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Water-Energy-Environment-Governance from Interdisciplinary Perspectives

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Preface

This book serves as the inaugural volume in the new Sustainable Development of Water Resource and Environmental Management Series, offering a comprehensive introduction to the critical themes within. Delving into the intricate realm of sustainable development and management in the water sector, it addresses the profound challenges facing water resources amidst current global changes.

In the wake of these transformations, the availability and quality of water resources confront imminent threats. Notably, sustainable development emerges as a pivotal concern across all sectors related to water resources management, carrying profound implications for both present and future generations.

Curated from the noteworthy contributions of the 6th International Symposium on Water Resource and Environmental Management (WREM 2023), this book presents a collection of carefully selected papers that explore key themes in water resource and environmental management. Readers will find a wealth of information encompassing the fundamental principles of sustainable water resources management, recent advances, insights into future research directions, and the formulation of policies aimed at fostering sustainable water resources management.

Designed to cater to a diverse audience, this book is a valuable resource for beginners, researchers, and professionals engaged in the fields of water pollution and treatment, water engineering, and engineering structures. Whether you are initiating your journey into this field or are an established expert, the content within promises to enhance your understanding and contribute to the ongoing discourse in sustainable water resources management.

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Contents

Chapter 1
Assessing the Drinking Water Quality Indexes of Borehole and Surface Water Close to a Mining Dump in Welkom, South Africa

Silent Ruzvidzo and Saheed Oke

Abstract Groundwater is an important source of drinking water in most parts of Southern Africa where access to tap water is limited. In most cases, groundwater is used untreated as it is considered safe to drink than surface water. However, anthropogenic activities such as agriculture, landfills, and mining have resulted in the contamination of groundwater sources. This study examines the drinking water quality standards of 5 boreholes and a stream of water which are located near a mining dump in Welkom, Free State. In the study, water samples were periodically collected between the Autumn and Summer seasons of 2022. The concentrations of the physical, chemical, and microbiological determinants; Electrical Conductivity (EC), Total Dissolved Solids (TDS), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), fluoride (F), chloride (Cl), nitrate (NO_3), sulphate (SO_4), calcium hardness ($CaCO_3$), phosphate (PO_4), Magnesium hardness, Total coliform, Faecal coliforms, and *Escherichia Coli* were assessed against the SANS 241 (Guidelines for drinking water quality, 2015) and the WHO (Guidelines for drinking-water quality. World Health Organization, Geneva, 2017) guidelines for water quality standards. The study results indicated that none of the 5 boreholes had safe drinking water as their Water Quality Indices were poor. Abnormally high concentrations of Total Coliforms and *Escherichia Coli* coupled with seasonal variations were also noticed for all boreholes. Recommendations based on these findings are that the Welkom area residents should avoid drinking any borehole water before purification and treatment. Furthermore, the local authorities should be urgently alerted to remedy the situation and discuss solutions on the safe disposal of mining waste with the mining company.

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Keywords Groundwater · Drinking · Water quality · Contamination · Mining dump · Human Health

1.1 Introduction

The access to safe drinking water is a fundamental human right (WHO 2008, 2017). The pollution of groundwater sources has become a global problem with adverse effects on human health and the environment (Satheeskumar et al. 2020). In areas close to mining operations or mining tailings, the pollution of ground and surface water sources need to be investigated as the implications of water contamination might have serious health consequences for humans as well as animals (Ding et al. 2021).

To protect humans' health, different countries and international organisations have developed statutory regulations which stipulate the standards of the quality of drinking water for their populations. In South Africa, the South African National Standard 241 (SANS 241), provides the drinking water quality guidelines for all the portable water. Moreover, the World Health Organisation (WHO) also provides water quality guidelines to safeguard the general world population in areas where the drinking water standards are not explicitly detailed. In all, the drinking water quality standards highlight the physical, chemical, and microbiological determinants and concentrations that determine the suitability of drinking water in terms of the public health regulations.

To assess the drinking water quality standards encompassing a variety of determinants, the Water Quality Index (WQI) was developed (Zhou et al. 2021). Initially proposed by Horton (1965) and Brown et al. (1970) in 1972, the WQI has been modified and developed into different varieties so that it can adapt to different environments (Malan et al. 2003; Wertz and Shank 2019). Most of the WQI methods utilise physical and chemical parameters to calculate the index in different ways (Lumb et al. 2011). The WQI is used to measure the quality of the drinking water as per the regulatory standards. It is a rating that reflects the compound effect of various water quality determinants on the total quality of water. In essence, the WQI is a mathematical tool used to convert large amounts of water quality information to a single number, which provides the tools and basis for water quality managers to determine the quality and potential uses of a given body of water. The inclusion of different water quality parameters in the Water Quality Index depends on the context, purpose, and approach of the investigation (WRC 2017).

This study was undertaken to investigate the drinking water quality of the groundwater from 5 boreholes in Welkom including an open water stream close to a gold mine dump which is the suspected contaminant source. The investigation involved the use of the SANS 241 (SANS 2015) as well as the WHO (2017) water quality guidelines to establish the water quality from the sources.

1.2 Materials and Methods

Groundwater from the Central University of Technology campus boreholes, located in Welkom, was periodically sampled, and analysed in the Autumn and Summer seasons of 2022. To provide snapshots of the water quality at different times of the seasons, the grab method was used to collect the samples from 6 sampling sites at least 3 times per each season. 5 of the sampling sites were boreholes, and the 6th one was an open water stream located at no less than 100 m from a nearby mining dump. The accessibility of the boreholes, as well as their proximity to the mining dump, made them ideal sampling sites for the investigation. Figure 1.1 shows the location of the sampling points 1–6 across the CUT campus in Welkom and the coordinates are represented in Table 1.1.

Fig. 1.1 Sampling points (1–6) along the Central University of Technology Welkom campus and an open stream close to the mining dump (Google Maps 2023)

Table 1.1 Geographical coordinates of the sampling points

Sampling point	Description	Longitude	Latitude	Elevation (m)
1	Borehole 1	27° 56′ 57.9″ S	26° 47′ 05.7″ E	1,396
2	Borehole 2	27° 56′ 58.6″ S	26° 47′ 05.5″ E	1,391
3	Borehole 3	27° 56′ 52.4″ S	26° 47′ 08.6″ E	1,386
4	Borehole 4	27° 56′ 57.4″ S	26° 46′ 58.4″ E	1,397
5	Borehole 5	27° 56′ 57.4″ S	26° 46′ 55.3″ E	1,399
6	Open stream	27° 56′ 52.7″ S	26° 46′ 41.1″ E	1,403

The collected samples were analysed for Physical, Chemical, and Microbiological elements. The physical water quality parameters such as electrical conductivity (EC), Total Dissolved Solids (TDS), temperature, and pH, were analysed onsite using the HANS instruments whilst the chemical and microbiological determinants were analysed at the Institute of Ground Water Services laboratories (IGS) at the University of the Free State (UFS). The chemical and microbiological elements analysed were, pH, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), fluoride (F), chloride (Cl), nitrate (NO_3), sulphate (SO_4), calcium hardness ($CaCO_3$), phosphate (PO_4), Magnesium hardness, Total coliform, Faecal coliforms, and *Escherichia Coli*. For laboratory chemical analyses, sterile 500 ml bottles were used, while for microbiological analyses, sterile 100 ml bottles were used to collect water samples. All samples destined for the laboratory were labelled appropriately and placed in an icebox before being transported to the laboratory where they were analysed within a 12-h period.

The results from the physical, chemical, and micro-biological analysis were compared with the South African National Standards (SANS) 241 of 2015 as well as the World Health Organisation (WHO) 2017 standards to establish the percentage compliance for each borehole sample as well as for each parameter. The water quality for each borehole and the stream water was also calculated using the weighted arithmetic index method. Additionally, the microbiological parameters from the water samples were compared with the SANS 241 (2015) standards.

1.2.1 Methodology for Calculating the Water Quality Index (WQI)

As the water samples were collected at different time intervals of the season and at varying frequencies, the Weighted Arithmetic Index (WAI) method was selected as the most suitable method for calculating the water quality. Furthermore, the WAI utilises less complicated calculations that are easy to apply as compared to the other water quality index calculation methods.

The WAI method consisted of the following steps:

Step 1: Data collection of the physico-chemical water quality parameters including pH, electrical conductivity, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), fluoride (F), chloride (Cl), nitrate (NO_3), and sulphate (SO_4).

Step 2: The proportionality constant "K" value was calculated using the formula:

$$\mathrm{k} = (1/(1/\sum si)) \quad (1.1)$$

where

"si" are the standard permissible for the *n*th parameter.

Table 1.2 Water class parameters for the weighted arithmetic index method

Water quality index	Water quality class
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
Above 100	Not suitable for drinking purposes

Rickwood and Carr (2007), Ratikane (2013)

Step 3: The quality rating for the *n*th parameter (qn) was calculated for n parameters using the formula:

$$qn = 100\{(v_n - vi_o)/(s_n - vi_o)\} \quad (1.2)$$

where

v_n Estimated value of the *n*th parameter of the given sampling station.
vi_o Ideal value of *n*th parameter in pure water, and
S_n Standard permissible value of the *n*th parameter.

Step 4: Calculation for the unit weight for the *n*th parameters using formula:

$$Wn = (k/Sn) \quad (1.3)$$

Step 5: Calculation of the Water Quality Index (WQI) using formula:

$$WQI = ((\Sigma Wn \times qn)/\Sigma Wn) \quad (1.4)$$

The WQI ranges and their classes were defined as shown in Table 1.2.

1.3 Results

The comparison of the average physical and chemical determinants with SANS 241 (2015) and WHO drinking water quality (2017) guidelines revealed that the water quality parameters in the boreholes and mine stream exceeded the recommended limits by varying margins. Table 1.3 indicates the percentage compliance of each borehole (B1–B5) as well as the stream water (S6) against the SANS 241 and WHO (2017) water quality guidelines.

The samples B3 and S6 from borehole 3 and stream water had the lowest compliance rate out of all the 6 samples assessed. While sample B3 exceeded the physical

Table 1.3 Comparison of the physical and chemical determinants with the SANS 241 and WHO, 2017 limit standards

Parameter	Limit standard (SANS 241)	Limit standard (WHO)	Risk	B1	B2	B3	B4	B5	Mean for boreholes	S6 (open stream)	Minimum	Maximum
EC (Electrical Conductivity)	(170 mS/m)	-	Acute Health	84.62	<14.7	202.31	62.75	138.89	122.14	2051.42	<14.7	2051.42
TDS (Total Dissolved Solids)	(1200 mg/l)	1000	Aesthetic	579.77	85.97	1234.44	433.16	891.73	645.01	17531.61	85.97	17531.61
pH	(5-9.7)	8.5	Operational	7.04	7.55	6.80	7.64	6.81	7.17	7.17	6.81	7.55
Calcium (Ca)	(150mg/L)	75	Aesthetic	68.60	10.82	79.63	55.61	93.06	61.54	896.04	10.82	896.04
Magnesium (Mg)	(70mg/L)	30	Aesthetic	28.69	3.21	41.37	22.98	36.53	26.56	856.49	3.21	41.37
Sodium (Na)	(200mg/L)	200	Aesthetic	73.92	13.22	307.61	49.72	146.79	118.25	3170.74	13.22	3170.74
Potassium (K)	(50mg/L)	10	Aesthetic	12.67	4.30	29.20	8.25	25.47	15.98	304.65	4.30	29.20
Fluoride (F)	(1.5mg/L)	1.5*	Chronic Health	0.37	<0.10	0.39	0.30	0.35	0.35	1.89	<0.10	1.89
Chloride (Cl)	(300mg/L)	250*	Aesthetic	85.25	18.89	317.05	63.82	194.54	135.91	6197	18.89	6197
Nitrate (NO_3)	(11mg/L)	50*	Acute Health	1.76	0.36	0.29	2.00	4.16	1.71	0.75	0.36	4.16
Sulphate ($S0_4$)	(500mg/L)	250	Acute Health	134.85	1.11	146.51	99.40	89.36	94.25	3075.46	1.11	3075.46
Total Hardness ($CaCO_3$)	(100mg/L)	-	Aesthetic	289.65	40.25	369.21	233.49	382.81	263.1	5764.44	40.25	5764.44
% Compliance				**92**	**100**	**58**	**92**	**92**	**100**	**17**		

Key		
	Sample exceeds the SANS (2015) limit standard	(red)
	WHO Guidelines for drinking water quality (2017); standards of health concern	*

parameters limits of EC, and TDS, by approximately 19% and 3% margins respectively, the samples from the stream water exceeded the same parameters by more than 200% and 14% respectively.

For the chemical parameters, the borehole samples B1, B3, B4, and B5 from boreholes 1, 3, 4, and 5 all exceeded the total hardness due to $CaCO_3$ as per the SANS 241 and WHO (2017) recommended guidelines. Additionally, sample B3 had excess Sodium and Chloride concentrations.

The stream water sample S6 exceeded all the chemical water quality guidelines with the exception of pH and Nitrate. The S6 sample also had the lowest compliance percentage of 17% with dangerous levels of Fluoride and Sulphates which are highlighted as the causes of some chronic and acute diseases in humans.

Some of the important water quality parameters in terms of aesthetics, and health were plotted against the SANS 241 limit standards. Figure 1.2 shows a plot of the EC recorded for all the samples against the SANS 241 limit standard.

The orange line in Fig. 1.2 represents the SANS limit standard of 170 mS/m whilst the blue line represents the average recorded EC values for each sample.

Figure 1.3 shows the limit standard for Nitrate values plotted against the SANS limit standard of 11 mg/L.

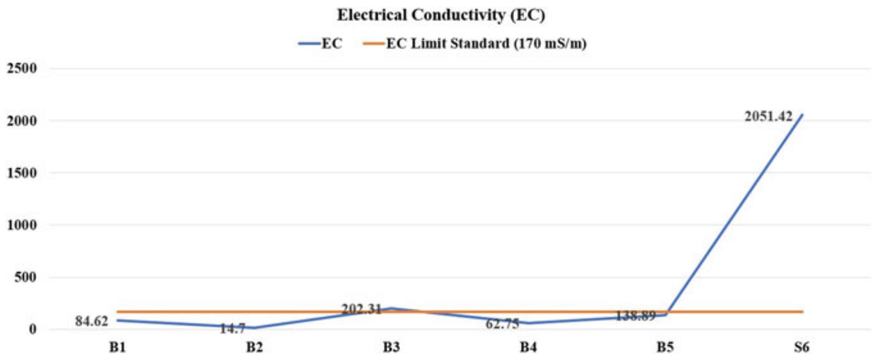

Fig. 1.2 Electrical Conductivity (EC) plotted against their SANS 241 limit standard

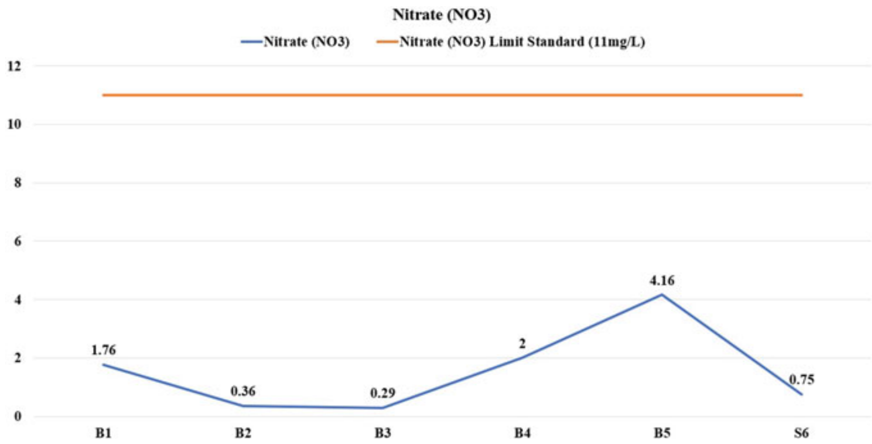

Fig. 1.3 Nitrates concentrations plotted against the SANS 241 limit standard

All the plotted nitrate values were below the SANS 241 limit standard. Figure 1.4 shows the plot of the average Fluoride concentrations per sample against the SANS 241 limit standard of 1.5 mg/L.

All samples except S6 had Fluoride concentration levels below the SANS limit standard.

1.3.1 Comparison of Microbiological Parameters

The analysis of the microbial parameters involved the assessment of Total Coliforms, Faecal Coliforms, and *Escherichia Coli* in all the borehole and stream samples in the Summer and Automn seasons of 2022 against the SANS 241 (2015) standards.

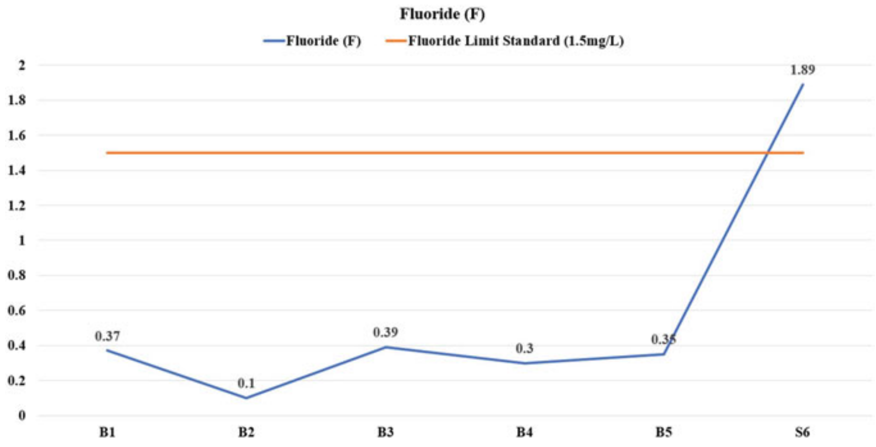

Fig. 1.4 Fluoride concentrations plotted against the SANS 241 limit standards

Samples B2, B3, and B5 had excess numbers of Total and Faecal Coliforms in the summer seasons for the boreholes whilst sample S6 had exceeded all the SANS 241 limits for all the parameters under investigation. Table 1.4 shows the percentage compliance of the microbiological parameters against the SANS 241 standards for the summer season.

For the Autumn season, all the 5 boreholes together with the stream sample exceeded the Total coliforms SANS 241 standard. None of the samples exceeded Faecal Coliforms SANS 241 standards and all samples but B3 exceeded the number of *Escherichia Coli* SANS standard as indicated in Table 1.5.

Table 1.4 Comparison of microbiological parameters-summer season

Parameter	SANS 241 Standard	Risk	B1	B2	B3	B4	B5	S6
Total coliforms	(<10 counts/100ml)	Operational	2	>2420	>2420	<1	127	>2420
Faecal Coliform	(Not detected in 100ml)	Acute Health	<1	67	4	<1	<1	613
Escherichia Coli	(Not detected in 100ml)	Acute Health	<1	<1	<1	<1	<1	1
Compliance %				33	33	100	67	0

Key	Sample exceeds the SANS (2015) limit standard.	

Table 1.5 Comparison of microbiological parameters-autumn season

Parameter	SANS 241 Standard		B1	B2	B3	B4	B5	S6
Total coliforms	(<10 counts/100ml)	Operational	>2420	>2420	10	2420	>1000	>2420
Faecal Coliform	(Not detected in 100ml)	Acute Health	326	1986	1	112	816	613
Escherichia Coli	(Not detected in 100ml)	Acute Health	5	>2420	<1	1	6	1
Compliance %				33	66	33	33	33

Key	Sample exceeds the SANS (2015) limit standard.	

Table 1.6 Water quality indexes

Borehole sample	Water quality index	water quality class
1	64.26	Poor
2	44.79	Good
3	63.06	Poor
4	31.78	Good
5	51.06	Poor
Mean	68.16	Poor
Stream water	544.31	Not suitable for drinking purposes

Table 1.6 shows the Water Quality Indexes for all the 6 samples together with their associated Water Quality Classes. All the Water Quality Indexes were calculated through the WAI method using the SANS 241 and WHO (2017) water quality guidelines. 3 out of the 5 boreholes had poor water quality whilst the other 2 boreholes had good water quality. The mean WQI calculated from all the 5 boreholes using the physical and chemical determinants indicated that the overall water quality was poor.

The stream WQI of 544.31 was 5 times higher than the minimum guideline requirements of 100 for very poor water quality making the water not suitable for drinking purposes.

1.4 Discussion

The results from the study indicate that the groundwater quality from the boreholes located at the CUT campus cannot be considered safe for drinking purposes. Despite the water quality indexes indicating that the water can be used for drinking purposes, the water is still not fit for human consumption as the microbiological water quality determinants for all samples exceed the threshold for drinking water quality guidelines as set by the SANS 241 and WHO (2017) standards.

The high levels of determinants found in the stream close to the mining dump can be possibly linked to the heavy leaching of contaminants from the mining dump. Similarly, the above average contamination of borehole 3 can also be linked to its close proximity to the contaminated stream water. No consistent direct correlations were found between the concentration of determinants in any sample and the number of microbial organisms found in both seasons. Further WQI assessments involving heavy metals might be necessary to explore further correlations with the microbial organisms.

The microbial contamination of the groundwater varied greatly for the Autumn and Summer seasons respectively with Total coliforms and *E. coli* being more dominant in the Autumn season whilst Total coliforms and Faecal coliforms are more dominant in the summer season. The variations in the seasonal microbial compositions can be attributed to the different weather patterns found in the Autumn and Summer seasons contributing variably to the microbial growths. The seasonal variations in microbial growth need to be closely traced as it can pose unexpected seasonal health risks to the Welkom population.

1.5 Conclusion

The groundwater in the CUT Welkom area is heavily contaminated by the physical, chemical, and micro-biological determinants from the nearby mine dump. The contamination deteriorates the water quality hence making it unsafe for drinking purposes. Despite some of the borehole water samples meeting some of the SANS 214 and WHO 2017, water quality guidelines for some determinants, none of the water samples collected from the boreholes were fully compliant in all the parameters. The use of the groundwater for drinking purposes might hence lead to some health complications in humans. Further testing is required to assess the presence of any heavy and or trace metals in the groundwater in order to establish vulnerability of the groundwater from the mine dump.

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Chapter 2
Small Watersheds Based on Game Theory Comprehensive Weight Method Flash Flood Disaster Risk Assessment

Qinxin He, Yunchu Ren, Yuyu Liu, and Bo Huang

Abstract In order to accurately assess the risk of flash flood disasters in small-scale river basins, this paper takes the small watershed of Beidasha River in Shandong Province as an example, selects 10 influencing indicators in view of the single method of flash flood disaster risk assessment in the past and the one-sided shortcomings of determining the weight coefficient of indicators, synthesizes the analytic hierarchy method and entropy method based on the principle of game theory, determines the more scientific index weight value, introduces the fuzzy comprehensive analysis method, constructs a flash flood disaster risk assessment model in the small watershed, and uses ArcGIS to divide the risk area. Combined with the township zoning and administrative village point layers, the raster was used as the evaluation unit to analyze the risk of flash flood disaster in the whole river basin. The results show that the annual rainstorm days are the most weighted among the indicators, followed by the topography index, and the vegetation index has the lowest weight. The area with high risk level accounted for 40.52% of the whole river basin, which was mainly distributed in the lower reaches of the river basin, and the evaluation results were consistent with the distribution of historical disasters, which could provide data support for flash flood disaster early warning.

Keywords Flash floods · Risk assessment · Game theory comprehensive weight method · Flood prevention · Disaster mitigation

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2.1 Introduction

Flash flood disasters are a series of disasters induced by heavy rainfall in mountainous areas, which directly or indirectly cause loss of life and property. It is sudden and destructive. Many cities in hilly areas in China occupy an area far exceeding the world average level, and are one of the countries most affected by disasters. Therefore, mountain torrent disaster prevention and comprehensive management of small watersheds in hilly areas have received more and more attention from the state and relevant departments. Risk assessment plays an important role in mountain torrent disaster prevention (Jiang et al. 2020; Wei et al. 2022). At present, researchers at home and abroad have studied many methods of mountain torrent disaster risk assessment, such as principal component analysis, analytic hierarchy process, entropy value method, fuzzy comprehensive analysis method, random forest method, artificial neural network method, multi-factor comprehensive index However, each evaluation method has its own advantages and disadvantages. The key is to determine the weight value of the impact index. Compared with the single method to determine the weight of the index, the comprehensive weight method of game theory can combine the advantages of each method. objectivity and accuracy (Yu et al. 2013; He et al. 2022; Liu et al. 2023).

In this paper, the Beidasha River Basin in Shandong Province is taken as the research area, and the 34 sub-watersheds divided based on ArcSWAT software are used as the evaluation objects, and the 30 × 30 m grid is used as the evaluation unit. The fuzzy comprehensive analysis method is used to determine the degree of membership of the hazard level, and the risk analysis of mountain torrent disasters in the Beidasha River Basin is transformed into a quantitative analysis. This research can provide more intuitive and reliable data information for regional flood control and disaster reduction, and can also provide further ideas for the risk assessment of flash flood disasters in similar regions.

The Beidasha River is a first-class tributary of the Yellow River, located in the east of Changqing District, Jinan City, with a total basin area of about 576 km^2, including 6 sub-districts and 282 administrative villages. The topography of the basin varies greatly, with the lowest elevation being 6 m and the highest elevation being 976 m. The hilly area accounts for about 81.3% of the total area. The upper reaches of the basin are low mountains and hills, the middle is the piedmont plain, and the lower reaches is the lowland along the Yellow River. The study area belongs to the warm temperate continental monsoon climate zone, with an average annual precipitation of about 644 mm. The precipitation is concentrated during the flood season from June to September. Extreme rainfall is the main cause of mountain torrent disasters in this basin, especially the catastrophic flood in Changqing District in 2007. Heavy rain, the maximum rainfall in the district reached more than 200 mm, and the direct economic loss reached 44.4 million yuan. There are 6 rainfall stations and Gushan hydrological stations in the basin, including Jieshou, Shihutong, Guanmachang, Wande, Jijiayu and Changqing.

2.2 Risk Assessment Methods of Flash Flood Disasters

2.2.1 Determine the Comprehensive Weight of Evaluation Indicators Based on Game Theory

Subjective and objective weighting methods. The judgment of the importance of the indicators by the analytic hierarchy process is often based on expert scoring or experience to determine the scale, which is greatly influenced by human subjectivity, while the entropy method uses the degree of dispersion of each indicator to determine the weight of each indicator by using information entropy. The method does not consider that the hierarchical relationship is too absolute (Liu et al. 2017; Yuan et al. 2018). Therefore, this paper neutralizes these two methods based on the principle of game theory, and takes their optimal solution as the comprehensive weight of the evaluation index.

The AHP is to divide complex problems from the top layer into target layer, criterion layer, and index layer to establish a corresponding hierarchical analysis system. The upper layer is influenced by the lower layer, and the indicators in the layer are independent of each other (Duan et al. 2021). The importance of each indicator is quantified by establishing a judgment matrix, and the saaty scaling method is often used for judgment.

The entropy value method is to normalize the judgment matrix according to the definition of entropy to obtain the entropy of the index, and determine the entropy weight by calculation w_i^* namely:

The judgment matrix $A_{i\times m}$ represents an evaluation index m area, $A_{i\times j} = (v_{ij})$ ($i = 1, 2, \ldots, n; j = 1, 2, \ldots, m$).

Matrix $A_{i\times j}$ is normalized to obtain matrix $B_{i\times j} = (b_{ij})$

$$b_{ij} = \begin{cases} \frac{v_{ij} - \min v_j}{\max v_i - \min v_j}, \text{Positive indicators} \\ \frac{\max v_i - v_{ij}}{\max v_i - \min v_j}, \text{Negative indicators} \end{cases} \tag{2.1}$$

In the formula, $\max v_i$ and $\min v_j$ represent the maximum value and minimum value in different regions under the same indicator, respectively.

$$H_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij} \text{ and } H_j \geq 0 \tag{2.2}$$

$$w_i^* = \frac{1 - H_j}{n - \sum_{j=1}^{n} H_j} \text{ and } \sum_{i=1}^{n} w_i^* = 1 \tag{2.3}$$

In the formula, P_{ij} is the ratio of different regions under each index; H_j is the entropy value of each index in different regions; w_i^* is the weight of each index calculated by the entropy value, $w_i^* \in [0,1]$.

The comprehensive weight is determined based on game theory. Game theory is based on the coordination goal of NASH equilibrium to construct the optimal countermeasure model, which can find the optimal solution among multiple indicators. Combining weights can minimize the dispersion of each evaluation index, integrate the advantages of subjective weighting method and objective weighting method, and make the distribution results more representative (Zhu et al. 2013).

Assuming that the index weights determined by different evaluation methods are used to construct the base vector set as $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_L)$, and the linear equations are formulated according to the differential principle, and the optimal base vector set λ is obtained through linear algebra calculations. After normalization, the combination weight W^*.

2.2.2 Fuzzy Comprehensive Evaluation Method

Membership function is a mathematical tool used to characterize the "real degree" of elements in fuzzy sets. It can be determined by fuzzy statistics, assignment methods, expert experience methods, binary comparison and sorting methods, etc., but its determination is usually subjective and difficult. It directly affects the accuracy of the evaluation results. In order to evaluate the reliability of the results, this paper adopts the method of assigning trapezoidal or semi-trapezoidal distribution functions to determine the membership degree of the index (Jing et al. 2018). Let $u_{i,n}(x)$ be the membership degree of evaluation index i to level n in target layer u, then the membership function is as follows:

$$u_{i,1}(x) = \begin{cases} 1, & x < a_1 \\ \frac{a_2 - x}{a_2 - a_1}, & a_1 \le x \le a_2 \\ 0, & x > a_2 \end{cases} \tag{2.4}$$

$$u_{i,j}(x) = \begin{cases} \frac{x - a_{j-1}}{a_j - a_{j-1}} & a_{j-1} \le x \le a_j \\ 1, & a_j \le x \le a_{j+1} \\ \frac{a_{j+2} - x}{a_{j+2} - a_{j+1}} & a_{j+1} \le x \le a_{j+2} \\ 0, & x < a_{j-1}, x > a_{j+2} \end{cases} \tag{2.5}$$

$$u_{i,n}(x) = \begin{cases} 0, & x < a_{n-1} \\ \frac{x - a_{n-1}}{a_n - a_{n-1}} & a_{n-1} \le x \le a_n \\ 1, & x > a_n \end{cases} \tag{2.6}$$

In the formula, x is the actual value of the evaluation index; a_n is the critical value of the corresponding category interval. The final evaluation is made according to the principle of the maximum degree of membership.

2.3 Comprehensive Risk Assessment of the Study Area

2.3.1 Index System Construction

According to the theory of mountain torrent disaster system (Ren et al. 2023), the risk evaluation index system in this paper selects 10 evaluation indexes from the three criteria of the hazard of the hazard, the sensitivity of the disaster-forming environment, and the vulnerability of the carrier to construct the evaluation index system. Evaluation set $M = \{$very low risk, low risk, medium risk, high risk, very high risk$\}$ with 5 levels in total. The average annual maximum 24-h rainfall, annual average rainfall, and annual number of rainstorm days are selected as the risk indicators of watershed disaster-causing factors; due to the large fluctuations in the topography of small watersheds in hilly areas, the slope of the terrain, the hydrological characteristics of the watershed, and the distribution of vegetation It has a greater impact on floods, so the elevation, slope, topographic index, and vegetation index are selected as the sensitivity indicators of the evaluation object; the small watershed is smaller in scale than the large watershed, and the vulnerability of the carrier is mainly on both sides of the river. Therefore, the population density, building density and GDP density are selected as the evaluation indicators of this criterion (Ge and Luo 2018; Sun et al. 2021; Wu et al. 2018; Meng et al. 2022).

According to the constructed indicator system to collect the relevant indicators raw data and processed, data information sources as shown in Table 2.1.

The data collected in Table 2.1 were processed in the ArcGIS platform in 30 m $\times$ 30 m rasters to obtain the required indicator layer data in Table 2.2, in which the indicator layer of the disaster-causing factors (annual maximum 24-h rainfall, annual average rainfall, and the number of days of heavy rainfall) was obtained by spatially interpolating seven stations in the watershed using the inverse distance-weighting method; the positive value in the topographic index map corresponds to the mountain ridges, the negative value corresponds to the valleys, and the zero value is for the flat

Table 2.1 Indicator data sources and precision

Indicator data	Source	Accurate
Rainfall data	Hydrological Yearbook 2007–2019	Daily rainfall
Elevation	Geospatial data cloud	30 m
Vegetation Index	NASA National Aeronautics and Space Administration	1 km
Population density	Resource Environment Data Center, Chinese Academy of Sciences	1 km
GDP density	Resource Environment Data Center, Chinese Academy of Sciences	1 km
Digital orthophoto	Google Maps	8 m

Table 2.2 Critical value of flash flood disaster assessment indicators in the Beidasha River Basin

Indicator threshold	Annual maximum 24 h average rainfall/mm	Annual average rainfall/mm	Rainstorm days/d	Elevation/m	Slope/(°)
a_1	67.59	483.06	1.85	4	0
a_2	77.19	531.75	1.99	108	6.20
a_3	84.74	573.72	2.13	221	12.57
a_4	91.22	619.05	2.29	348	20.31
a_5	96.17	655.99	2.49	513	29.70
a_6	101.54	697.12	2.70	976	64.33

Indicator threshold	Terrain index	Vegetation index	Population/(person km^{-2})	Architecture/(room km^{-2})	GDP/(million yuan km^{-2})
a_1	−31.67	0.22	358	22.13	1,796
a_2	−3.49	0.36	480	227.69	3,045
a_3	−0.95	0.41	610	358.12	4,397
a_4	0.90	0.45	770	504.38	6,776
a_5	3.20	0.50	955	702.02	10,666
a_6	27.22	0.61	1640	1,030.11	19,339

area; and the building density map was obtained by kernel density analysis of the data collected from the building points in the digital orthophotographs (Fig. 2.1).

Each evaluation index layer is divided into five interval categories using the natural discontinuity grading method, and the critical value of each interval is used as the discontinuity point of the membership function to determine the degree of membership. The specific values of each index are shown in Table 2.2.

2.3.2 *Comprehensive Risk Assessment*

The weight values of each index are calculated by different methods, as shown in Table 2.3, method 1 is the AHP subjective weight method, method 2 is the entropy weight method (objective assignment method), and method 3 is the integrated weight method based on game theory, which is the weight value obtained by combining the first two methods.

According to the constructed trapezoidal or semi-trapezoidal distribution function, the judgment matrix of the membership degree of 34 risk levels is obtained, and the risk evaluation matrix of 34 watersheds is obtained through the linear algebra calculation of the comprehensive weight matrix of each index and the judgment matrix, and the risk level is determined according to the principle of the maximum degree of membership, using ArcGIS to assign values to the small watershed boundary and

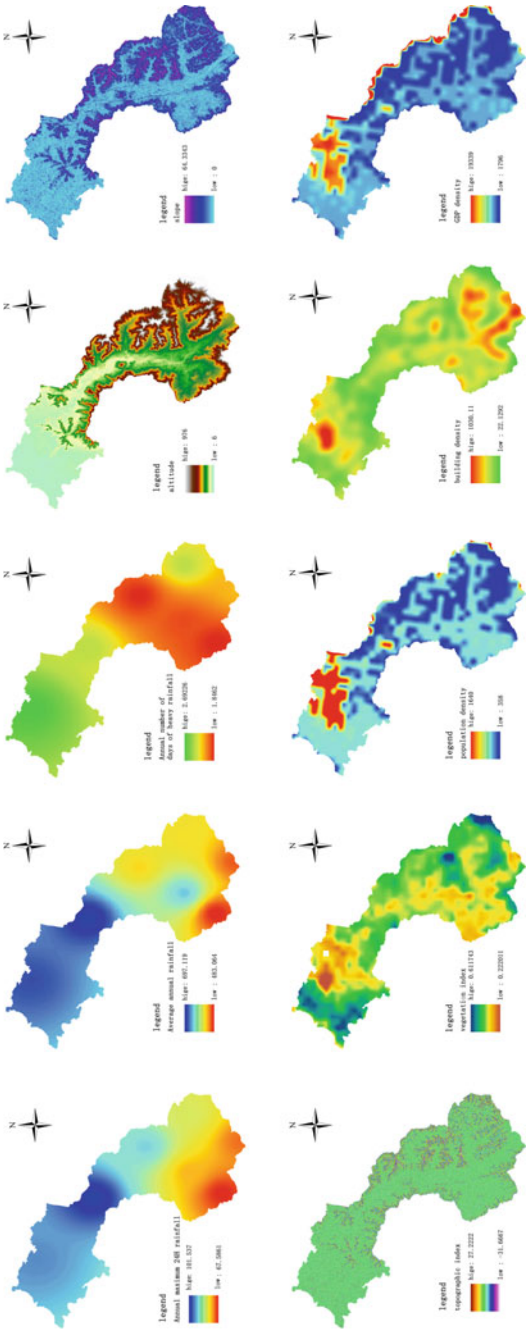


Fig. 2.1 Map of the spatial distribution of the evaluation indicators in the North Dasha River

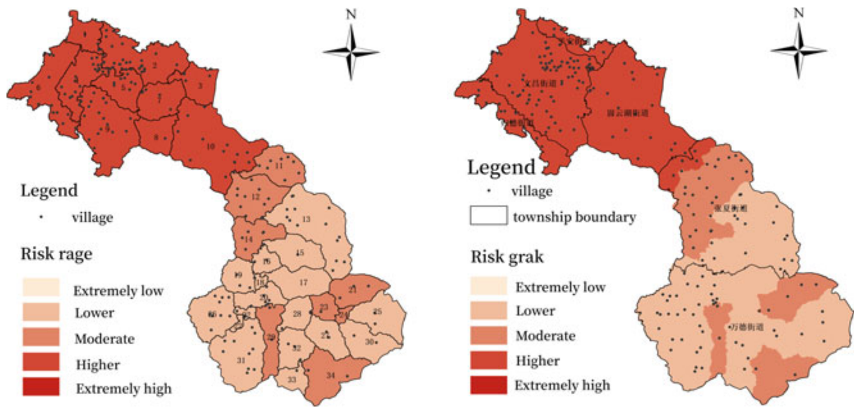
Table 2.3 Index data source and accuracy

Impact indicators	Annual maximum 24 h average rainfall	Annual average rainfall	Number of rainstorm days per year	Elevation	Slope
Method 1	0.065	0.119	0.216	0.064	0.111
Method 2	0.077	0.080	0.133	0.104	0.098
Method 3	0.076	0.116	0.205	0.085	0.116

Impact indicators	Terrain index	Vegetation index	Population density	Building density	GDP density
Method 1	0.187	0.038	0.089	0.077	0.034
Method 2	0.062	0.074	0.173	0.049	0.1514
Method 3	0.158	0.055	0.129	0.074	0.158

township zoning layer, and perform zoning statistics to obtain the mountain torrent disaster risk zoning map of the Beidasha River Basin, as shown in Fig. 2.2.

It can be seen from Fig. 2.2 that the proportion of areas with extremely high and extremely low risk levels in the Beidasha River Basin is zero, and the overall risk of flash flood disasters in the whole region is relatively high. The high-risk areas of mountain torrent disasters are concentrated, mainly distributed in 10 small watersheds downstream of the watershed, including Guyunhu Street, Wenchang Street, and parts of Zhangxia Street, Guide Street, and Pingan Street, including 165 administrative villages; Medium-risk areas are evenly distributed in Wande Street and Zhangxia Street, including 47 administrative villages; lower-risk areas include 70 administrative villages. Through calculation, the areas of higher risk, medium risk, and lower



(a) Comprehensive evaluation map of mountain torrent disasters in 34 small watersheds.

(b) Comprehensive evaluation map of mountain torrent disasters in each township.

Fig. 2.2 Zoning map of mountain torrent disaster risk in the Beidasha River Basin