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Research Article

Selecting Optimal Water Supply Sources Using Multi-Criteria Decision-Making Model for Rural Communities in South Africa

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ABSTRACT

Water poverty remains one of the most significant global challenges, restricting sustainable development, particularly in poor communities. Selecting an optimal water supply solution for rural South African communities is a complex process due to multiple factors, including cost, availability, accessibility, and water quality. This paper presents a Multi-Criteria Decision-Making (MCDM) model that incorporates the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (F-TOPSIS) and the Fuzzy Analytic Hierarchy Process (F-AHP), to assess and prioritize various options for water supply. Developed model accounts for trade-offs and prioritizes options based on weighted criteria that reflect the unique needs of rural communities with respect to water supply. Findings demonstrate model's effectiveness in providing a structured, data-driven approach to water supply decision-making. Groundwater emerges as the most sustainable water source, followed by pipeline-supplied water. Surface water is deemed undesirable due to poor quality and long distances from the supply sources. The result from the study indicates that ground water has a co-efficient closeness of 0.93, followed by pipeline-supplied water with 0.88. The study underscores the need for government intervention in groundwater supply to support rural communities facing high unemployment and poverty. By employing this model, South Africa can enhance its water supply strategies, ensuring that appropriate solutions are identified for rural communities that are both practical and sustainable.

Keywords: F-TOPSIS, F-AHP, MCDM, Water Supply, Rural communities.

1. INTRODUCTION

The Sustainable Development Goal (SDG) number six is to guarantee that everyone has access to sanitary facilities and clean water. Health, economic development, and environmental protection all depend on clean water. Improving the quality of the water is necessary to accomplish this goal, use it efficiently, and ensure everyone can access it fairly, especially marginalized communities. By ensuring sustainable water practices, there is a possibility to build resilience to climate change, improve food security, and create a more sustainable future.

Water remains the amplest resource on earth which stays essential to most of its key systems, such as the climate, weather, ecosystems, and global economy. Water makes up almost 70% of the earth's surface, with fresh water making up 2.5% and salty water making up 97.5%. The amount of available fresh water is less than 1% of the 2.5% [1]. Lack of access to sufficient, safe, and reasonably priced water for fundamental human requirements including drinking, cooking, sanitation, and hygiene is known as water poverty. One of the biggest worldwide issues that significantly impedes the sustainable growth of economies and societies, particularly in underprivileged areas, is water poverty [2]. Majority of countries in the Sub-Saharan Africa still have restricted access to drinking water, according to a World Health Organization (WHO) research [3]. Water is a crucial component of the environment; but surface water and groundwater quality have long been deteriorating due to both natural and human-related activities and this adds to the effect of water poverty [4]. The deep tube wells and rainwater collection systems

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received ratings of first and second, respectively, when evaluated amongst pond sand filter, shallow tube well and pond using the AHP, Fuzzy AHP and the TOPSIS [5].

South Africa is currently dealing with an intensifying water crisis due to a declining water supply, in addition to the deterioration of water quality. Major cities have predicted water shortages, necessitating interventions in the near future. New demands due to urbanization includes housing projects, densification, informal settlements, and shared services accompany will also necessitates innovative ways to address water shortages [6]. Water is also essential to the biology of the majority of living things. The basic characteristics and attributes of water are chemical, physical as well as biological. In South Africa, having access to a clean and dependable water supply is crucial, particularly in rural areas where resources are often limited and unevenly distributed. Given the diverse challenges posed by varying climatic conditions, infrastructural deficits, and socio-economic factors, Choosing the best water supply sources necessitates a careful process.

A methodical framework for assessing and ranking several options according to a variety of criteria is provided by multi-criteria decision-making (MCDM) techniques, including cost, quality, accessibility, and sustainability. The use of MCDM approaches in choosing the best sources of water supply in South Africa is examined in this study, emphasizing how crucial data-driven decision-making and stakeholder interaction are to ensuring fair and sustainable access to water resources. By employing these methodologies, decision-makers can navigate the complexities of water supply management, ultimately contributing to improved public health and enhanced quality of life for communities across the nation.

2. LITERATURE REVIEW

A. Common water sources in SA

This study's section addresses the standards used to choose the best water sources for the rural regions in question. To find the pertinent criteria applied in related studies and to make observations about the areas in question, a thorough literature review was carried out. Water supply sources can vary widely in rural areas depending on geographical typography, climatology, and the local infrastructure. The majority of South African populations depend on surface water from lakes, ponds, and rivers as a major supply for necessities. The phrase "surface water" refers to water that is found on the surface of the Earth, such as rivers, lakes, and wetlands [7]. In this definition, the ocean is typically left out because of its size and salinity [8]. For ecological and human systems, surface water bodies are essential freshwater supplies. Research on the quality of various types of water, such as drinking water, wastewater, groundwater, surface water, ocean, and freshwater, is difficult because of their intrinsic differences [9].

A popular supply of water, particularly in places without consistent surface water, is groundwater. In general, groundwater is regarded as safe to drink. Its quality, however, differs from location to location and occasionally is influenced by differing climates. Twenty drinking water samples were taken from boreholes at homes and communities and their quality evaluated in the study conducted by [10]. The results demonstrated that 95% of the samples had pH values below the World Health Organization's (WHO) suggested range of 6.5 to 8.5 for drinking water. The pH values that were found fell between 4.33 to 7.03. The WHO's drinking water limits were met by the other physicochemical characteristics. One of the natural water sources for household tasks including washing, bathing, as well as for agriculture purposes [11]. Another significant source of drinking water is groundwater. Therefore, it is necessary to guarantee the safety of groundwater for human health. Machine learning offers a wide range of potential applications in groundwater analysis, such as the evaluation and forecasting of groundwater quality and sources of pollution [9]. According to [12], One major worry regarding the threats to public health is the susceptibility of ground water from boreholes to pollution. This study demonstrates that borehole water safety in rural locations cannot be guaranteed and is dependent on the location of the borehole as well as the state of the infrastructure, such as the pump and distribution system.

South Africa is currently experiencing a rise in the use of water tankers. Most commonly in areas where infrastructure is lacking, water may be delivered by tankers, especially during dry seasons [13]. Development and population growth are frequently linked to rising water demands that frequently surpass the capacity of available resources, resulting in water shortages, particularly in urban areas, where more than 60% of the world's population resides. In many developing communities including South Africa, shortages often force households to depend on water tankers

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amongst other available or potential sources for the delivery of water for domestic and/or potable use. Although water tankers are now a necessary component of many nations' water supply networks, the industry is frequently uncontrolled and functions with minimal government oversight [14]. Using water tankers as a practice-based strategy has been demonstrated to be impacted in different ways by the identities, preferences, and motivations of drivers, teamwork, and the tangible items required for water delivery, such as trucks and storage tanks [15]. Through the implementation of practical arrangements by the utility, such as designated water filling stations, and through government and local legislation, tanker water delivery is integrated into the formal system.

Water from far-off sources is frequently obtained via pipelines. In South Africa, pipes from larger municipal systems or reservoirs may supply water to certain rural regions. The fundamental distribution infrastructure that enables an effective water delivery is Water Distribution Systems (WDS) [16]. The pipeline is an important means of delivering water to customers across short or long distances in a variety of situations from water sources (reservoirs, water tanks) [17]. Significant market developments have frequently been brought about by the development of drinking water pipeline materials, both in terms of increased cost and static and hydraulic performance. The study by [18], suggested a measure called the In Situ Sustainability measure (ISSI), which considers both technical and environmental factors when choosing pipeline materials for drinking water systems. Given the enormous amount of water lost due to leaks and other potential hydraulic failures, Water Pipeline Monitoring Systems (WPMS) are extremely vital [18]. Other sources of water common in South Africa include:

1) Particularly in regions with seasonal rainfall, rainwater harvesting the process of gathering and storing rainwater from roofs and other surfaces can offer a sustainable supply.

2) Spring Water, which is natural springs, can provide clean, reliable sources of water, often with good quality.

3) Desalination, commonly found in coastal areas, that can provide fresh water from seawater, although this is less common in rural settings.

B. South Africa's water supply issues

Both urban and rural communities in South Africa are impacted by the complex and serious water supply issues. Firstly, water scarcity is a significant issue in the country due to drought. Given its variable rainfall patterns and propensity for droughts, South Africa is categorized as a water-scarce country. Excessive groundwater extraction and the depletion of aquifers threaten long-term water availability, especially in South Africa where the country has huge mining operations. The study by [19] examines the potential benefits of participatory science in addressing water supply issues in developing nations experiencing water scarcity. This study found that active citizen participation requires cooperation between those who are responsible for water supply and citizens or communities including continuous engagement and training to provide solutions. The current water supply in communities is typically strained by population expansion, water consumption projections, and the rate of urbanization [20].

Study by [21] determines that the supply of water services for rural communities faces several obstacles, from unlawful connections in the communities being served to a lack of capacity and expertise at municipalities. The process of providing services to communities is hampered by these issues, which the relevant authorities must appropriately address. Many water delivery systems in impoverished nations like South Africa are antiquated and badly maintained, which frequently results in leaks and water losses [22]. Service delivery is hampered by inadequate funding for the construction and upkeep of water infrastructure, particularly in rural areas. Pollution from agricultural runoff, industrial discharges, and inadequate sanitation facilities compromises water quality in Sub-Saharan countries [23]. Some areas lack the infrastructure required for water treatment to provide safe drinking water. After almost 30 years of democracy, South Africa still experiences inequitable access to basic needs such as water supplies [24]. Disparities in resources is huge in rural areas when compared it to urban areas. When it comes to acquiring clean water, rural communities frequently face more obstacles than metropolitan ones, leading to health disparities. Socioeconomic factors such as poverty and lack of resources hinder many households from accessing reliable water sources.

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Recently, South Africa has experienced significant changing weather patterns as well as extreme weather events. Climate change exacerbates existing water scarcity through increased droughts and changing rainfall patterns [25]. Flooding and other extreme weather events can also disrupt water supply systems and lead to contamination.

The country also requires effective policies to ensure that all communities can access basic needs such as water and electricity. Challenges in water governance and policy implementation can hinder effective management of water resources [26]. Corruption and mismanagement within water supply systems can also lead to inefficiencies and inequitable distribution of resources.

South Africa's urbanization and population growth are outpacing those of the majority of the continent's nations, which raises the demand for water [27]. Urbanization and rapid population increase put further strain on already limited water supplies. Many informal settlements that are mushrooming around major cities like Tshwane and Johannesburg are leading to lack of access to formal water supply systems, exacerbating inequities.

Finally, the absence of potable water in rural regions would inevitably lead to the emergence and spread of waterborne illnesses. Public health is impacted by waterborne disease prevalence, which is influenced by poor water quality and inadequate sanitation [28]. To solve these issues and provide fair and sustainable access to water in rural areas, the government, non-governmental organizations, the commercial sector, and local communities must work together. The sustainability and accessibility of these resources might differ greatly depending on regional circumstances and management techniques.

A comprehensive strategy involving infrastructure investment, efficient governance, sustainable management techniques, and community involvement is needed to address these issues. By tackling these issues holistically, South Africa can work toward achieving water security for all its citizens.

C. Selection criteria for the optimal source of water supply

1. Water Quality

One of the most significant variables influencing human health is the quality of drinking water. However, many nations, particularly developing nations, have unsatisfactory drinking water quality, which has led to a number of waterborne illnesses [29]. One common method for assessing the quality of surface water is the water quality index (WQI) model. It makes use of aggregation techniques to turn large amounts of data about water quality into a single value or index [4].

Water quality in South Africa can vary significantly based on the source—rivers, boreholes, pipelines, and water tankers. Rivers are the most common surface water of which quality is often variable and can be impacted by agricultural runoff, industrial discharges, and urban waste [30]. Water from rivers may contain pathogens, heavy metals, and nutrients leading to eutrophication. This usually requires extensive treatment before it is safe for drinking.

Government and individual households in rural areas often prefer boreholes as a source of water. Borehole water is generally cleaner, but quality can vary depending on the depth and geological conditions and constitute about 97% of global freshwater [31]. In most cases there is a potential for high mineral content (like fluoride or nitrates), and contamination from nearby agricultural or industrial activities. This usually need filtration or treatment depending on the specific contaminants.

Pipeline water in South Africa is provided by municipalities which is typically treated to meet safety standards; however, aging infrastructure can affect quality. Possible contaminants include chlorine by products, leaks from pipes, and microbial contaminants if there are breaks in the system [32]. Pipelines have to be regularly treated and monitored to comply with health regulations.

Water tankers are often used in South Africa. Quality of water provided by tankers can vary widely depending on the source and cleanliness of the tanker [33]. The risk of contamination during transport and storage; can include pathogens if tanks are not cleaned properly. This supply from tanker are also often not treated, so it's essential to ensure the water is sourced from reliable suppliers.

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2. Accessibility

Accessibility considers the proximity of the water source to the community to reduce transportation costs and time. Accessibility also includes physical accessibility which includes evaluating terrain and road conditions for ease of access.

One of the most effective ways to lower the risk of infectious diseases linked to water in low- and middle-income nations is to increase the amount of water accessible for drinking and hygiene. These effects are frequently linked to the accessibility of water supplies (such as collection time or distance) and are used to support funding for access improvements [34].

The study by [35] argues that because domestic water use intensities (WUIdom) are unclear and variable, little is known about how improving water accessibility affects domestic water demand and surface-water deficit (the amount of water demand that exceeds surface-water availability). According to the study, in order to achieve universal water accessibility by 2030, developing and least-developed nations would probably experience further domestic surface-water deficits.

Water accessibility in South Africa varies significantly between rivers, boreholes, pipelines, and water tankers. Water from rivers accessibility can be challenging, especially in remote areas. This often requires additional infrastructure (e.g., pumps, filtration systems) for safe usage. Water rights and environmental regulations may limit access.

Borehole water is generally more accessible in rural areas where surface water sources are scarce. Boreholes require significant initial investment for drilling and installation, which can limit access for some communities.

Pipeline water is generally very accessible in urban areas with developed municipal infrastructure. Accessibility can, however, be impacted by maintenance issues or water restrictions during droughts. In rural areas, access may be inconsistent or non-existent, leading to reliance on other sources.

Water supplied by tankers provides flexible access where other sources are insufficient, especially during crises. This, though, is dependent on local suppliers and logistics, making it less predictable.

3. Cost

The cost for water supply involves the initial investment, operational and maintenance costs. Using a bottom-up cost approach, a cost model was created to project the price of building irrigation water pipes. Engineers can evaluate the expenses of labor, equipment, backfill materials, and a variety of pipe types and sizes using this model. Lastly, the model indicated that the cost per square meter of building the irrigation system for the cultivated area of the evaluated golf course would be almost $236.50 [36].

When buried water pipelines are loaded during an earthquake, they sustain significant damage. The impacts of corrosion deterioration are frequently overlooked in empirical models used to evaluate the likelihood of seismic damage to subterranean pipes. Water distribution systems' (WDS) seismic reliability is greatly diminished by corrosion-induced deterioration, which also affects the pipeline's resistance capability. To aid in the creation of a successful and efficient renewal strategy, improved seismic damage estimation of subterranean water pipelines must take corrosion's impact on seismic performance into account [37]. One of the most important natural resource endowments is water, and resource pricing ought to adhere to the just and sensible guidelines of sustainable development. These guidelines state that the water price should take into account the resources' geographic characteristics. [38].

The cost of water from different sources in South Africa varies based on factors such as infrastructure, accessibility, and treatment requirements. The cost of water from rivers is generally low or free if accessed directly, but costs can arise from treatment and infrastructure development. Access may require investment in filtration systems and purification processes, especially for safe drinking water. Borehole initial setup cost can be high i.e. drilling and equipment installation, but ongoing costs are typically lower. Maintenance and potential treatment costs can add to the overall expense, but if water is used sustainably, it can be cost-effective in the long run. Pipeline water supplied by the municipality is generally the most expensive per litre due to water treatment, infrastructure maintenance, and operational costs. Prices can vary based on local government tariffs and the distance from water sources to

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consumers. Water tankers costs vary, often more expensive than municipal water due to additional transport fuelling and bulk water handling fees. The price can fluctuate based on demand, source quality, and delivery logistics. Emergency supply can be particularly costly.

4. Availability

Water scarcity has become a major issue to sustainable development. It can be estimated by available freshwater resources and human water withdrawal, which are affected by both climate change and human activities. However, Due to significant uncertainty in the estimates of the contributions from changes in water withdrawal and availability, the primary drivers of changes in water shortage on a worldwide scale are still unknown [39]. Additionally, it's critical to evaluate water availability all year round, particularly during dry seasons. This is crucial to make sure the water supply and infrastructure can supply the community's needs.

Water availability in South Africa varies significantly across different sources such as rivers, boreholes, pipelines, and water tankers. Water availability from rivers dependent on seasonal rainfall and regional climate. Some rivers may run dry in drought periods. Communities can find it challenging to access in remote areas; water rights and regulations also affect availability. This source is often unreliable for consistent supply, especially in times of drought or heavy pollution. Borehole water availability is generally more reliable, especially in rural areas where surface water is scarce. Long-term sustainability for borehole water depends on recharge rates and local water management practices.

Pipeline water is generally reliable in urban areas with developed infrastructure but can be affected by breakdowns or maintenance. Typically, easy to access in cities; rural areas may experience intermittent supply or lack of connection. This source is also subject to water restrictions during droughts or water shortages, impacting availability. Finally, water tankers can be a flexible option where other sources are limited, especially in emergencies or remote areas. Availability depends on supplier logistics and demand; often used when other sources fail. Water tankers are less reliable for consistent, long-term supply; quality and availability can vary by supplier.

3. MATERIALS AND METHODS

Various studies have been conducted using MCDM techniques to address water supply problems, however, very few studies were conducted to assess different water supply systems with the aim of alleviating water poverty. The study by [40] demonstrates that the Fuzzy AHP technique found that, with 19.5% and 19%, respectively, the technical performance criteria and financial autonomy were crucial for assessing the performance of water delivery systems. An automated framework was proposed for decision making which was developed empirically to identify a location objectively and cognitively considering all relevant indicators for the selection of an optimal solution for surface water treatment plant location [41].

Building temporary storage dams and rerouting water from a river were ranked highly when AHP, Fuzzy AHP as well as TOPSIS were used to compare alternative methods for water supply. However, The pipeline branching to a local village or city received the least amount of importance [42]. The TOPSIS is an MCDM that is predicated on the assumption that the optimal option should be the one with the least geometric distance from the PIS and the longest geometric distance from the NIS.

Study by [43] proposed a multifaceted study that uses energy, economic, and environmental factors to evaluate various groundwater pumping choices according to water storage and energy resources. According to the corresponding water storage conditions and the chosen energy resource solar, diesel, or grid the study used AHP and TOPSIS methodologies to rank the groundwater pumping options. The results of the study by [44] show how effective TOPSIS approaches are at assessing projects using sustainable development standards.

MCDM methods are useful for selecting the best water supply options in South Africa, given the various factors that influence such decisions. In this section some commonly used MCDM methods along with their applications in water supply selection are discussed. The first technique that could be used to determine criteria weights and alternative ranking is AHP. AHP involves breaking down a decision into smaller, more manageable parts and ranking them based on pairwise comparisons. AHP is useful for prioritizing different criteria (e.g., cost, quality, accessibility) and alternatives (e.g., boreholes, surface water, rainwater harvesting).

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In this work, AHP results are validated using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). By measuring each alternative's distance from the ideal answer, the TOPSIS approach finds solutions from a limited number of options. This helps determine the best option by ranking different water supply options based on how well they perform in relation to a set of criteria. The Fuzzy MCDM combines MCDM with fuzzy logic to handle uncertainty and subjective judgments in criteria evaluation. This is useful in contexts where data may be uncertain or imprecise, such as estimating water quality or community preferences.

The MCDM approach followed for evaluating and selecting the best water supply system in rural areas in South Africa is customized to ensure that challenges faced by rural communities considered. It is important to have a framework to guide the process of model development and the interpretation of the results. Figure 1 presents a framework that provides the methodology for the mathematical model for better decision-making in the selection of the most optimum water supply system for rural communities.

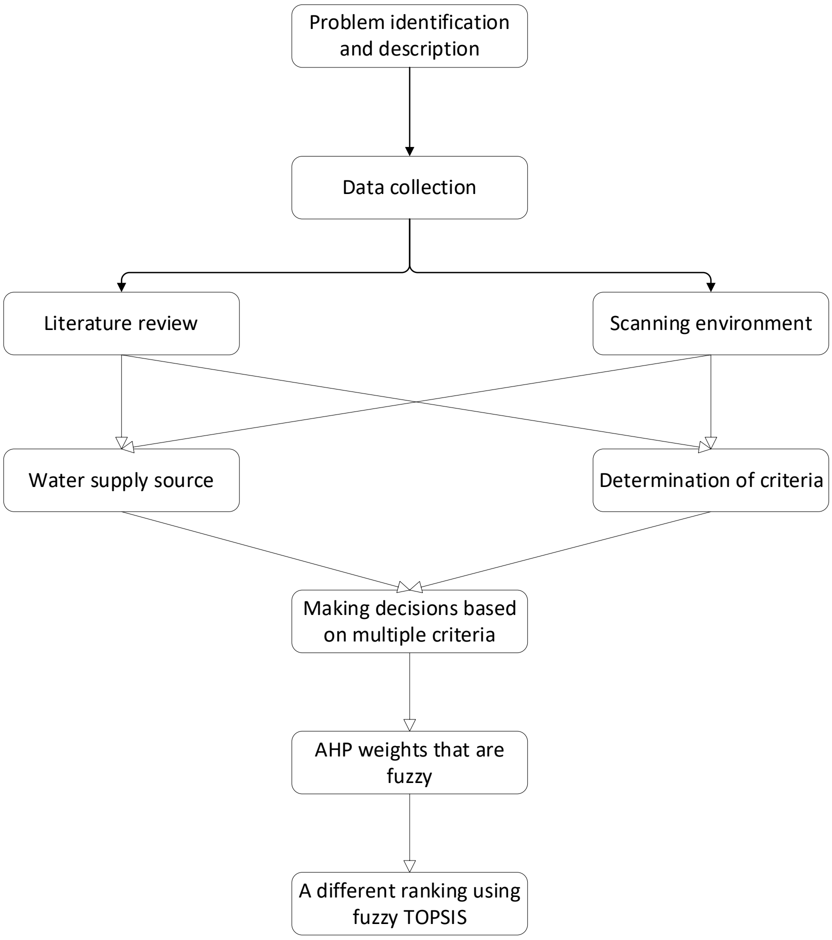

Fig. 1 A suggested framework for determining the optimal water supply system.

The framework begins with problem identification. The authors must invest a significant amount of time in reviewing the material and examining the surroundings by looking at how rural populations obtain their water. This process enables the process of alternative and criteria identification.

1. Problem structuring

The approach to solve the problem at hand begins with the identification of the problem to be solved. This is followed by the identification of the appropriate criteria for the evaluation of alternatives or sources of water supply. In this case the literature proposes several criteria, however, there is a need to select the most appropriate criteria as different environments will require relevant or suitable criteria. Figure 2 summarizes the problem with the chosen criteria to evaluate the suitability of different alternatives. The following steps were followed to resolve the problem at hand.

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Step 1: Development the problem hierarchy and outlining the requirements.

The challenge of choosing the best water source to enhance the rural people' access to water is explained in this stage. The problem is to select the best water source for the community when four alternatives of surface water, ground water, pipeline water and water tankers are available for use. The criteria used to evaluate the four alternatives are the cost, quality, availability and accessibility.

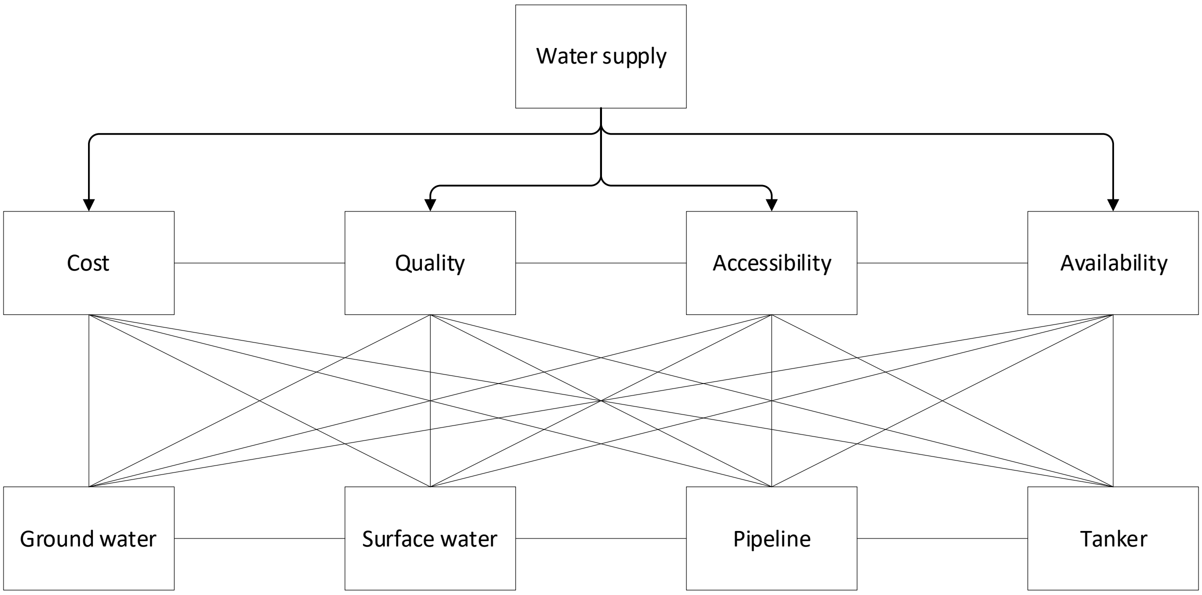

Fig. 2 Water Supply Decision Hierarchy

The water supply problem that the current study deals with is very common and at the same time involves conflicting decision criteria in rural areas of South Africa. It is a challenge to determine a safe, cost-effective, and reliable water supply alternative considering the social, economic, and technical needs for communities.

Step 2: Choosing the language scale to be applied in the evaluation.

The literature provides a variety of scales that are used to evaluate alternatives and establish criteria weights. The literature does not, however, dictate which scale should be applied in what situations. Numerous Likert scales, including the 5-point, 7-point, and 10-point versions, have been employed for a variety of purposes, including energy and layout design. The five-point Likert scale used in this study was taken from Saaty (1981). The criteria weights have been rated using both fuzzy and crisp sets theory linguistic phrases as proposed by [45]

Step 3 Fuzzy Weight determination

A team of experts deliberated on the criteria to be used to evaluate the four alternatives. A pairwise comparison based on the scale in Table 1 was conducted for the four identified criteria. The authors decided to use the fuzzy AHP which is a more powerful technique than the classical AHP.

The following equation is a matrix that is adopted and used when the triangular fuzzy numbers are used, where the attributes are indicated as $a_1, a_2, \ldots, a_n$ and the weights are $w_1, w_2, \ldots, w_n$.

$$A = \begin{bmatrix} a_{l1} & \cdots & a_{lj} & \cdots & a_{ln} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

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where $a_{ij} = \frac{1}{a_{ji}}$ (positive reciprocal) and $a_{ij} = a_{ik}/a_{jk}$. In real situations w_i/w_j is usually unknown. Therefore, the problem is to find a_{ij} such that $a_{ij} \cong w_i/w_j$

where $a_{ij} = \frac{1}{a_{ji}}$ (positive reciprocal) and $a_{ij} = w_i/w_j$ is usually unknown. Therefore, the problem for the AHP is to find a_{ij} such that $a_{ij} \cong w_i/w_j$

The weight matrix can be represented as:

$$W = \begin{matrix} & \begin{matrix} w_1 & \cdots & w_j & \cdots & w_n \end{matrix} \\ \begin{matrix} w_1 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{matrix} & \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_j & \cdots & w_1/w_n \\ \vdots & & \vdots & & \vdots \\ w_i/w_1 & \cdots & w_i/w_j & \cdots & w_i/w_n \\ \vdots & & \vdots & & \vdots \\ w_n/w_1 & \cdots & w_n/w_j & \cdots & w_n/w_n \end{bmatrix} \end{matrix} \quad (2)$$

If W is multiplied by w we get

$$W \times \omega = \begin{matrix} & \begin{matrix} w_1 & \cdots & w_j & \cdots & w_n \end{matrix} \\ \begin{matrix} w_1 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{matrix} & \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_j & \cdots & w_1/w_n \\ \vdots & & \vdots & & \vdots \\ w_i/w_1 & \cdots & w_i/w_j & \cdots & w_i/w_n \\ \vdots & & \vdots & & \vdots \\ w_n/w_1 & \cdots & w_n/w_j & \cdots & w_n/w_n \end{bmatrix} \end{matrix} \begin{bmatrix} w_1 \\ \vdots \\ w_j \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ \vdots \\ w_j \\ \vdots \\ w_n \end{bmatrix} \quad (3)$$

Table I depicts the pairwise comparison for the four criteria with cost and access being non-beneficial criteria and availability and quality being beneficial criteria.

TABLE I PAIRWISE COMPARISON FOR CRITERIA

Criteria	**Quality**	**Access**	**Cost**	**Availability**
Quality	(1,1,1)	(4,5,6)	(1,2,3)	(2,3,4)
Access	(0,166, 0,2, 0,25)	(1,1,1)	(2,3,4)	(0,25, 0,333, 0,5)
Cost	(0,333, 0,5, 1)	(0,25, 0,33, 0,5)	(1,1,1)	(0,25, 0,33, 0,5)
Availability	(0,25, 0,33, 0,5)	(2,3,4)	(1,2,3)	(1,1,1)

Table II displays the fuzzy weights and fuzzy geometric mean for each of the four criteria.

TABLE I FUZZY WEIGHTS

Criteria	**Fuzzy Geometric Mean**			**Fuzzy Weights**			**Defuzzified Weights**
Quality	2,5149	3,2011	3,8337	0,362	0,578	0,8976	0,567
Access	0,5368	0,667	0,8409	0,0773	0,1205	0,1969	0,1217
Cost	0,379	0,4831	0,7071	0,0546	0,0872	0,1656	0,0948
Availability	0,8409	1,1862	1,5651	0,1211	0,2142	0,3664	0,2165

Step 4: Ranking by the Fuzzy TOPSIS technique.

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Table III depicts the decision matrix for the four alternative water supply source and the four criteria. The linguistic and fuzzy scale used in the table was adopted from [46].

TABLE II DECISION MATRIX FOR THE WATER SUPPLY SOURCES

Criteria	Water Supply Sources			
	Surface Water	Ground Water	Pipeline Water	Water Tankers
Cost	(5,7,9)	(1,3,5)	(1,1,3)	(1,3,5)
Access	(1,1,3)	(7,9,9)	(5,7,9)	(5,7,9)
Quality	(1,1,3)	(5,7,9)	(7,9,9)	(3,5,7)
Availability	(1,3,5)	(7,9,9)	(5,7,9)	(5,7,9)

The normalized weights for the four alternatives are depicted in table IV.

TABLE IV NORMALIZED WEIGHTS FOR THE FOUR WATER SOURCES

Criteria	Water Supply Sources			
	Surface Water	Ground Water	Pipeline Water	Water Tankers
Cost	(0.11, 0.14,0.03)	(0.2,0.2,0.33)	(0.33,1,1)	(0.2,0.33,1)
Access	(1,1,3)	(7,9,9)	(5,7,9)	(5,7,9)
Quality	(0.11, 0.33,0,56)	(0.56,0.78,1)	(0.78,1,1)	(0.33,0.16,0.78)
Availability	(0.11,0.33,0.56)	(0.78,1,1)	(0.56,0.78,1	(0.56,0.78,1)

Step 6 Determine the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS)

The determination of the FPIS and FNIS starts with the determination of the maximum represented by A+ and a minimum value A-, as shown in the table V.

TABLE III MAXIMUM AND MINIMUM VALUES FOR EACH CRITERION

Criteria	Distance of each criterion to the FPIS and FNIS	
	A+	A-
Cost	(0,018184, 0.08724, 0.16554)	(0.00606,0.01246,0.03311)
Access	(0,540862; 1.08418, 1.77177)	(0.07727, 0.12046, 0.59059)
Quality	(0,281572, 0.57808,0.8975)	(0.04022, 0.06423,0.29917)
Availability	(0,094149,0.21422,0.3664)	(0.01345, 0.07141, 0.20356)

The FPIS for the four water supply alternatives are summarized in table VI. It is clear that Pipeline water is the one which is the closest to the ideal positive solution.

TABLE IV FUZZY POSITIVE IDEAL SOLUTION FOR THE WATER SUPPLY SOURCES

Fuzzy Positive Ideal solution				
Criteria	**Surface Water**	**Ground Water**	**Pipeline Water**	**Water Tankers**
Cost	0,088084435	0,033838366	0	0,03383837
Access	0,919935421	0	0,165253785	0,16525378
Quality	0,476198634	0,087511363	0	0,31831057

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Availability	0,133450031	0	0,031568761	0,03156876

Table VII depicts the fuzzy negative ideal solution for the alternative water supply sources.

TABLE V FUZZY NEGATIVE IDEAL SOLUTION FOR THE WATER SUPPLY SOURCES

Fuzzy Negative Ideal Solution				
Criteria	**Surface Water**	**Ground Water**	**Pipeline Water**	**Water Tankers**
Cost	0	0,077111	0,08808443	0,07711
Access	0	0,919935	0,81917005	0,81917
Quality	0	0,421274	0,47619863	0,2354
Availability	0	0,13345	0,11325183	0,11325

It is extremely doubtful that Surface Water One will be taken into consideration since, as shown by the results in Table VIII, it is extremely close to the negative optimum solution.

TABLE VIII CLOSENESS CO-EFFICIENT FOR NON-BATCHING MODELLING

	di*+di-	**Cci**	**Rank**
Surface Water	1,617668521	0	4
Ground Water	1,673120541	0,927471018	1
Pipeline Water	1,693527501	0,88377954	2
Water Tankers	1,793908332	0,69398019	3

Figure three depicts the coefficient index for the four alternatives.

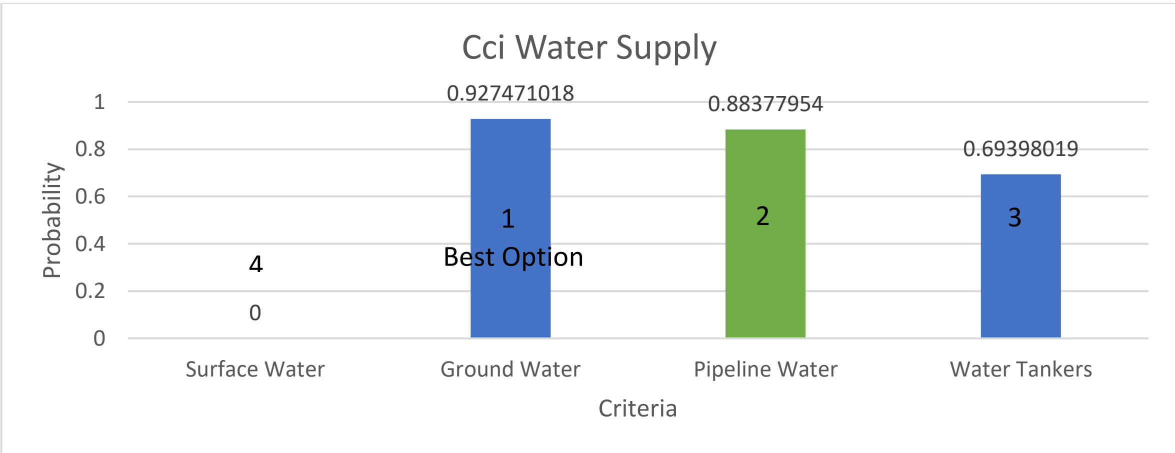

Fig. 3 Cci Water Supply.

The results when the Fuzzy TOPSIS technique indicates that for the rural community concerned Ground water ranked the first followed by pipeline water supply. Surface water was the most undesirable water supply source. This might be due to the fact that surface water is mainly from the rivers which are far away from residential areas.

4. CONCLUSSION

One of the most important steps in resolving South Africa's continuous water problems is the use of Multi-Criteria Decision-Making (MCDM) techniques to choose the best sources of water supply. By systematically evaluating

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alternatives based on cost, quality, accessibility, and availability, the Fuzzy AHP-TOPSIS approach enables policymakers to make informed decisions that balance practicality and sustainability. The study finds that groundwater is the most viable water supply source, followed by pipeline-supplied water. Surfae water, due to long distances from the supply source and poor quality, is not a favourable option. Therefore, government support is essential to ensure the availability of groundwater services, particularly in rural communities facing unemployment and poverty. Investment in borehole infrastructure, water treatment, and maintenance programs should be prioritized to improve long-term water security. Furthermore, future research should explore real-time decision-support systems integrating AI and geospatial data to enhance water supply planning. As South Africa continues to grapple with water scarcity, leveraging data-driven approaches such as MCDM will contribute to more effective water resource management and greater resilience in rural communities.

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