources has increased (Davidson et al., 2012; Romanchuk, 2021).

Zufiaurre et al. (2020) found excess of *Escherichia coli* in well water with increased nitrate concentration, confirming their anthropogenic origin.

In a study of nitrate contamination of Texvalli groundwater in southern India, Karunanidhi et al. (2021) used the United State Environmental Protection Agency health risk assessment model to calculate the HQs for nitrate exposure in various age groups by oral and cutaneous routes. It was discovered that between 48 and 87% of the samples were harmful to the health of infants, teenagers, adults, and the elderly. The magnitude of the risk surpassed unity, and the cutaneous risk of nitrates was negligibly low.

The study conducted by Radfard et al. (2018) in rural areas of Iran showed that the HQ does not exceed unity for nitrate content in drinking water at or below the allowable level.

In a study carried out in the rural areas of Yantai, China, Yu et al. (2020) found that even when cutaneous nitrate expo-

sure was not taken into account, the HQ values for youth were significantly higher than for adults. It was also established that adult women are more susceptible to the effects of nitrates than men, but the difference is not significant.

According to Qasemi et al. (2018), groundwater nitrates have a considerable negative impact on the health of children and infants in rural Azadshahr (Iran) because their HQ values for 41% of these age groups were above the safety standard, or more than unity. In our investigation, we also obtained similar results (Valerko, 2021).

The findings of Moldovan et al. (2020) indicate that both anthropogenic (agricultural practices) and natural (rock dissolution and weathering) factors have an impact on groundwater quality, as the total hazard index from the intake of nitrates and heavy metals into the human body in autumn and summer had higher values than in the cold season.

Conclusion

According to studies on the total iron content, only Korosten district had an average amount of iron that was within the allowable range of 1 mg/dm^3. In the drinking water of the other districts, it exceeded the allowable level, from 1.5 times in Novohrad-Volinsky district to 2.8 times in Berdichev district. The average manganese content was generally within the allowable range. The majority of samples with excessive manganese concentration (19.4%) were found in Novohrad-Volinsky district. The average nitrate concentration in the investigated districts was below the allowable level, and the percentage of samples exceeding the permitted level was 42.9% for Berdichev district, 22.7% for Zhytomyr district, 22.6% for Korosten district, and 34% for Novohrad-Volinsky district. The calculated average daily intake doses of nitrates in the children's bodies with drinking water were the highest for children aged 2–6 and teenagers. Even with iron content over the allowable level, the magnitude of the risk to children from constant water consumption did not surpass unity, indicating a negligibly low level of risk. The risk associated with manganese concentration was likewise negligibly low. The magnitude of the risk of adverse effects on children's health from drinking water with a nitrate content that did not exceed the standard was greater than unity only for children aged 2–6 in Berdichev and Korosten districts. In Korosten district, at the maximum nitrate content, a high level of danger had been recorded because the value of the HQ ranged from 5 to 10, and the critical level of danger had been recorded for children aged 2–6 years. The magnitude of the total risk to children's health due to intake of iron, manganese and nitrates from drinking water was the highest for children aged 6–12. For teenagers, the level of risk was about 30 % lower than for children and remained almost at the same level as that of adults aged 16–18. In the total risk structure, nitrates accounted for the greatest share of 67%–84%. Total iron took the second place, with manganese having the least significant impact.

To improve the quality of drinking water in rural settlements, it is necessary to carry out constant evaluation of the quality of water in wells and bores, raise the awareness of the rural population, select inexpensive household means of water purification, and so on.

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