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Groundwater quality assessment using health risk-based weighting

***V. Bezsonnyi** *(Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine; V. N. Karazin Kharkiv National University, Kharkiv, Ukraine)*, **O. Tretyakov** *(State Non-Commercial Company «State University «Kyiv Aviation Institute»)*, **A. Nekos** *(V. N. Karazin Kharkiv National University, Kharkiv, Ukraine)*, **L. Plyatsuk** *(Sumy State University, Sumy, Ukraine)*, **R. Ponomarenko** *(Institute of Scientific Research on Civil Protection of the National University of Civil Protection of Ukraine, Dmytrivka, Kyiv region)*, **O. Davydova** *(Simon Kuznets Kharkiv National University of Economics, Kharkiv, Ukraine)*

SUMMARY

The study assesses groundwater quality using the Health Risk Weighting Model (HRWM) and compares it with traditional methods: the Importance Scale Weighting Model (ISWM) and the Entropy Weighting Model (EWM). The main objective is to determine the most reliable method for evaluating groundwater quality and associated health risks. Based on the collected data, the Water Quality Index (WQI) was calculated using three methods: ISWM, which relies on expert assessments and may be subjective; EWM, which considers the statistical variability of pollutant concentrations; and HRWM, which incorporates toxicological indicators such as the reference dose (RfD) and carcinogenic coefficient (CIC). The results showed that HRWM identified manganese, sulfates, and iron as the most hazardous pollutants, assigning them the highest weighting coefficients. The highest levels of contamination and health risks were observed in wells N82 and N62, whereas well N63 exhibited the best water quality indicators. The WQI values varied significantly depending on the assessment method, with HRWM yielding the most critical results. The study confirmed that HRWM provides a more accurate risk assessment by considering the actual toxicological impact of pollutants, whereas traditional methods such as ISWM and EWM may underestimate hazards, particularly for highly toxic substances present in low concentrations.

Introduction

Environmental pollution is one of the key ecological challenges of modern times, requiring the application of various monitoring and risk assessment methods. Research on the spatial distribution of soil magnetic susceptibility has proven its effectiveness as an indicator of urban pollution (Menshov et al., 2023). At the same time, multifactor mathematical modeling is widely used for evaluating environmental and economic aspects (Horoshkova et al., 2020). Artificial intelligence and machine learning methods are also increasingly applied in predicting environmental trends (Guryanova et al., 2021). In the field of water resources, research on ecological risks in the context of military threats highlights the importance of adapting assessment methodologies for extreme conditions (Bezsonnyi & Nekos, 2022, 2023). The assessment of surface water ecological safety helps develop recommendations for reducing anthropogenic pressure and improving water quality (Bezsonnyi et al., 2023). Traditional water quality assessment methods rely on comparing pollutant concentrations with maximum allowable concentrations (MAC) or on integrated approaches such as the Water Quality Index (WQI). WQI allows for the transformation of a set of physicochemical water parameters into a single numerical indicator, which is convenient for comparing different water sources (Sutadian et al., 2016). However, the selection of weighting coefficients for WQI is critically important, as different weighting methods can significantly alter the final assessment (Li et al., 2019). Traditionally, Importance Scale Weighting Model (ISWM) is applied, which is based on subjective assessments of the importance of each parameter. However, this method has certain limitations related to variability in expert opinions and the lack of an objective consideration of pollutants' effects on human health (Pesce & Wunderlin, 2000). An alternative is the Entropy Weighting Model (EWM), which relies on statistical patterns in the variation of pollutant concentrations. However, this method does not account for the actual toxicological hazard of each substance (Zhang et al., 2017). A novel and promising approach is Health Risk Weighting Model (HRWM), proposed by Fanghui Yi et al. (2018). This method is based on medical and ecological assessments and employs reference doses (RfD) and carcinogenic coefficients (CIC) to determine the weight of each pollutant. Modern approaches to groundwater assessment can be divided into traditional and integrated methods. Traditional methods involve comparing actual pollutant concentrations with regulatory standards (Liang et al., 2021). However, they do not allow for an objective comparison of different water sources. In contrast, integrated methods, particularly the Water Quality Index (WQI), enable the aggregation of chemical analysis results into a single numerical indicator (Sutadian et al., 2016). One of the key steps in calculating WQI is determining the weighting coefficients of pollutants, which directly influence the final result. ISWM (Importance Scale Weighting Model) is an expert-based weighting method. It is simple but subjective, as it depends on expert evaluations (Pesce & Wunderlin, 2000). EWM (Entropy Weighting Model) is based on data variability. If the concentration of a specific pollutant fluctuates significantly between sampling points, it is assigned a higher weight (Zhang et al., 2017). HRWM (Health Risk Weighting Model) is a novel approach that considers the toxicological impact of pollutants and their health hazards (Fanghui Yi et al., 2018). HRWM helps avoid underestimating hazardous substances, which may have low concentrations but high toxicity (e.g., nitrites or heavy metals). The main advantage of HRWM is the use of medical data on reference doses (RfD) and carcinogenic coefficients (CIC), allowing for a more accurate consideration of each pollutant's impact on public health (USEPA, 2021). Previous studies have shown that HRWM provides more critical assessments than ISWM and EWM, particularly in cases of significant contamination by heavy metals and organic compounds (Li et al., 2019).

The objective of this study is to assess the quality of groundwater using health risk-based weighting (HRWM) and compare its results with traditional methods (ISWM, EWM). The main tasks of the study include: a) Determining the physicochemical parameters of water in six wells of the Bukinske water intake in Izium for the period 2003–2012. b) Calculating WQI using ISWM, EWM, and HRWM methods. c) Analyzing discrepancies between methods and evaluating the impact of different pollutants on the final WQI value. d) Identifying the wells with the highest environmental risk and developing recommendations for improving groundwater quality.

Method and Theory

The study includes three main stages: 1) Collection and analysis of data on the physicochemical parameters of groundwater. 2) Calculation of the Water Quality Index (WQI) using three weighting methods (ISWM, EWM, HRWM). 3) Comparative analysis of the obtained results and health risk assessment (HRWM). The study is based on data collected from six wells in Izium (Kharkiv region, Ukraine) for the period 2003–2012. Physicochemical parameters analyzed: Nitrogen compounds: NH_4^+ (ammonium nitrogen), NO_2^- (nitrite nitrogen), NO_3^- (nitrate nitrogen). Metals: Mn (manganese), Cu (copper), Fe (iron). Physicochemical characteristics: pH, hardness, chlorides, oxidizability, sulfates.

Water Quality Index (WQI) Calculation Methods. Importance Scale Weighting Model (ISWM) is an expert-based weighting approach where experts assign weighting coefficients to each pollutant (Pesce & Wunderlin, 2000). The formula for calculating WQI:

$$WQI_i = \sum_{j=1}^{n} \left(w_j \times \frac{x_{ij}}{c_j} \right)$$

where: w_j – expert weighting coefficient; x_{ij} – pollutant concentration in well i. c_j – maximum allowable concentration (MAC).

Entropy Weighting Model (EWM) relies on statistical patterns in data variability (Zhang et al., 2017). The formula for entropy H_j:

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^{m} f_{ij} \ln f_{ij}$$

where: $f_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}$ – normalized value; m – number of wells.

Health Risk Weighting Model (HRWM) accounts for the impact of each pollutant on human health and is based on medical indicators such as the reference dose (RfD) and carcinogenic coefficient (CIC). The formula for the weighting coefficient w_j:

$$w_j = \frac{C + \left(\sum_m p_{ij}\right)/m}{\sum_{j=1}^{n}\left(C + \left(\sum_m p_{ij}\right)/m\right)}$$

where:

p_{ij} – pollutant contribution to total risk; $C = 0.25$ – correction coefficient.

Health Risk Assessment (HRWM) assessment methodology is based on the USEPA (2021) approach. Non-carcinogenic risk

$$r_{ij} = \frac{IN_{ij} \times 10^{-6}}{RFD_j \times 70}$$

where:

IN_{ij} – intake level of pollutant; RFD_j – reference dose.

Carcinogenic risk

$$r_{ij} = \frac{1 - \exp\left(-IN_{ij} \times CIC_j\right)}{70}$$

where:

CIC_j – carcinogenic coefficient.

Comparative Analysis of Methods. The criteria for comparing ISWM, EWM, and HRWM include: Differences in WQI values for each well. Sensitivity of the methods to hazardous pollutants. Identification of wells with the greatest discrepancies in WQI values. It is expected that HRWM will produce the most critical results since it accounts for the impact of each pollutant on human health.

Results

The results of groundwater quality assessment and health risk evaluation in six wells of the Bukinske water intake in Izium for the period 2003–2012 are presented below. The annual average pollutant concentrations were calculated for each well. Wells No. 82 and No. 62 exhibit the highest contamination, particularly with manganese (Mn), iron (Fe), and sulfates (SO_4^{2-}). Meanwhile, Well No. 63 has the best water quality indicators. Weighting coefficients for each pollutant were determined using three methods: ISWM, EWM, and HRWM (Table 1).

Table 1 *Weighting coefficients for pollutants*

Pollutant	ISWM	EWM	HRWM
NH_4^+ (Ammonium nitrogen)	0.10	0.065	0.084
NO_2^- (Nitrite nitrogen)	0.08	0.072	0.097
NO_3^- (Nitrate nitrogen)	0.09	0.078	0.091
Mn (Manganese)	0.12	0.157	0.202
Cu (Copper)	0.05	0.045	0.056
Fe (Iron)	0.10	0.102	0.126
pH	0.06	0.040	0.038
Hardness	0.09	0.088	0.095
Chlorides	0.07	0.052	0.058
Oxidizability	0.09	0.125	0.146
Sulfates	0.15	0.176	0.207

HRWM assigns the highest weights to manganese (Mn) and sulfates (SO_4^{2-}), reflecting their impact on human health. ISWM distributes the weights more evenly, which may lead to an underestimation of risks. WQI Calculation Using Three Methods (Table 2)

Table 2 *Water Quality Index (WQI) for different methods*

Well	WQI (ISWM)	WQI (EWM)	WQI (HRWM)	Category (HRWM)
No. 4	42.6	47.2	55.2	Moderate
No. 5	50.8	58.5	63.7	Moderate
No. 61	65.3	72.8	81.4	Moderate
No. 62	118.2	132.6	149.2	Poor
No. 63	38.9	45.1	47.8	Good
No. 82	129.6	146.4	163.8	Very Poor

HRWM provides the most critical assessments compared to ISWM and EWM. Wells No. 82 and No. 62 exhibit the worst water quality, while Well No. 63 is the cleanest. The total health risk (HRWM, R_i) for each well is as follows: No. 4 – 0.134; No. 5 – 0.151; No. 61 – 0.232; No. 62 – 0.389; No. 63 – 0.112; No. 82 – 0.448. Wells No. 82 and No. 62 pose the highest health risk. The primary pollutants responsible for this are manganese, sulfates, and iron.

Conclusions

Significant variations in groundwater quality were observed among the wells. The study revealed that Wells No. 82 and No. 62 are the most contaminated, while Wells No. 4 and No. 63 have relatively clean water. The main pollutants affecting water quality are manganese (Mn), sulfates (SO_4^{2-}), and iron (Fe). The choice of weighting method significantly affects the final WQI values. A comparison of ISWM, EWM, and HRWM demonstrated that HRWM provides the most critical assessments because it considers the actual toxicological impact of pollutants on human health. ISWM (expert-based weighting) underestimates the hazards of manganese and sulfates. EWM (entropy-based weighting) does not incorporate medical risk factors. Wells No. 82 and No. 62 pose the highest health risks. The health risk assessment (HRWM, RiR_i) identified the highest risks in Well No. 82 (0.448) and Well No. 62 (0.389), confirming their significant environmental hazard. Well No. 63 has the best water quality. Well No. 63 has the lowest WQI and HRWM values, indicating the least risk to public health. HRWM is the most reliable method for groundwater quality assessment. HRWM allows for the identification of the most hazardous pollutants, which traditional approaches fail to detect adequately.

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