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Application of selected groundwater quality indices in anthropogenically transformed areas

Abstract: Correctly assessing the impact of waste landfills on groundwater quality requires the development and use of comprehensive tools that consider the content of individual components in water, as well as those relating to the hydrochemical background. The article presents a comparative analysis of selected water quality indices used around the world to assess the environmental threat caused by sources of pollution. The paper includes the following indicators: Water Quality Index, Landfill Water Pollution Index, Nemerow Pollution Index, Backman Index, Canadian Water Quality Index, Horizontal Ratio, Enrichment Factor and Fuzzy Water Quality. Attention was paid to the values of individual indices, their applicability in municipal and industrial waste landfills, and limitations in their use. A literature review has proven that some indices, such as the Landfill Water Pollution Index and Nemerow Pollution Index, are used very often as they provide reliable results. Index methods help conduct rational water management, complement groundwater quality monitoring, and serve as a tool for making decisions in various water protection areas.

Keywords: groundwater; industrial landfill; leachate; municipal landfill; surface water

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Introduction

Water is essential for the existence of humanity (Kumar, 2018), which requires maintaining its best quality (Dąbrowska et al., 2023; Sitek et al., 2023). Surface and groundwaters are the most critical drinking water sources (Paun et al., 2016). Thus, it seems advisable to use solutions such as Managed Aquifer Recharge (MAR), i.e. the intentional recharge of water from various sources to a suitable aquifer under controlled conditions for later needs (Alam et al., 2021). These systems sustain and enhance groundwater quality and quantity (Dillon et al., 2019).

Pollution sources such as landfills (Esmaeilian et al., 2018) and waste incineration and composting plants pose a real threat to surface and groundwater (Jousma and Roelofsen, 2004; Bhuiyan et al., 2016; Dąbrowska et al., 2018B; Dąbrowska and Witkowski, 2022; Dąbrowska and Rykała, 2021; Sołtysiak et al., 2018). This applies not only to closed landfills with no ground protection (Sołtysiak and Dąbrowska, 2016) but also to new landfills whose protection has been destroyed (Slack et al., 2005; Sun et al., 2019; Dąbrowska, 2022). This is because waste contains heavy metals, persistent organic pollutants, sulphates, chlorides, and polycyclic aromatic hydrocarbons (Yin et al., 2017). The danger from waste increases when burned (Zhu et al., 2018) as the mobility of waste components in leachates from incinerated waste is greater (Gwenzi et al., 2016; Rykała et al., 2022).

Maintaining good water quality requires reliable monitoring (Nielsen, 2006; Quevauviller et al., 2009; Liu et al., 2012; Dąbrowska et al., 2016; Liu et al., 2023). The systems of groundwater monitoring and leachate disposal (Vilomet et al., 2001) are regulated by law. In Poland, this is the Minister of Climate and Environment Regulation of 19 March 2021, amending the landfill regulation. However, the range of parameters and the number of observation points in the context of a reliable risk assessment for groundwater and human health may not be sufficient. Still, the basic parameters can be used to calculate water quality indices, which is particularly important in rational water management.

Predictive models (Blachnik et al., 2019; Baghanam et al., 2022), monitoring, isotopic research, laboratory tests, spatiotemporal variation analysis (Tanna et al., 2020), using artificial neural networks (Włodarczyk-Sielicka and Połap, 2019) and various pollution indices (Shah and Joshi, 2017) are the most popular methods used for assessing changes in groundwater quality. The challenges in using water quality indices to assess the risk or vulnerability of water resources have been repeatedly addressed (Dooge, 2009; Lumb et al., 2011; Kurnaz et al., 2016; Kumar et al., 2019; Schreiber et al., 2022). However, they are still used, especially in water pollution sources.

The article presents the results of a review of indices used to assess surface and groundwater quality, with particular emphasis on those used in municipal and industrial waste landfills. The paper focuses on using indices in water pollution sources, showing limitations and necessary data. Eight different indices were taken into account.

Methodology

The suitability of water sources for human consumption, groundwater risk assessment (Rykala et al., 2022; Sitek et al., 2023) in pollution sources and groundwater quality assessment can be described using different indices (Srinivasa et al., 2015; Zakhemand and Hafez, 2015; Sunny, 2023). The article focuses on indicators that can be used to assess the risk to groundwater in landfills. All indices have been described using the formula and data necessary to perform the calculations and the characteristics of the limit values for various classes of individual indices. First, each of the presented indices can be used to assess the risk to surface or groundwater in pollution hotspots, such as industrial or municipal waste landfills. The selection of the most appropriate index should take into account the purpose of the analysis, the scope of available monitoring data, and the type of water pollution, i.e. whether, for example, in the case of selecting an indicator based on the value of an immobile parameter, this parameter is not the primary source of pollution. The indices are assessed in terms of five criteria: the number and type of parameters necessary to be used in the calculations, the freedom to choose reference values, the number of index value ranges and determining how much pollution is in a given area, the need to use specialised software to calculate a given index, and the need to combine other methods to assess risk to water.

Water Quality Index (WQI)

The Water Quality Index (WQI) is one of the most effective ways to describe water quality. It summarises data in a single numeric expression to understand its quality for different purposes (La Mora-Orozco et al., 2017). First proposed by Horton (1965), the WQI involves assigning weights (wi) to different water quality parameters based on their health implications in potable water (Chegbeleh et al., 2020). Calculations of this index involve the following steps: (i) assigning weights to the physicochemical parameters, (ii) developing a rating scale, and (iii) computing WQI (Chandra et al., 2017).

The computation of relative weights (Wi) is as follows:

$$W_i = \frac{w_i}{\sum w_i}$$

where w_i is the weight values for parameters.

After that, calculating the quality rating scale (qi) is needed. It is obtained from the following formula:

$$q_i = \frac{C_i}{S_i} \cdot 100$$

where:
C_i is the concentration of parameters,
S_i is the standard value of parameters.

After that, the calculation of the subindex SI is needed from the formula:

$$SI = W_i \cdot q_i$$

Finally, WQI is calculated using the formula:

$$WQI = \sum_{n=1}^{N} SI$$

This index can be calculated using any number of parameters. As a reference value, upper limit values of the hydrogeochemical background can be used (based on, e.g. regulations or natural background). The index classifies water into five classes: excellent (0–25), good (26–50), poor (51–70), very poor (71–90), and unsuitable for drinking (91–100). No specialised software is required to calculate this index besides a simple spreadsheet. The index does not require the use of any additional methods to provide a water risk assessment. The main disadvantage of this indicator is the selection of weights. These may be literature data, but at the same time, additional mathematical methods to assess the value of the scales or hydrogeological knowledge can be used.

Landfill Water Pollution Index (LWPI)

The Landfill Water Pollution Index considers the connection between the parameter values measured in water samples and the values of individual components in the water inflow in the landfill area. It is calculated using the following formula:

$$S_i = \frac{C_p}{C_b}$$

where:
C_p is the concentration of the i-th parameter in each of the polluted groundwater samples,
C_b is the concentration of the i-th parameter in the inflow groundwater sample.

The general formula is as follows (Talalaj and Biedka, 2016):

$$\text{LWPI} = \frac{\sum_{i=1}^{n} S_i w_i}{w_i}$$

where:
w_i is the weight of the i-th pollutant variable,
n is the number of groundwater pollutants.

This index, like WQI, can be calculated using any number of parameters. As a reference value, upper limit values of the hydrogeochemical background can be used (based on, e.g. regulations or natural background). In the original approach, the concentration of the i-th parameter in the inflow groundwater sample was taken as the background value. Theoretically, everything is correct, but in exceptional cases, even the groundwater inflow contains pollutants if the landfill is located in an area with other pollution sources. The index assigns weights to particular parameters. Determining the weights is rather important because it significantly affects the value of the final index. Weights can be assigned to individual parameters based on knowledge and data from other publications (Talalaj, 2014). For example, according to the assumptions of Talalaj (2015), parameters such as electrical conductivity and pH should have the lowest weights. This is because they are not components of groundwater but reflect its properties.

The LWPI classifies water into five classes: an LWPI value of ≤1 denotes water under no landfill impact; (1 < LWPI ≤ 2) indicates moderately polluted water due to minor landfill impact; (2 < LWPI ≤ 5) is poor water with an evident impact of landfill; and LWPI > 5 signifies strongly polluted water (Baghanam, 2020; Dąbrowska, 2022). No specialised software is required to calculate this index besides a simple spreadsheet. The index does not require the use of any additional methods to provide a water risk assessment.

Nemerow Pollution Index (NPI)

The Nemerow Pollution Index (Łukasik and Dąbrowska, 2022; Yang et al., 2022) is a measure considering the relationship between the value of a given parameter measured in groundwater and the hydrogeochemical background or selected value for this parameter calculated from the formula:

$$NPI = \frac{C_i}{L_i}$$

where:
C_1 is the measured value of each of parameter,
$L_1$is the allowable limit of each of the parameter.

This index can also be calculated using any number of parameters. As a reference value, upper limit values of the hydrogeochemical background can be used (based on, e.g. regulations or natural background). The NPI classifies water into three classes: an index value < 1 suggests low pollution, a value from 1 to 3 indicates moderate pollution, and a value from 3 to 6 and the remaining values indicate very high pollution. In the case of this index, the scale of values is very narrow. Any index with a value between 3 and 6 suggests high pollution.

The Nemerow Pollution Index is one of the easiest to use in assessing the risk to groundwater and determining water quality since there is no need to apply weights for individual indicators (Dąbrowska et al., 2018A; Lalik and Dąbrowska, 2024). No specialised software is required to calculate this index besides a simple spreadsheet. The index does not require the use of any additional methods to provide a water risk assessment.

Backman Index (Contamination Index)

The Backman (or Contamination) Index is based on chemical data from groundwater monitoring. This measure determines the amount of groundwater contamination relative to the natural hydrogeochemical background. The contamination index is calculated using the following formula (Backman et al., 1998; Christensen et al., 2001; Knopek and Dąbrowska, 2021):

$$C_d = \sum_{i=1}^{n} C_{fi}$$

where:

$$C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1$$

Cfi is the contamination factor for the i^th^ component,
CAi is the analytical value of the i^th^ component,
CNi is the upper range of natural hydrogeochemical background.

The formula for this index is similar to the WQI, but the total value is reduced by 1. This index can also be calculated using any number of parameters. As a reference value, upper limit values of the hydrogeochemical background can be used (based on, e.g. regulations or natural background). Along with the increase in the concentration of a given component relative to the natural hydrogeochemical background, the value of the contamination index grows. This index classifies water into three classes: the threat to groundwater is high in an area with an index value above 3, moderate with a value of 1–3, and low when the index value is below 1. Such a small number of intervals makes interpreting the obtained index value challenging. No specialised software is required to calculate this index besides a simple spreadsheet. The index does not require the use of any additional methods to provide a water risk assessment.

Canadian Water Quality Index (CCME WQI)

The Canadian Council of Ministers of the Environment (CCME) has created their own Water Quality Index (CCME WQI). This communications tool tests multiple variable water quality data against specific user-defined water quality benchmarks. This method combines three measures of variance (scope, frequency and amplitude) to produce a one-unit smaller number representing the overall water quality at a given location relative to a selected reference point (Al Janabi et al., 2012). A final score is a single number without a unit ranging from 0 to 100, where 100 means the variables were similar to or below the selected benchmarks. The general formula for calculating this index is as follows:

$$CCME\ WQI = 100 - \left(\sqrt{\frac{F_1^2 + F_2^2 + F_3^2}{1.732}}\right)$$

where:
F_1 represents scope, i.e. the percentage of variables above the guideline,
F_1= [no. of variables whose objectives are met/total no of variables]*100,
F_2 represents frequency, i.e. the frequency by which the objectives are not met,
F_2= [no of tests whose objectives are not met /total no of tests]*100,
F_3 represents amplitude, i.e. the range to which the failed tests are above the guideline,
(a) Range/Excursion$_i$ = [failed test value/objectives]-1,
(b) nse = $\sum$ /no of tests,
(c) F3= [nse/0.01nse+0.01].

The CCME WQI relies on measures of the scope, frequency and amplitude of excursions from objectives. Similarly to the previous ones, this indicator can support groundwater risk assessment and conduct rational water management. However, the disadvantage of this method is that the visibility of individual parameters is limited to the values F_1, F_2, F_3.

The CCME WQI value can range from 0–100. Its advantage is the five score evaluation categories: excellent (95–100), good (80–94), fair (65–79), marginal (45–64) and poor (0–44). The index can be used for any research area and any data. The calculations for this indicator are more complicated than those for previous measures. Therefore, it is recommended to use ready-made macros in Excel to prepare the analysis (Wright et al., 1999). The index does not require the use of any additional methods to provide a water risk assessment.

Horizontal Ratio (HR)

The values of individual components in the water can be assessed using the Horizontal Ratio (HR) in the direction of groundwater flow (Olagunju et al., 2020; Dąbrowska and

Witkowski, 2022) at a certain distance from one piezometer (e.g. groundwater inflow). The Horizontal Ratio is calculated using the following formula:

$$H_R = \frac{Cf_A}{Cf_B}$$

where:
C_{fA} is the concentration of the parameter on site A,
C_{fB} is the concentration of the parameter on site B.

An indicator value greater than 1 for each parameter suggests no impact, while an indicator value less than 1 for a single parameter suggests anthropogenic impact on groundwater. No knowledge of any reference values is required for this index. However, the values used for calculations may be controversial. When calculating this index, it is essential to know the hydrodynamic conditions of the examined area to assess which observation point is located on the groundwater inflow to the pollution source. Additionally, it is necessary to consider that the composition of the water at that point should be similar to the hydrogeochemical background. In reality, this does not always occur. Additionally, the interpretation of the index value is based only on one value, i.e. smaller or greater than 1. It proves that this index is not the best measure for assessing the groundwater risk level. No specialised software is required to calculate this index besides a simple spreadsheet. The index does not require the use of any additional methods to provide a water risk assessment.

Enrichment Factor (EF)

The Enrichment Factor (EF) is a measure that considers the relationship between the measured concentration of a given parameter and the concentration of an immobile parameter. This index is calculated using the formula:

$$EF = \frac{\frac{CF_m}{cmi}}{\frac{CF_b}{cbi}}$$

where:
the numerator is the ratio of heavy metal to immobile element in the analysed sample,
the denominator is the ratio of heavy metal to immobile element in the background sample.

The EF index can be calculated using any number of parameters, and the values of the hydrogeochemical background can be used as a reference upper limit (based on, e.g., regulations or natural background). The higher the indicator's value, the more polluted the waters are. The index classifies water into five classes: its value of <2 suggests minimal enrichment, values of 2 to 5 suggest moderate enrichment, 5 to 20 significant enrichment, 20 to 40 very high enrichment and a value over 40 extremely high enrichment. The examples of immobile parameters are Al, Fe, Mn, Sc, B or Ti (Childs, 1973;

Mishra et al., 2004; Dąbrowska and Witkowski, 2022). The index does not require the use of any additional methods to provide a water risk assessment.

For the EF index, it needs to be decided which parameter is used as the immobile parameter. Additionally, it is necessary to decide what values are used as the upper limit value of the hydrogeochemical background. Depending on the choice of these values, the final risk assessment for groundwater may vary. This is not the best solution for risk assessment in the area of, for example, steelworks, where metal contamination may be high, and it is challenging to select an immobile parameter.

Fuzzy water quality

Fuzzy variable set theory is the uncertainty analysis method introduced by Chen (1998). In the case of water resources, it was developed by Wang et al. (2014). Fuzzy Logic maps input to output using Fuzzy Inference System (FIS). It combines experts' knowledge via four main components – fuzzification, fuzzy inference rules, aggregation and defuzzification with fuzzy logic. The primary data on water resources generally has crisp values. Measured values are not essentially deterministic, and fuzzification is a mechanism by which observed crisp values are changed into fuzzy ones. Different methods, such as inference or rank-ordering can be used here. The converted fuzzy values lie in the range of 0 and 1. This process can be described by the following equation:

$$\mu_A : X \rightarrow [0,1]$$

where:
X is the universal set,
A is a given crisp set.

The last process of using fuzzy logic is defuzzification. It is the process of transforming fuzzy data into clear data. The output of a fuzzy system is fuzzy or linguistic variables, but real applications require explicit values for further processing. This method uses another index, such as WQI (Sivanandam et al., 2007). The final classification of the value of this indicator requires the use of the matrix theory. It is important to remember that if the fuzzy water method is used, the first stages of the analysis can be prepared using an Excel spreadsheet and GIS software. However, the final calculations require Matlab software or programming languages like Python. This is a different approach than simple calculations, as in the case of previous measures.

Results

The results below present selected applications of the described indices to assess the risk to water in waste landfills or surface waters subject to negative anthropogenic activity.

Water Quality Index (WQI)

The article by Ferreira et al. (2023), describes the research on groundwater quality near the Olusosun landfill in Lagos, Nigeria. Samples for testing were taken from wells and boreholes and analysed regarding their physicochemical parameters. Differences between locations and seasons, as well as changes in the WQI values, were statistically calculated. The results concluded that heavy metals, such as Pb^{2+}, Ni^{+}, Mn^{2+}, Fe^{2+}, Cr^{6+}, and cations, such as Ca^{2+}, Mg^{2+}, K^{+}, and pH and total hardness, are the main water pollutants. It was also observed that water quality standards were exceeded during the rainy season, and some groundwater properties (e.g., Fe^{2+}, Pb^{2+}, NO_3^{-}) were negatively related to the distance from the landfill. The WQI ranged from excellent (6–24% of sites during the study period) to unsuitable for drinking purposes (12–18%), but good quality prevailed in most sites (35–47%). It did not matter that in 2020, groundwater quality decreased in 24% of locations, and the results showed improvement compared to the previous ten years. Research has clearly shown a problem with good water quality, indicating a potential threat to human health. In this case, mitigation strategies must be implemented to protect public health and sustainability of water resources.

The next article (Ravi et al., 2023) discusses samples collected from the Ghaghara River, Nepal, examined and analysed to determine their quality and suitability for domestic, agricultural and industrial use. The article was not directly related to landfills but concerned anthropogenic pollutants that may migrate to groundwater due to contact between surface water and groundwater. In the Ghaghara River, cations were in the order $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$, while anions were in the order $HCO_3^{-} > SO_4^{2-} > Cl^{-} > NO_3^{-} > F^{-}$. The high concentration of ions in the river was mainly caused by chemical weathering in the river basin. The weak acid anions dominated over the strong acids, indicating the type of water as Ca-HCO_3. Based on the WQI values, the water quality class ranged from 19 to 49 during the pre-monsoon season, 11 to 70 during the monsoon, and 53 to 142 during the post-monsoon season. The parameters of concern were pH and fluoride ion concentration, which exceeded the permissible limits during the post-monsoon season and negatively affected the WQI values to an inappropriate category. The calculated value of agricultural indicators, including sodium absorption rate (SAR), sodium percentage (Na%), Kelly's ratio (KR), permeability index (PI), magnesium absorption rate (MAR) and potential salinity (PS) showed that the water quality was suitable for use in agriculture. The Langelier saturation index values showed that 39% of the collected samples were unsuitable due to scale forming and corrosive properties of the source water. The Ryznar stability index values indicated that the water in the Ghaghara River was corrosive and unsuitable for industrial use. Proper water treatment is necessary and can be achieved by building more sewage treatment plants, limiting the discharge of untreated sewage into the river, and limiting the use of fertilisers and pesticides.

The article by Sunny (2023) analysed groundwater quality near abandoned landfills in Port Harcourt, an industrial city in Nigeria. Nine samples were collected from three abandoned landfills and analysed for physicochemical parameters and heavy metals. Water pollution indicators, such as the Water Quality Index (WQI), Pollution Load Index (PLI), Heavy Metal Evaluation Index (HEI), and Heavy Metal Pollution Index (HPI), were used to analyse water quality. Studies showed that in all locations, only nickel (Ni-0.06 mg/l) exceeded the concentration of heavy metals. This study's water quality index (WQI) was designed to measure human water consumption potential. Sample performance (WQI) was estimated based on Sahu and Sikdar (2008), where excellent water was about 35 and good water was about 61. The PLI ranged from about 0.14 to 0.17, and the HEI from 4.9 to 5.1, meaning there was no pollution or its level was low. However, in two samples, the HPI was positive, while in one, it was negative, which meant the water was unsuitable for drinking.

The article by Kareem et al. (2021) described studies of the water quality of a river by calculating three types of water quality indicators in two ways, including and excluding the concentration of phosphates (PO_4). This parameter best met the water quality standard. The water quality indicators used were the Arithmetic Weighted Water Quality Index (WAWQI), the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI), and the Oregon Water Quality Index (OWQI). Water quality was tested using 15 parameters: pH, biological oxygen demand, turbidity, total hardness, orthophosphates, sulphates, nitrates, alkalinity, potassium, sodium, magnesium, chloride, dissolved oxygen, calcium and total dissolved solids. The average value of the results for the WAWQI index for three sites of Al-Kufa, Al-Manathera and Al-Abbassia, including PO_4, were 34, 44 and 38, respectively, which is a good result. However, after excluding PO_4, the water quality was described as very poor depending on the values obtained, which were 87, 89 and 92. The CCME WQI values for the three sites were about 64, 60 and 56, including PO_4, so the water quality was satisfactory. According to the OWQI, the water quality for the three sites was very poor in two cases, as its value was below 59.

The use of the WQI requires calculating weights for individual parameters. It is the only limitation to the applicability of this method. Additionally, it is worth conducting a comparative analysis of the results by determining seasonality or considering climatic conditions.

Landfill Water Pollution Index (LWPI)

The first example of using the LWPI is the assessment of spatiotemporal variability of water pollution near a municipal waste landfill based on analyses for heavy metals and 23 physicochemical parameters (Baghanam et al., 2020). The research was complemented by comparing the results of principal component analysis and self-organising map (SOM). In this study, contaminated samples ranged from 1 to 43. Clustering results showed that both methods divided surface and groundwater samples into five clusters, while the index classified them into three groups.

The article by Gorzelak and Dąbrowska (2021) describes water and leachate monitoring in the landfill in Poczesna, Poland, using the Landfill Water Pollution Index (LWPI). In the years 2015–2019, samples were taken from six piezometers and tested for such physicochemical parameters as pH, electrical conductivity (EC), total organic carbon (TOC), polycyclic aromatic hydrocarbons (PAH), Cd, Pb, Zn, Cu, Cr and Hg. The LWPI results in groundwater samples ranged from 1 to 3. This showed that the water quality was poor and that landfills impacted it. As the studies showed, the groundwater quality in the landfill area was higher in the Jurassic aquifer than in the Quaternary one.

The LWPI was also used in the article by Knopek and Dąbrowska (2021) to study the variability of groundwater contamination in the municipal waste landfill in Sosnowiec in southern Poland. Five physicochemical indicators were used to monitor water quality from 2014 to 2019: EC, SO_4^{2-}, Cl^-, Na and Fe. In addition, this study used the Backman Pollution Index (BPI). The results confirmed the negative impact of the landfill on the environment. A particularly negative impact was observed in the southern part of the study area, where the BPI values were as high as approximately 1400, while the LWPI reached 305.

The LWPI was purposely created to assess the risk to water in landfills. In the first article describing it, weights for individual parameters were specified and then considered. However, they can be modified according to the individual authors' knowledge. The weight selection used in Baghanam's work certainly provides an alternative to the traditional approach to this task.

Nemerov Pollution Index (NPI)

In the article by Dąbrowska and Witkowski (2022), 32 groundwater samples from 1995, 2003, 2010 and 2021 were used to assess the water quality near the municipal waste landfill in Tychy, Poland. Four water quality indicators, including the NPI, were used. Metals (Pb, Cd, Ni, Cu, Fe and Zn) were taken into account, as well as chlorides, sulphates and NH_4^+, which had a significant impact on the final results of the indicators. In 1995, the NPI showed that the water in the piezometer at the groundwater outflow was five times higher than in the one between the landfills. With subsequent tests, these differences increased to over 50 times. The lowest index values were observed in the piezometer west of the closed landfill. This study shows how very high values of the NPI can be obtained.

Based on the article authored by Łukasik and Dąbrowska (2022), using the Nemerov Pollution Index (NPI) based on data from the five-year monitoring of water quality at Lipówka I and Lipówka II municipal waste landfills in Dąbrowa Górnicza (southern Poland), a comprehensive assessment of the state of groundwater in this area was carried out. Seven key parameters were considered: pH, electrical conductivity, and concentrations of chlorides, sulphates, ammonium ions, boron and Fe^{2+}. The limits set for class III water quality were adopted as a reference point. It is not, however, the only possible variant of selecting the hydrochemical background. The results of the NPI calculations indicated that the highest values occured in piezometers PZ5 and T5, located at the outflow from Lipówka I landfill. For these piezometers, the values of specific electrical conductivity alone reached 2000 μS/cm. Particularly high values of the NPI were recorded for ammonium ions, reaching over 36 in the case of the PZ5 piezometer and 17 in the case of T5. Nevertheless, the remaining parameters did not indicate a significant impact of landfills' location on groundwater quality. Chlorides also contributed to the indicator's high values. Apart from significant differences in the content of ammonium ions, the values of the NPI for electrical conductivity were twice as high for PZ5 as for the others and four times higher than for boron.

Backman Index

In the article by Karkocha (2021), the main aim of the research was to precisely determine groundwater quality in the landfill in Wojkowice (southern Poland). In this context, the Backman Index was used to provide a comprehensive assessment of the state of the aquatic environment. A novelty was the use of a much wider range of parameters compared to those included in the original publication of the formula. The pollution index was calculated separately for each water sample, considering parameters such as EC, TOC, Cd, Pb, Zn, Cu, Cr^{6+}, NO_3^-, NO_2^- and NH_4^+. The index values ranged from -5 (the piezometer located in the groundwater inflow to the landfill) to 603, constituting a significant variation. The values exceeding 3 suggest the facility's impact on groundwater.

Another example of BI use is the article by Sołtysiak et al. (2018), in which a comprehensive attempt was made to determine the degree of sensitivity of groundwater in an industrialised area in the Dąbrowa Górnicza district (southern Poland). The Backman's Index was calculated and supplemented with two dynamic leaching tests and two static tests, using different slag samples from one of the industrial waste landfills. The analysis of pollutants according to the Backman Index gave a result exceeding 30. This index considered chlorides, sulphates, sodium, potassium, magnesium, and calcium. In the case of this study, the values of the hydrogeochemical background were taken from the paper by Różkowska et al. (1972), based on the data from the 1960s. It is one of the examples where the background was not based on regulations but on the hydrogeological conditions before anthropogenic changes.

The BI is simple to use. It is important to note that the authors of the articles above based their calculations on different reference values. However, using the natural hydrogeochemical background data was possible in one of the studies.

Canadian Water Quality Index (CCME WQI)

The Canadian WQI was used, among others, by Ahmed et al. (2020). As part of the study, water quality tests were carried out in 65 samples in 2016. These samples were subjected to experiments during which physicochemical parameters were determined. The parameters were assessed by comparing their values with the standards set by the Bureau of Indian Standards (BIS). The analysis showed that the values of total hardness, total dissolved solids, chlorides and magnesium significantly exceeded (>50%) the permissible limits. Most samples had high levels of nitrates and chlorides. The Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} sources were related to weathering processes. With ion exchange, agriculture and sewage disposal, complex weathering processes regulate water chemistry. The indicators' values ranged from 1.9 to 82, which suggests differences between good and poor water status. As a complementary element of the study, a map of the distribution of this index in the analysed research area was created using Inverse Distance Weighting (IDW) one of types of deterministic method for multivariate interpolation.

A detailed assessment of groundwater quality for drinking and irrigation near the Rooppur Nuclear Power Plant in Bangladesh was described in the article by Uddin et al. (2023). The research area was subject to the water monitoring guidelines as landfills, so research conducted at such a facility can be considered a good example of using the described index. In this study, nine groundwater samples were collected seasonally in both the dry and rainy seasons. Then, seventeen hydrogeochemical indicators were analysed (temperature, electrical conductivity, pH, total dissolved solids, total alkalinity, total hardness, total organic carbon, bicarbonates, chlorides, phosphates, sulphates, nitrites, nitrates, sodium, potassium, calcium and magnesium). The average index values ranged from 48 to 74 in the dry season and 40 to 65 in the wet season. These values suggested that groundwater quality needed to be classified as "poor" and "marginal" in the rainy season, indicating that the water was unsuitable for human consumption. Irrigation rates mostly confirmed that the water was suitable for growing crops during the dry season.

In the case of this index, attention should be paid to the final result of the calculations. The final value of the index is incomparable to other measures because increasing values show better water quality.

Horizontal Ratio

The Horizontal Ratio index was used in two studies: by Olagunju et al. (2020) and Dąbrowska and Witkowski (2022). In the earlier, the indicator was used for soils in a landfill area in Nigeria. For a single component, the highest recorded value was 2.5 (Cu), while the total value for the parameters Zn, Ni, Pb, Cd, and Fe was approximately 10. In that case, the indicator was used for soil, difficult to compare with that calculated for groundwater. In the latter article, the index was used to assess the risk of groundwater and human health in the vicinity of the municipal waste landfill in Tychy, Poland, in 2003 and 2010. The index values for 2003 indicated that the water in all piezometers was more polluted at the start of the system operation than after flowing under the landfill. This would suggest that the landfill did not impact the water quality, which was an incorrect conclusion considering groundwater monitoring results. The indicator’s total value, which was very high, resulted from identical low values of heavy metals in water both in the piezometer located at the groundwater inflow to the landfill and in the other piezometers. In 2010, the index values already indicated the impact of the landfill on groundwater. In one case, the value of the index was greater than 10, which was related to the low content of sulphates in the water of that specific piezometer. This result was related to the low content of sulphates in the piezometer waters, which showed the greatest contamination. The Horizontal Ratio indicator has not been used for groundwater in Poland, and its applicability is controversial.

Enrichment Factor

The Enrichment Factor (EF) was described in the abovementioned article by Dąbrowska and Witkowski (2022). A set of data, including Pb, Cd, Cr, Ni, Cu, Fe, Zn, chlorides, sulphates, and NH_4, were used in this study. The EF values fluctuated significantly in different measurement years. The 1995 and 2003 years showed comparable values of most piezometers, except for the one located between the closed and active landfills. There very high values were recorded of about 18 000 in 1995 and almost 300 in 2003. During these two years, significant changes were observed, such as a six-fold reduction in the water indicators values in the piezometer located west of the closed landfill and a more than four-fold reduction in one of the points located at the outflow from the old landfill. Ammonium ion was an additional component that contributed to the increase of this indicator for most parameters. The Enrichment Factor, primarily used for soil contamination, was used once in groundwater studies (Hakanson, 1980). The values mentioned there ranged from -61 to 43, which indicated a low risk for water. However, the values of this indicator for individual ingredients recorded in the 2022 study were over 4000.

It is important to note that the values for the immobile parameter should be used for this index. Additionally, the final results of the calculations may not be as objective as those obtained using indicators that refer to the hydrogeochemical background for all parameters.

Fuzzy water quality

The article by Zeng et al. (2022) uses the so-called Pollution Scale Weighting Model (PSWM) based on improved fuzzy variable theory. This model was introduced in place of the entropy weights model, which is considered an objective method of adjusting weights for individual parameters used to assess water quality. However, in the case of a pollutant that classifies waters as highly contaminated, the entropy model often neglects its significance due to its low degree of discrimination. In the new model, the higher the degree of pollution, the greater its weight, and vice versa. The model was applied to assess water quality in southeastern China, where the following levels for COD, NH3-N and phosphorus were obtained: 0.4, 0.3 and 1, respectively, their weights being 0.2, 0.19 and 0.58. The water quality indices in the studied waters were 36.2, 28.6, 25.7 and 21.1, all falling into the "poor" quality category. Using the new model highlights the role of parameters with higher concentrations that negatively impact overall water quality.

Furthermore, the article by Jha et al. (2020) used a combination of Geographic Information System (GIS) tools with water quality indices and presented an innovative hybrid structure that adds Fuzzy Logic to the whole. The article concerned the assessment of the quality of groundwater and its spatial variability. The proposed hybrid framework was applied in a case study conducted in the hard, rocky terrain of South India. The article used ten water quality parameters measured at different times of the year. Two conventional GIS-based water quality index models were developed for ten and seven physicochemical parameters. Additionally, the results of the hybrid model for seven parameters were presented in the article. The content of calcium, magnesium, sulphates, sodium, chlorides, potassium, sodium, fluorine, nitrates, total dissolved substances and hardness were taken into account. Comparative analysis of the baseline models showed that the hybrid model predicted groundwater quality better than conventional models. The study also found that groundwater quality deteriorated during the monsoon season compared to the pre-monsoon season, indicating an increased influx of pollutants from various anthropogenic sources. The entire study confirms that using advanced mathematical methods when assessing water quality gives much better results than traditional methods.

Water risk analysis based on the fuzzy water quality index is incomparable to previous indicators. The process involves several stages and requires using GIS tools and a programming environment. However, in the case of other measures, various sets of parameters subject to analysis can be considered in this approach.

Summary and Conclusions

This article reviewed the most common indices used to assess groundwater quality. The review concerned the Water Quality Index, Landfill Water Pollution Index, Nemerow Pollution Index, Backman Index, Canadian Water Quality Index, Water Quality Index, Horizontal Ratio, Enrichment Factor and Fuzzy water quality. Most indices can be used for any number of physicochemical parameters for which data is obtained by monitoring groundwater. These methods may be particularly applicable in areas of groundwater pollution sources, such as industrial and municipal landfills and incinerators. Among one group of indices, there are those for which the parameters have the same impact on the overall index value (indices without using weights), e.g. the Nemerow Pollution Index or Backman Index, and which use weights assigned to individual parameters, e.g. the Landfill Water Pollution Index. The second group is more challenging due to the need to adjust the weights based on hydrogeological knowledge or using mathematical methods. However, all indices use reference values to which the monitoring results are related. The best solution is to determine the water quality relative to the natural hydrogeochemical background, which is impossible in many cases, especially in industrialised areas. Hence, regulations regarding water quality, especially for human consumption, are applied. Additionally, an immobile parameter needs to be selected in the case of some indicators, such as the Enrichment Factor. This parameter should not be subject to various chemical processes, and the values of individual parameters should be related to it. In industrial waste landfills, selecting an immobile parameter may be difficult because such an area may be highly contaminated with metals, and this parameter is often chosen due to low redox potential. This causes further discussions on the appropriate selection of such an element. Another example of an index that may be controversial is the Horizontal Ratio, which imposes the selection of an observation point for which the distances between other points are calculated and which constitutes the background. In the case of highly industrialised regions, even points located at the inflow of groundwater to, for example, a landfill may be subject to the influence of other pollutants.

To present the risk to water as simply as possible, the method should be limited to selecting indices that refer directly to the upper limit values of hydrogeochemical background, such as the Nemerow Index. However, this approach means each parameter similarly impacts the final index value. Parameters close to the background value lower the index value. The choice of indices that include weights for various components will always be controversial because the weights can be adjusted to highlight the impact of specific water components while concealing the importance of others. Using the Canadian Water Quality Index requires analysing additional explanations of how this index was calculated. Additionally, it should always be considered who the recipient of the prepared analysis is, how easy it will be to understand the results, and what impact of individual parameters on the index's total value will be.

All indices are supporting tools for assessing the groundwater quality and can be used to assess risk to water. However, they should be used considering knowledge of the hydrogeological conditions of analysed areas and knowledge of, e.g. failures at landfills, the type of waste collected at the landfill, its amount, storage conditions, methods of leachate disposal and thermal conditions. Analysis of the possibilities of using the described indices does not guarantee the selection of the best one. However, considering the number of possible parameters used when calculating the index, the reference values that can be used for calculations, the number of intervals into which the index is divided, the need to use specialised software and the need to combine a given index with another method for unambiguous interpretation, the Water Quality Index seems to be the most optimal for assessing the risk to groundwater.

References

Ahmed, S.M., Taha, O.M., Najemalden, M.A., Ahmed, R.T., Abedulwahab, A.A. (2020). Assessment of Lower Zab river water quality using both Canadian Water Quality Index Method and NSF Water Quality Index Method. *Scientific Review Engineering and Environmental Sciences (SREES)*, *29* (2), 155–171. doi: https://doi.org/10.22630/PNIKS.2020.29.2.14

Alam, S., Borthakur, A., Ravi, S., Gebremichael, M., Mohanty, S.K. (2021). Managed aquifer recharge implementation criteria to achieve water sustainability. *Sci. Total Environ*, *768*, 144992. doi: https://doi.org/10.1016/j.scitotenv.2021.144992

Al-Janabi, Z., Kubaisi, A.R., Jwad Al-Obaidy, A.M. (2012). Assessment of Water Quality of Tigris River by using Water Quality Index (CCME -WQI). *Journal of Al-Nahrain University*, *15*(1), 119–126.

Backman, B., Bodis, D., Lahermo, P., Rapant, S., Tarvainen, T. (1998). Application of a contamination index in Finland and Slovakia. *Environmental Geology*, *36*(1–2), 55–64.

Baghanam, A., Nourani, V., Aslani, H., Taghipour, H. (2020). Spatiotemporal variation of water pollution near landfill site: Application of clustering methods to assess the admissibility of LWPI. *Journal of Hydrology*, *591*. doi: https://doi.org/125581.10.1016/j.jhydrol.2020.125581

Baghanam, A.H., Vakili, A.T., Nourani, V., Dąbrowska, D.A., Sołtysiak, M. (2022). AI-based ensemble modeling of landfill leakage employing a lysimeter, climatic data and transfer learning. *Journal of Hydrology*, *612*. doi: https://doi.org/10.1016/j.jhydrol.2022.128243

Bhuiyan, M., Bodrud-Doza, M., Islam, A., Rakib, M., Rahman, M., Ramanthan, A. (2016). Assessment of groundwater quality of Lakshimpur district of Bangladesh using water quality indices, geostatistical methods and multivariate analysis. *Environmental Earth Sciences*, *75*, 12. doi: https://doi/org/10.1007/s12665-016-5823-y

Blachnik, M., Sołtysiak, M., Dąbrowska, D. (2019). Predicting presence of amphibian species using features obtained from gis and satellite images. *ISPRS International Journal of Geo-Information*, *8*(3), 123.

Chandra, S.D., Asadi, S.S., Raju, M.V.S. (2017). Estimation of water quality index by weighted arithmetic water quality index method: a model study. *Int Journal of Civil Engineering and Technology*, *8*(4), 1215–1222.

Chegbeleh, L.P., Akurugu, B.A., Yidana, S.M. (2020). Assessment of groundwater quality in
the Talensi District, Northern Ghana. *The Scientific World Journal*, 8450860. https://doi.org/10.1155/2020/8450860

Chen, S.Y. (1998). *Engineering Fuzzy Set Theory and Application*. Beijing: Natl Def Ind Press.

Childs, C. (1973). Relative Mobility of Iron and Manganese in Sedimentary Processes. *Nature Physical Science*, *241*, 119.

Christensen, T., Kjeldsen, P., Bjerg, P., Jensen, D., Christensen, J., Baun, A., Albrechtsen, H., Heron, G. (2001). Biogeochemistry of landfill leachate plumes. *Applied Geochemistry*, *16*, 659–718.

Dąbrowska, D. (2022). The HYPERLINK "https://scholar.google.com/citations?view_op=view_citation&hl=pl&user=YD4lK3IAAAAJ&sortby=pubdate&citation_for_view=YD4lK3IAAAAJ:vV6vV6tmYwMC"Lipówka HYPERLINK "https://scholar.google.com/citations?view_op=view_citation&hl=pl&user=YD4lK3IAAAAJ&sortby=pubdate&citation_for_view=YD4lK3IAAAAJ:vV6vV6tmYwMC" landfills: a case study in groundwater quality assessment. *Acta Scientiarum Polonorum: Formatio Circumiectus*, *21*(1).

Dąbrowska, D., Rykała, W. (2021). A Review of Lysimeter Experiments Carried Out on Municipal Landfill Waste. *Toxics*, *9*(26). doi: https://doi.org/10.3390/toxics9020026

Dąbrowska, D., Rykała, W., Nourani, V. (2023). The impact of weather conditions on the quality of groundwater in the area of a municipal waste landfill*. Environmental & Socio-economic Studies*, *11*(3), 14–21.

Dąbrowska, D.A., Kucharski, R., Witkowski, A.J. (2016). The representativity index of a simple monitoring network with regular theoretical shapes and its practical application for the existing groundwater monitoring network of the Tychy-Urbanowice landfills, Poland. *Environmental Earth Sciences*, *75*, 1–9.

Dąbrowska, D., Witkowski, A., Sołtysiak, M. (2018a). Application of pollution indices for the assessment of the negative impact of a municipal landfill on groundwater (Tychy, southern Poland). *Geological Quarterly*, *62*(3), 496–508.

Dąbrowska, D., Witkowski, A., Sołtysiak, M. (2018b). Representativeness of the groundwater monitoring results in the context of its methodology: case study of a municipal landfill complex in Poland. *Environmental Earth Sciences*, *77*, 266. doi: https://doi.org/10.1007/s12665-018-7455-x

Dąbrowska, D., Witkowski, A. (2022). Groundwater and Human Health Risk Assessment in the Vicinity of a Municipal Waste Landfill in Tychy, Poland. *Applied Sciences*, *12*(24), 12898

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R.D.G. et. al. (2019). Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal*, *27*(1), 1–30.

Dooge, J. (2009). *Fresh Surface Water*. Oxford: Eolss Publishers Company Limited.

Esmaeilian, B., Wang, B., Lewis, K., Duarte, F., Ratti, C. et. al. (2018). The future of waste management in smart and sustainable cities: A review and concept paper. *Waste Management*, *81*, 177–195.
Ferreira, C., Adama-Ajonye, O., Ikenna, A. Kalantari, Z. (2023). Groundwater quality in the vicinity of a dumpsite in Lagos metropolis, Nigeria. *Geography and Sustainability*, *4*(4), 379–390. doi: https://doi.org/10.1016/j.geosus.2023.09.005
Gorzelak, M., Dąbrowska, D. (2021). Assessment of changes in the quality of ground water in the area of landfill site in Poczesna (South Poland) using the LWPI index. *Environmental & Socio-economic Studies*, *9*, 35–43.
Gwenzi, W., Gora, D., Chaukura, N., Tauro, T. (2016). Potential for leaching of heavy metals in open-burning bottom ash and soil from a non-engineered solid waste landfill. *Chemosphere*, *147*, 144–154.
Horton, R.K. (1965). An index number system for rating water quality. *Journal of the Water Pollution Control Federation*, *37*(3), 300–306.
Hakanson, L. (1980). An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Research*, *14*, 975–1001.
Jha, M., Shekhar, A. Jenifer, M. (2020). Assessing groundwater quality for drinking water supply using hybrid fuzzy-GIS-based water quality index. *Water Research*, *179*. doi: https://doi.org/10.1016/j.watres.2020.115867
Jousma, G., Roelofsen, F.J. (2004). *World-wide inventory on groundwater monitoring*. Report nr. GP 2004–1. IGRAC, Utrecht.
Kareem, S., Jaber, W., Al-Maliki, L., Al-husseiny, R., Al-Mamoori, S., Alansari, N. (2021). Water quality assessment and phosphorus effect using water quality indices: Euphrates River-Iraq as a case study. *Groundwater For Sustainable Development*, *14.* doi: https://doi.org/10.1016/j.gsd.2021.100630
Karkocha, R. (2021). Assessment of changes in the quality of groundwater in the region of the municipal landfill in Wojkowice. *Acta Scientiarum Polonorum. Formatio Circumiectus*, *20*(1), 43–54.
Knopek T., Dabrowska D. 2021. The Use of the Contamination Index and the LWPI Index to Assess the Quality of Groundwater in the Area of a Municipal Waste Landfill. *Toxics*, *9*, 66. doi: https://doi.org/10.3390/toxics9030066
Kumar, P. (2018). Simulation of Gomti River (Lucknow City, India) future water quality under different mitigation strategies. *Heliyon*, *4*. doi: https://doi.org/10.1016/j.heliy on. 2018. e01074
Kumar, V., Parihar, P., Sharma, A., Bakshi, P., Sidhu, G., Bali, A., Karaouzas, I., Bhardwaj, R., Thukral, A., Gyasi-Agyei, Y. (2019). Global evaluation of heavy metal content in surface water bodies: a meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *Chemosphere*, *236*, 124364
Kurnaz, A., Mutlu, E., Uncumusaoğlu, A. (2016). Determination of water quality parameters and heavy metal content in surface water of çiğdem pond (kastamonu/Turkey). *Turkish Journal of Agriculture – Food Science and Technology*, *4*, 907–913
Lalik, M., Dąbrowska, D. (2024). Groundwater Chemical Status Assessment in the Area of the Waste Landfill in Chorzów – Southern Poland. *Sustainability*, *16*(2), 763. doi: https://doi.org/10.3390/su16020763
La Mora-Orozco, D., Flores-Lopez, H., Rubio-Arias, H., Chavez-Duran, A., Ochoa-Rivero, J. (2017). Developing a water quality index (WQI) for an irrigation dam. *International Journal of Environmental Research and Public Health*, *14*(5), 439.
Li, Y., Li, J., Chen, S., Diao, W. (2012). Establishing indices for groundwater contamination risk assessment in the vicinity of hazardous waste landfills in China. *Environmental Pollution*, *165*, 77–90.
Liu, J., Gao, Z., Feng, J., Wang, M. (2023). Identification of the hydrochemical features, genesis, water quality and potential health hazards of groundwater in Dawen River Basin, North China. *Ecological Indicators*, *149*, 110175.
Lumb, A., Sharma, T., Bibeault, J. (2011). A review of genesis and evolution of water quality index (wqi) and some future directions. *Water Quality, Exposure and Health*, *3*, 11–24.

Łukasik, M., Dąbrowska, D. (2022). Groundwater quality testing in the area of municipal waste landfill sites in Dąbrowa Górnicza (southern Poland). *Environmental & Socio-economic Studies*, *10*(1),13–21. doi: https://doi.org/10.2478/environ-2022-0002

Mishra, V., Kim, K., Kang, C., Choi, K. (2004). Wintertime sources and distribution of airborne lead in Korea. *Atmos Environ*, *38*(17), 2653–2664.

Nielsen, D. (2006). *Practical Handbook of Environmental Site Characterization and Ground-water Monitoring*. 2nd edition. CRC Press Taylor & Francis Group.

Olagunju, T., Olagunju, A., Akawu, I., Ugokwe, C. (2020). Quantification and Risk Assessment of Heavy Metals in Groundwater and Soil of Residential Areas around Awotan Landfill, Ibadan, Southwest-Nigeria. *Journal of Toxicology and Risk Assessment*, *6*, 033. doi: https://doi.org/10.23937/2572–4061.1510033

Paun, I., Cruceru, L., Chiriac, F.L., Niculescu, M., Vasile, G.G., Marin, N.M. (2016). Water quality indices – methods for evaluating the quality of drinking water. In: *Proceedings of the 19th INCD ECOIND International Symposium – SIMI 2016. "The Environment and the Industry," Bucharest, Romania, 13–14 October 2016*, 395–402. doi: https:// doi. org/10. 21698/ simi. 2016. 0055

Quevauviller, P., Fouillac, A., Grath, J., Ward, R. (eds.). (2009). Groundwater monitoring. Water Quality Measurements Series, John Willey & Sons, Ltd.

Ravi, N.K., Jha, P.K., Varma, K., Tripathi, P., Gautam, S.K., Ram, K., Kumar, M., Tripathi, V. (2023). Application of water quality index (WQI) and statistical techniques to assess water quality for drinking, irrigation, and industrial purposes of the Ghaghara River, India. *Total Environment Research Themes*, 6, 100049.

Różkowska, A., Różkowski, A., Rudzińska, T. (1972). Hydrochemical characteristics of the Triassic aquifer of Silesia – Cracow region. *Biuletyn Państwowego Instytutu Geologicznego*, *282*.

Rykała, W., Fabiańska, M.J., Dąbrowska, D. (2022). The Influence of a Fire at an Illegal Landfill in Southern Poland on the Formation of Toxic Compounds and Their Impact on the Natural Environment. *International Journal of Environmental Research and Public Health*, *19*, 13613. doi: https://doi.org/10.3390/ijerph192013613

Sahu, P., Sikdar, P.K. (2008). Hydrochemical Framework of the Aquifer in and around East Kolkata Wetlands, West Bengal, India. *Environmental Geology*, *55*, 823–835.

doi: https://doi.org/10.1007/s00254-007-1034-x

Schreiber, S., Schreiber, S., Tanna, R., Roberts, D., Arciszewski, T. (2022). Statistical tools for water quality assessment and monitoring in river ecosystems – a scoping review and recommendations for data analysis. *Water Quality Research Journal*, *57*, 40–57.

Shah, K.A., Joshi, G.S. (2017). Evaluation of water quality index for River Sabarmati, Gujarat, India. *Applied Water Science*, *7*, 1349–1358. doi: https://doi.org/10.1007/s13201-015-0318-7

Sitek, S., Janik, K.R., Dąbrowska, D.A., Różkowski, J., Wojtal, G. et. al. (2023). Risk assessment for the prevention of managed aquifer recharge (MAR) facility failure during the operation and the expansion phases. *Journal of Hydrology*, *621*.

Sivanandam, S.N., Sumathi, S., Deepa, S.N. (2007). I*ntroduction to fuzzy logic using MATLAB*. Berlin–Heidelberg: Springer.

Slack, R., Gronow, J., Voulvoulis, N. (2005). Household hazardous waste in municipal landfills: contaminants in leachate. *Science of the Total Environment*, *33*, 119–137.

Sołtysiak, M., Dąbrowska, D. (2016). The smoothing methods used in assessing the influence of pollution sources on groundwater quality – a case study of metallurgical landfill in Lipówka (southern Poland). *Environmental & Socio-economic Studies*, *4*, 61–67.

Sołtysiak, M., Dąbrowska, D., Jałowiecki, K., Nourani, V. (2018). A multi-method approach to groundwater risk assessment: A case study of a landfill in southern Poland. *Geological Quarterly*, *62*(2), 361–374.

Srinivasa, R., Bhakara, P., Singha, A.P. (2015). Groundwater quality assessment in some selected area of Rajasthan, India using fuzzy multi-criteria decision making tool. International Conference on Water Resources, Coastal and Ocean Engineering (ICWRCOE, 2015). *Aquatic Procedia*, *4*, 1023–1030. doi: https://doi.org/10.1016/j.aqpro.2015.02.129.

Sun, X., Xu, Y., Liu, Y., Nai, Ch., Dong, L. (2019). Evolution of geomembrane degradation and defects in a landfill: Impacts on long-term leachate leakage and groundwater quality. *Journal of Cleaner Production*, *224*, 335–345.

Sunny, O. (2023). Quality assessment of groundwater sourced from nearby abandoned landfills from Industrial City in Nigeria: Water pollution indices approach. *HydroResearch*, *6*(1), 130–137. doi: https://doi.org/10.1016/j.hydres.2023.03.002.

Talalaj, I. (2014). Assessment of groundwater quality near the landfill site using the modified water quality index. *Environmental Monitoring and Assessment*, *186*, 3673–3683.

Talalaj, I. (2015). Mineral and organic compounds in leachate from landfill with concentrate recirculation. *Environmental Science and Pollution Research*, 22 (4), 2622–2633.

Talalaj, I., Biedka, P. (2016). Use of the Landfill Water Pollution Index (LWPI) for Groundwater Quality Assessment Near the Landfill Sites. *Environmental Science and Pollution Research*, *23*, 24601–24613.

Tanna, R., Moncur, M., Birks, J., Gibson, J., Ptacek, C. et al. (2020). Utility of a mul-ti-tracer approach as a component of adaptive monitoring for municipal wastewater impacts. *Water Quality Research Journal*, *55*, 327–341.

Uddin, M.G., Diganta, M., Sajib, A., Hasan, M., Moniruzzaman, M. et. al. (2023). Assessment of hydrogeochemistry in groundwater using water quality index model and indices approaches. *Heliyon*, *9*(9), e19668. doi: https://doi.org/10.1016/j.heliyon.2023.e19668

Vilomet, J., Angeletti, B., Moustier, S., Ambrosi, J., Wiesner, M., Bottero, J., Chatelet- Snidaro, L. (2001). Application of strontium isotopes for tracing landfill leachate plumes in groundwater. *Environmental Science & Technology*, *35*, 4586–4591.

Wang, Y.K., Sheng, D., Wang, D., Ma, H.Q., Wu, J.C., Xu, F. (2014). Variable fuzzy set theory to assess water quality of the Meiliang Bay in Taihu Lake Basin. *Water Resources Management, 28*(3), 867–880.

Włodarczyk-Sielicka, M., Połap, D. (2019). Automatic Classification Using Machine Learning for Non-Conventional Vessels on Inland Waters. *Sensors*, *19*, 3051. doi: https://doi.org/10.3390/s19143051

Wright, C.R., Saffran, K., Anderson, A., Neilson, R., MacAlpine, N., Cooke S. (1999). A Water Quality Index for Agricultural Streams in Alberta: The Alberta Agricultural Water Quality Index (AAWQI). Prepared for the Alberta Environmentally Sustainable Agriculture Program (AESA). Published by Alberta Agriculture, Food and Rural Development. Edmonton.

Yang, Q., Zhang, L., Wang, H., Martín, J.D. (2022). Bioavailability and health risk of toxic heavy metals (As, Hg, Pb and Cd) in urban soils: a Monte Carlo simulation approach. *Environmental Research*, 214, 113772. https://doi.org/10.1016/j.envres.2022.113772

Yin, K., Tong, H., Giannis, A., Wang, J.Y. (2017). Chang, V.W.C. Multiple geophysical surveys for old landfill monitoring in Singapore. *Environmental Monitoring and Assessment*, *189*. doi: https://doi.org/10.1007/s10661-016-5722-4

Zakhem, B.A., Hafez, R. (2015). Heavy metal pollution index for groundwater quality assessment in Damascus Oasis, Syria. *Environmental Earth Sciences*, *73*, 6591–6600. doi: https://doi.org/10.1007/s12665-014-3882-5

Zeng, Q., Luo, X., Yan, F. (2022). The pollution scale weighting model in water quality evaluation based on the improved fuzzy variable theory. *Ecological Indicators*, *135*. doi: https://doi.org/10.1016/j.ecolind.2022.108562

Zhu, X., Chen, X., Struble, L., Yang, E. (2018). Characterization of calcium-containing phases in alkali-activated municipal solid waste incineration bottom ash binder through chemical extraction and deconvoluted Fourier transform infrared spectra. *Journal of Cleaner Production*, *192*, 782–789. doi: https://doi.org/10.1016/j.jclepro.2018.05.049

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