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Feasibility Assessment of the Application of Groundwater Remediation Techniques in Rural Areas: A Case Study of Rural Areas in the Soutpansberg Region, Limpopo Province, South Africa

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Abstract: Groundwater contribution towards human health and livelihood depends on the contaminants level in groundwater. Many people in rural communities are being exposed to waterborne diseases resulting from drinking untreated contaminated groundwater. This study argues that the lack of implementation of available groundwater remediation methods and associated high costs are exposing rural communities to health risks. This study assessed 22 years of groundwater quality data from 12 boreholes and 2 springs to understand the contaminants level in the Soutpansberg region. A feasibility assessment of the application and design of a sustainable groundwater remediation technique was carried out based on individual- and community-based groundwater remediation types. The assessment considered groundwater management, cost and risk of theft and damage to infrastructure model for rural settings. This study determined that groundwater was not suitable for drinking purposes in some parts due to high concentration levels of NO_3^- and F^-. The feasibility assessment indicated that community-based groundwater remediation schemes are more sustainable in rural areas when compared to individual household remediation. In this study, it is recommended that groundwater remediation plans must be included in any proposed water supply or drought intervention project in rural communities.

Keywords: contaminants; groundwater quality; rural areas; remediation; human health

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1. Introduction

Groundwater has become a very important source of freshwater supply for domestic use in most rural areas across the world, owing to various factors such as climatic variation and socioeconomics [1–4]. The occurrence of potentially toxic elements in groundwater is a rising topic of interest to environmental scientists globally [5]. Groundwater is most likely to be vulnerable to various types of pollutants that may make it unfit for human consumption [6–8]. Groundwater contamination may result from natural geogenic sources and anthropogenic sources [7,9–11]. Various studies on a global scale [1,2] and on a regional scale [12–15] have assessed groundwater quality data and determined that concentration levels of contaminants such as nitrate (NO_3^-), fluoride (F^-), Total Dissolved Solids (TDS), chromium (Cr^{2+}) and arsenic (As^{3+}) were high in groundwater. In the Soupansberg region, South Africa, recent studies [16–21] have determined that groundwater was not suitable for drinking purposes owing to high concentration levels of NO_3^-, F^-, Cl^-, Na^+ and Total Dissolved Solids. The high concentration of nitrate and fluoride in the Soutpansberg region can cause health issues such as methemoglobinemia and dental fluorosis [14,22]. To improve access to safe drinkable groundwater, there is a need to understand the hydro-geochemical processes controlling groundwater quality in various aquifers [23]. Various studies applied a number of techniques such as Piper, Durov, Gibbs, Schoeller's diagrams, bivariate plots, Pearson correlation matrix, saturation index (SI) and chloro-alkaline indices (CIA) to understand and determine the hydro-geochemical processes controlling groundwater in the last decade [15,19,23–29]. For instance, processes such as anthropogenic activities, weathering of silicates, carbonates and halites minerals are common hydro-geochemical processes influencing groundwater quality across the world. In the Soutpansberg region, recent studies attributed high concentrations of NO_3^- to anthropogenic sources and a high concentration of F^- to the dissolution of fluorite (CaF_2) in groundwater [16–19,23]. To increase the availability and access to safe drinking groundwater in rural areas, studies by [23,30] recommended that a reliable and adequate groundwater remediation technique be applied before groundwater can be used for drinking purposes. Various groundwater remediation methods (chemical, physical and biological) have been applied globally with varying rates of success [31–33]. Ex situ remediation methods, where groundwater is pumped and treated (pump and treat) outside the aquifer, seem to be more favourable in rural areas than in situ methods. Groundwater is treated in its natural habitat (aquifer) when an in situ method is applied and this requires extensive and detailed study of the aquifer characteristics [8,34,35]. Historically, in situ remediation methods were more commonly applied than ex situ methods until early 2000, where the situation changed and ex situ methods became more common [36]. Groundwater does not require immediate use when the pump and treat ex situ method is applied [37]. This can be an advantage for rural groundwater supply, as treated groundwater can be stored before distribution. When it comes to application globally, Ayyasamy et al. [38] applied chemical (coagulation with lime) and biological methods to treat groundwater in India. Both methods removed up to 86% of NO_3^- in groundwater in 72 h. Epsztein et al. [39] applied hybrid nano-filtration and reverse osmosis filtration methods to remove NO_3^- in groundwater in Israel. The nano-filtration method removed 91.6% and reverse osmosis removed 94.3% of NO_3^- concentration in groundwater. In Morocco, Amarine et al. [40] applied the electro-coagulation method to remove NO_3^- in groundwater. NO_3^- removal of between 88.5% and 94.1% was recorded in four samples in 120 min. In South Africa, Israel et al. [41] used sawdust as a carbon source to remove NO_3^- from groundwater. This experiment reduced NO_3^- in groundwater to below acceptable drinking water limits of 10 mg/L. Various studies have managed to reduce or remove F^- from groundwater globally; for instance, Sivasankar et al. [42] removed 91% of F^- from groundwater using tamarind fruit shell carbon and Singh et al. [43] removed 60% of F^- in groundwater using a zirconium impregnated hybrid anion exchange (HAIZ-Zr) within 30 min. Recent studies by [23,44] suggested that small-scale or community scheme groundwater remediation plants in rural areas can assist in eliminating waterborne diseases. This study argues that there is no lack of groundwater remediation techniques suitable for rural areas setups, there seems to be a lack of an adequate and sustainable groundwater remediation design and application. For instance, there are individual household remediation methods being applied between the borehole and water tank/tap. There are also existing groundwater schemes where groundwater remediation is not being applied due to a lack of knowledge owing to parachute research discussed by [20]. The issue of groundwater management (monitoring groundwater abstraction, levels and quality) is not usually considered when designing groundwater supply and remediation techniques. The aim of the current study is to assess the feasibility of applying an adequate and sustainable remediation method suitable for rural areas settings. This study intends to assess the reasons and factors why groundwater remediation in rural communities is not being applied, and what type of groundwater remediation design is suitable for rural communities. Groundwater remediation in rural communities in very important for improved rural health and livelihood as the majority of people depend on these resources.

2. Material and Methods

2.1. Study Area Description

The Soutpansberg region is situated in the northern rural part of Limpopo Province in South Africa (Figure 1). This region covers about 3099.6 km^2 and lies between 250 and 1719 m above mean sea level. In terms of climatic conditions, the Soutpansberg region is in an arid region, with an average rainfall of 497.7 mm/a. The Soutpansberg region has been identified as a strategic water source area, indicating a high availability of groundwater and national importance of this region [45]. The Department of Water and Sanitation is currently monitoring groundwater quality in 12 boreholes and 2 geothermal springs in the Soutpansberg region as part of the National Groundwater Quality Monitoring Programme. A total volume of 148.3 Mm^3/a of groundwater has been allocated for water supply, domestic use and irrigation. Groundwater in the Soutpansberg region is hosted by the fractured sedimentary Soutpansberg Group deposited about 1800 million years ago [46,47]. The Soutpansberg Group is sub-divided into five formations (Figure 1), which are Tshifhefhe, Sibasa, Fundudzi, Wyllie's Poort, and Nzhelele Formations [48–50]. The oldest Formation at the Soutpansberg Group is the basaltic Tshifhefhe formation, which is only developed at the eastern side of this unit (Figure 1). Tshifhefhe formation is between 0 and 9 m in thickness. Locally, the lithology of Tshifhefhe formation is dominated by epidotised clastic sedimentary ranging from greywacke, shale and conglomerate derived locally [48–50]. Overlaying Tshifhefhe Formation is the extruded basaltic Sibasa formation, which is between 0 and 3300 m in thickness. Sibasa formation lithology comprises massive basalt, epidotised and local amygdaloidal and pyroclastic sandstone [48]. Pyroclastic sandstones are 200 m thick locally and the clastic sedimentary lenses reach 400 m in thickness [48]. Succeeding Sibasa Formation in the Soutpansberg Group is Fundudzi formation, which is between 0–2800 in thickness. Fundudzi formation is predominantly siliciclastic in terms of hydrogeology; groundwater occurrence and flow in the Soutpansberg area is mainly influenced by underlying geological settings and topographical gradients. Groundwater is stored in three types of unconfined aquifers in the Soutpansberg area (Figure 2). The dominant aquifer type is the fractured aquifer, with an average borehole yield ranging between 0 and 0.5 L/s. Some small part of this fractured aquifer average borehole yield can reach 2 L/s. The southern part of the Soutpansberg is underlain by the intergranular and fractured aquifer, with an average borehole yield between 0 and 0.2 L/s. Groundwater is also hosted by the intergranular aquifer in some small parts of the Soutpansberg area. The Soutpansberg region is dominated by Ca-HCO_3 and mixed Ca-Mg-Cl water types, the least dominant being Ca-Na-HCO_3 and Na-Cl water types.

2.2. Sampling

Physio-chemical parameters, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), silica (SiO_2), total dissolved solids (TDS), pH, electrical conductivity (EC) and Temperature (T) were determined from 1995 to 2017 twice a year (i.e., wet and dry seasons) from 12 boreholes and 2 springs (124 samples). EC, T, pH and TDS were measured using a YSI Professional Multi-parameter probe. Groundwater samples were collected as part of an active national groundwater quality monitoring network using sampling methods derived from [51]. Boreholes were purged until T, EC and pH stabilised to obtain a representative sample from the aquifer. The groundwater was collected using 500 mL polyethylene sampling bottles. The samples were analysed at the Department of Water and Sanitation's (DWS) laboratory. Anions were analysed using ion chromatography, while cations were analysed using inductively coupled plasma mass spectrometry (ICP-MS). Historical data were available from the DWS's water management system (WMS) as record reviews. To determine the accuracy, precision and reliability of the data, the ion balance error (IBE) was calculated for all samples and determined to be between 0 and 9%, lower than 10% [52].

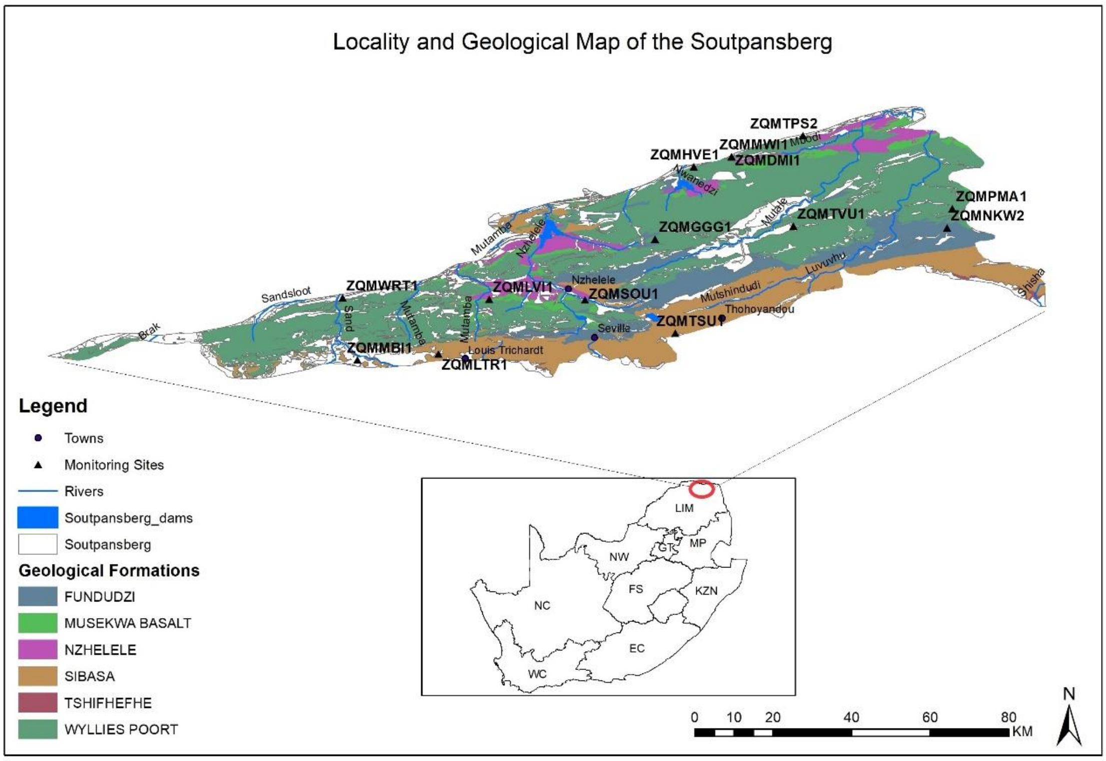

Figure 1. Locality and geological settings of the Soutpansberg region.

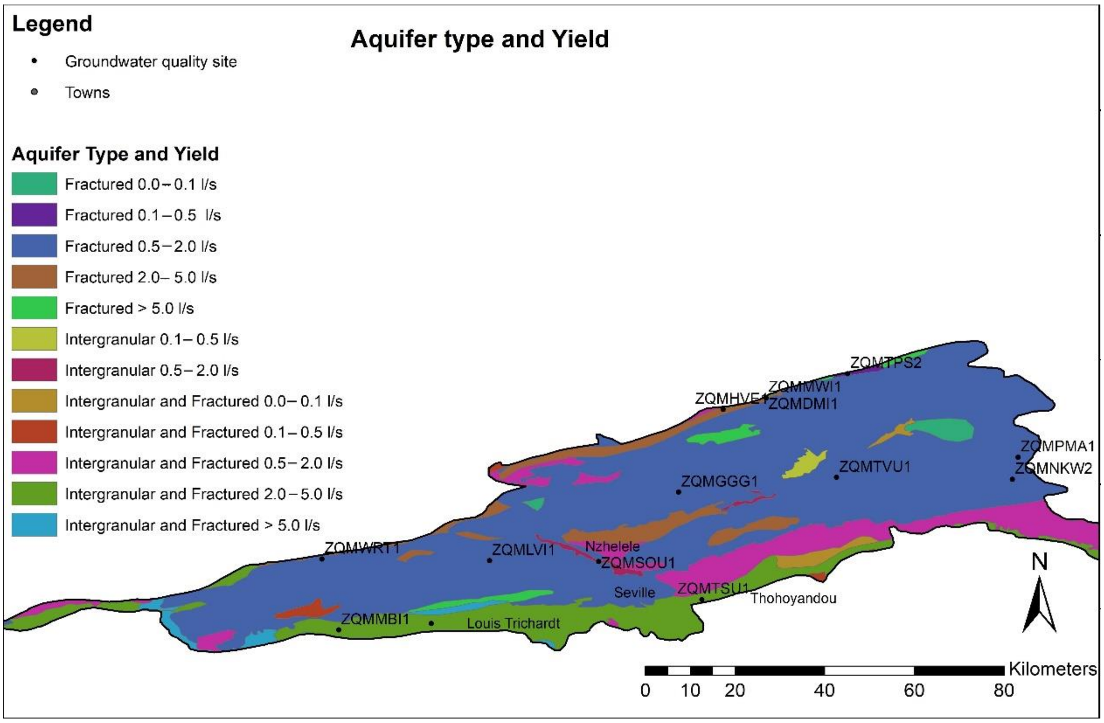

Figure 2. Hydrogeological settings of the Soutpansberg region.

2.3. Feasibility Assessment

The feasibility assessment of designing an adequate and sustainable groundwater remediation technique for rural areas was based on groundwater management, cost and risk associated with rural settings. Under groundwater management criteria, factors such as monitoring groundwater abstraction and groundwater level and quality monitoring were considered. Monitoring of groundwater level and abstraction volumes will assist in the sustainability of the resource, while groundwater quality will determine the effectiveness of the remediation technique. The second factor that was considered was the risk of damage or theft of infrastructure designed as part of the remediation process. It is common that boreholes, pumps and power sources are usually vandalised or stolen. To have an effective and sustainable remediation process, infrastructure is key. Risk factor also includes the health risk associated with consuming contaminated groundwater. The final factor to be considered was the finances/cost of running an adequate groundwater remediation technique in rural areas. Financial factors include the cost of the power source and infrastructure associated with the supply of water from borehole to household (pipelines).

3. Results and Discussion

3.1. Chemical Composition of Groundwater

The mean results of the physical parameters and major ions in this study area for each groundwater monitoring sites are tabulated in Table 1. pH is one the main parameters used to determine if water is acidic (pH < 7), neutral (pH = 7) or alkaline (pH > 7) [53]. In the Soutpansberg region, the average pH ranged from 7.7 to 9.3, which indicated that the groundwater was alkaline in nature owing to high concentrations of Na^+, Mg^{2+}, Ca^{2+} and HCO_3^- from the lithological settings. TDS classification by Freeze and Cherry [54] indicated that 85.7% of the monitoring sites were classified as fresh (TDS < 1000 mg/L), and 14.3% of the sites were classified as brackish (TDS > 1000–10,000 mg/L). Electrical Conductivity (EC) in the Soutpansberg ranged from 5 to 279 mS/m with a mean of 59 mS/m between 1995 and 2017.

The major cation dominance order in Soutpansberg was $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, and for major anions it was $HCO_3^- > Cl^- > SO_4^{2-}$. Sodium ($Na^+$), as a dominant cation, ranged from 12 to 424 mg/L. Calcium (Ca^{2+}) ranged from 2 to 86 mg/L, while Mg^{2+} ion ranged from 1 to 118 mg/L. In terms of major anions, the dominant HCO_3^- ranged from 28 to 455 mg/L (Table 1). Concentration of Cl^- ranged from 5 to 664 mg/L. Recent studies in and around the Soutpansberg region [16–20] determined that concentration levels NO_3^- and F^- were above the WHO [22] and SABS [55] drinking water limits of 11 mg/L. The spatial distributions of NO_3^- and F^- in the Soutpansbeg are presented in Figures 3 and 4. Mean NO_3^- concentrations of 22, 15 and 15 mg/L were determined in ZQMMBI1 (Maebane), ZQMGGG1 (Gogogo) and ZQMTVU1 (Tshitavha Sambandou), respectively (Table 1). The historical trends of NO_3^- are presented in Figure 5a–c. In Gogogo, NO_3^- concentration levels were less than 5 mg/L between 2002 and 2014 (Figure 5a), and an increase from 3 to 37 mg/L was recorded between 2014 and 2016, with the last concentration of 15 mg/L in October 2017. In Maebane (Figure 5b), concentration levels of NO_3^- have been over [21,54] the limit for drinking water between 1995 (26 mg/L) and 2017 (19 mg/L). In Tshitavha Sambandou Village (Figure 5c), a decreasing NO_3^- concentration trend was noted between 2014 (27 mg/L) and 2017 (13 mg/L). Recent studies [19,20,23] attributed high concentration levels of NO_3^- in groundwater of the Soutpansberg region to anthropogenic activities such as the input of fertilizers during irrigation. Groundwater from Siloam Village (Figure 5d) contained a concentration level of F^- above the recommended 1.5 mg/L [22,55]. Concentration levels of F^- were high between 1996 (2.7 mg/L) and 2017 (2.6 mg/L). The main challenge is that majority of people in the Soutpansberg regions use groundwater for domestic use without treatment or knowledge of contaminants levels [20], and this can expose them to various waterborne diseases. The high F^- concurs with a previous study in ZQMSOU1 and the surrounding area of Siloam that showed the high concentration resulted from fluorite (CaF_2) minerals associated with igneous and sedimentary rocks in the area [16]. Dental fluorosis resulting from a high F^- concentration in groundwater already poses health risks in the Siloam area [16,18].

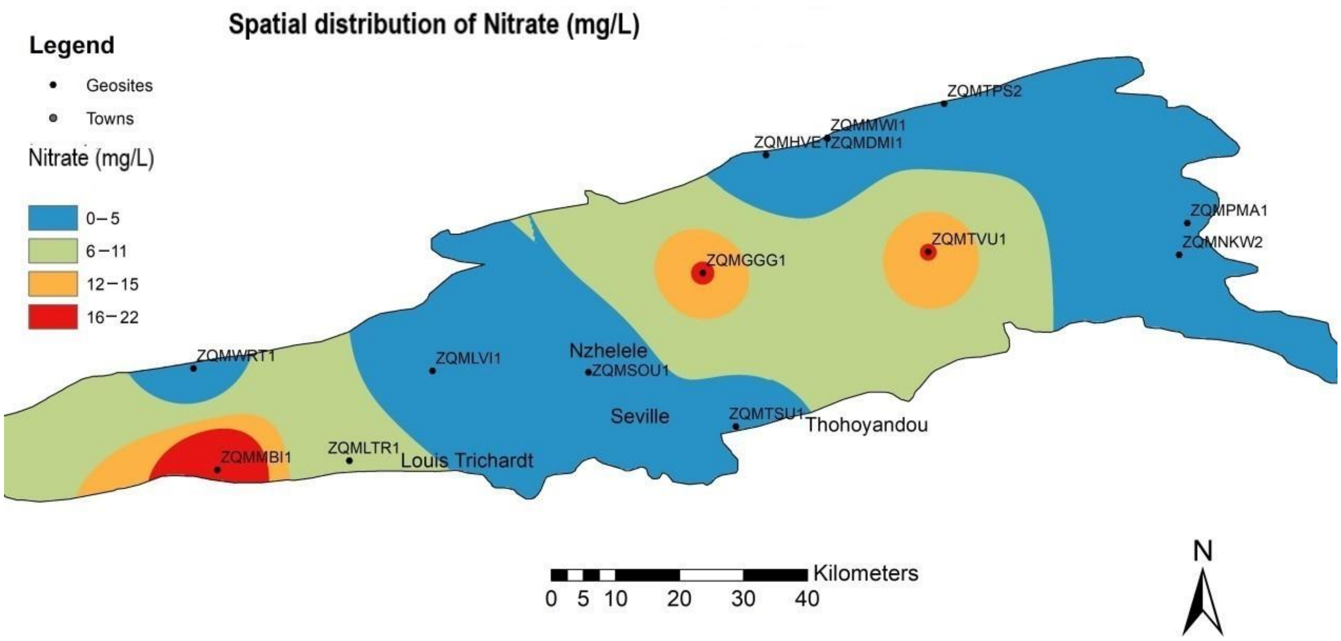

Figure 3. Spatial distribution of nitrate in the Soutpansberg region.

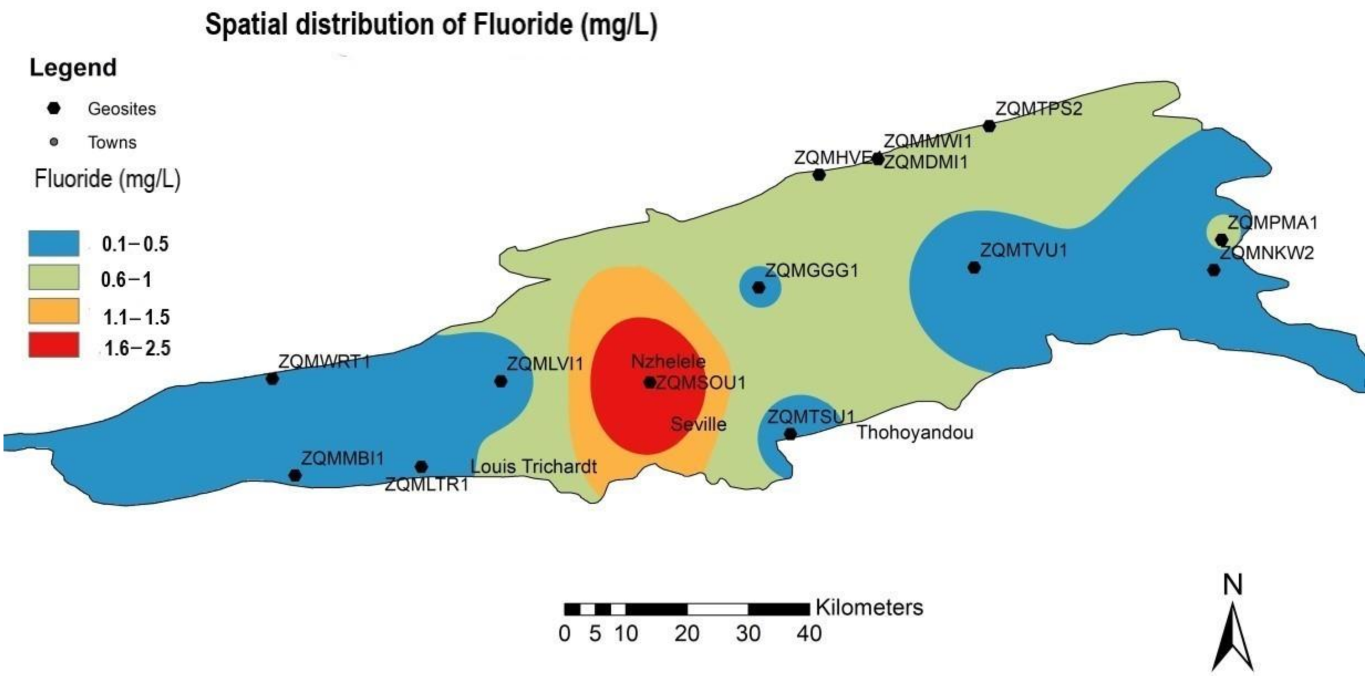

Figure 4. Spatial distribution of fluoride in the Soutpansberg region.

Table 1. Physico-chemical results of each monitoring site in the Soutpansberg region.

Site ID	pH	T	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3^{-}	SiO_2	F^{-}	SO_4^{2-}
ZQMPMA1	7.9	27	279	1810	86	61	424	2	664	452	0	30	0.5	22
ZQMSOU1	8.2	39	36	262	12	10	45	2	33	119	1	22	2.5	10
ZQMTPS2	9.3	45	34	231	2	1	66	2	39	84	0	34	0.7	19
ZQMLRT1	8.3	22	88	697	43	47	76	4	76	335	7	21	0.4	14
ZQMNKW2	7.7	24	20	125	8	7	16	1	25	50	1	17	0.1	4
ZQMDMI1	8.4	22	89	633	53	40	68	3	146	227	5	11	0.4	25
ZQMHVE1	8.2	26	48	328	15	9	64	2	55	122	2	19	0.8	26

Table 1. *Cont.*

Site ID	pH	T	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3^{-}	SiO_2	F^{-}	SO_4^{2-}
ZQMMBI1	8.3	26	202	1418	64	118	175	8	334	455	22	30	0.3	65
ZQMMWI1	8.5	24	70	494	41	29	59	3	109	183	2	10	0.7	20
ZQMGGG1	8.1	24	123	905	50	77	97	4	192	322	15	26	0.4	24
ZQMWRT1	8.4	23	22	155	12	11	12	1	20	74	1	11	0.1	5
ZQMTSU1	8.2	25	25	180	16	12	13	1	15	87	3	25	0.3	2
ZQMTVU1	7.8	26	28	179	13	10	22	1	29	28	15	7	0.2	2
ZQMLVI1	8.3	25	50	360	30	25	32	1	62	156	2	18	0.3	12
Min	6.7	13	5	33	1	1	3	0	5	5	0	2	0	1
Max	9.6	47	287	1869	99	154	460	10	755	612	37	58	3	71
Mean	8.4	31	59	372	22	23	65	2	75	170	4	23	1	14
Median	8.3	28	36	248	13	10	59	2	34	109	1	22.0	0	11
Detection limit	2	0	1	1	1	1	2	0.1	3	4	0.01	0.4	0.1	0.8

Unit of measurement: all in mg/L, EC in mS/m.

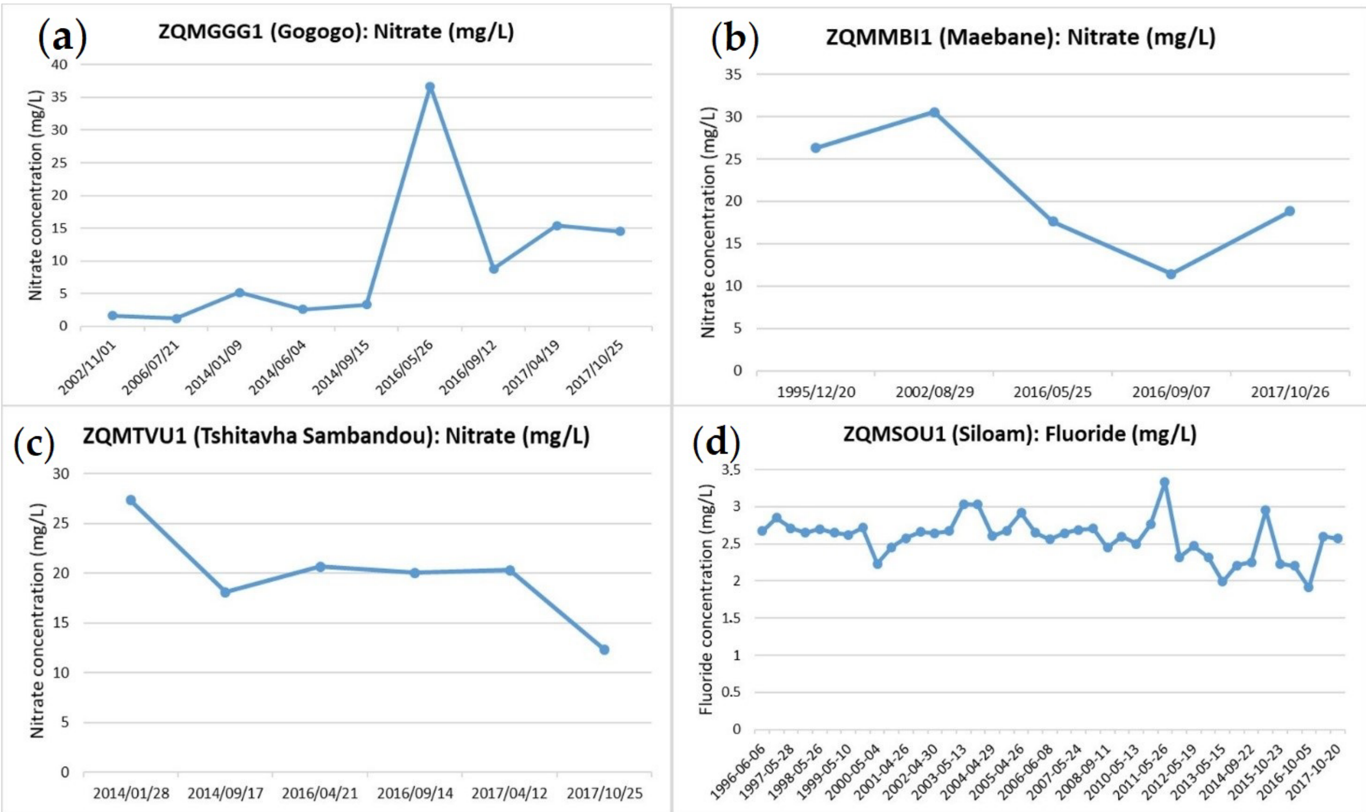

Figure 5. Trend analysis of nitrate and fluoride in the Soutpansberg region (1995–2017), (**a**) Gogogo (**b**) Maebane (**c**) Tshitavha Sambandou (**d**) Siloam.

3.2. Feasibility of an Adequate Groundwater Remediation Technique

Individual household remediation type is a common technique being practiced in rural areas, where each household has access to a borehole, filtering system and a water tank in their own yard. Community scheme remediation type is applied in some rural areas, where boreholes are drilled in one area and electrical/solar/hand-pump abstraction methods are installed. In some few instances, groundwater monitoring and remediation systems are also installed. Individual advantages and disadvantages are tabulated in Table 2. Groundwater characteristics is one of the major factors that should be considered when piloting an appropriate groundwater remediation technique. In individual household remediation types, groundwater monitoring is possible if boreholes are designed in a way that allows such. The main challenge will be cost-associated with groundwater sampling and laboratory analysis. If each individual household is pumping and remediating groundwater, the cost of energy might be higher than community-based scheme remediation, as the costs might be shared or covered by water supply authorities (municipalities or water bodies). The cost factor is also dependent on the type of power source used. Electricity or solar powered pumps can support groundwater abstraction. In terms of infrastructure associated with power source, the risk of theft or vandalism is very low in individual household remediation types. Individual household remediation can expose groundwater users to the risk of being affected by waterborne diseases, owing to socio-economic related factors. For instance, not all households in a community can afford to drill a borehole, install solar/electric pumps and sample and analyse groundwater quality.

Table 2. Advantages and disadvantages of individual household and community schemes remediation techniques (Pump and Treat).

Remediation Type	Individual Household		Community Scheme	
	Advantages	Disadvantages	Advantages	Disadvantages
Groundwater Quality management	• Monitoring is possible, however high cost of water analysis may prove to be a challenge.	• Groundwater monitoring is a challenge. • Uncontrolled groundwater abstraction.	• Groundwater monitoring (abstraction, levels, quality) is manageable. • Controlled groundwater abstraction.	• Possible high-cost associated with monitoring
Risk	• Low risk of vandalism and theft.	• Increased health risk due to lack of groundwater quality monitoring.	• Low health risk as groundwater quality monitoring will be active.	• High risk of vandalism/theft.
Cost	• No cost for security.	• High energy cost of pumping and remediation. • High cost of water analysis.	• Shared cost of energy of pumping and remediation (local water authorities may cover costs). • Low cost of water analysis.	• Increased cost associated with hiring of security at pumping stations.

Recent studies [23,44] suggested that there is a need to design small-scale community groundwater remediation schemes as it will assist in reducing the risk of water borne diseases in rural areas. Groundwater monitoring as a key factor in groundwater management is highly possible in community-based remediation schemes. Groundwater abstraction volumes can be controlled and recorded for improved groundwater governance. In terms of groundwater quality monitoring, community-based remediation schemes can form part of a national water quality monitoring network where such monitoring exists. Many of the groundwater remediation techniques in various studies [40–43] allow groundwater to be stored after remediation. Groundwater can be pumped, remediated and stored before distribution in community-based schemes. The cost factor will depend on available water supply policies in various areas. In South Africa, for instance, the local water authority (municipalities) or the Department of Water and Sanitation may carry the cost of water analysis, power source and maintenance of the community-based groundwater remediation and supply schemes. The risk of theft and vandalism of infrastructure may be high in community-based groundwater remediation schemes. There is a need to secure community-based groundwater remediation schemes similar to current wastewater and water purification plants. The norm of treating groundwater as a back-up resource is affecting how communities across the world view and treat groundwater. The development of groundwater-related infrastructure such as pumping stations, remediation plants and pipelines should be included during the planning phase of each groundwater supply system. Usually, boreholes are just being drilled where water is being sited during geophysical surveys and remediation and supply are not being considered. It is a common practise that most people view groundwater infrastructures as only a hand-pump.

A number of studies [23,56–61] recommend that suitable and environmentally friendly remediation techniques be applied to improve groundwater for drinking purposes. Improvements in groundwater quality will reduce the health risk and exposure [62] associated with elevated nitrate and fluoride in rural areas such as Soutpansberg. A small-scale community-based groundwater remediation scheme suggested by [44] and discussed in Table 2 consider the issue of socio-economic factors. For instance, not all households in rural areas can afford to drill, equip, install water filters and sustain the cost associated with individual household remediation techniques. Households that continue to use contaminated groundwater for drinking purposes, such as in Siloam Village, where majority (up to 80%) of users were found to have dental fluorosis [16], will be further exposed to health risks. A community-based groundwater remediation technique can assist rural areas to improve health and well-being aligned to the United Nation's Sustainable Development Goal 3. This study suggests that groundwater remediation method applications should consider issues associated with socio-hydrogeology and groundwater management in general. Application and design of community groundwater remediation techniques should be set up in a way that brings water closer to the people for improved health and livelihood. It is recommended that a groundwater remediation technique should be part of any planned groundwater supply scheme.

4. Conclusions

In conclusion, this study managed to determine that concentration levels of parameters such as NO_3^- and F^- were high in certain parts of the Soutpansberg region. Groundwater from Gogogo, Siloam, Maebane and Tshitavha Sambandou Villages requires interventions such as treatment before it can be used for drinking purposes to avoid further risk and exposure to waterborne diseases. The feasibility assessment conducted indicated that a community-based groundwater remediation scheme is a better option compared to individual household groundwater remediation techniques in rural areas such as the Soutpansberg region. To deal with the socio-economic dynamics of rural communities, community-based groundwater remediation techniques are recommended. To protect the health and livelihood of communities in rural areas, this study recommends that groundwater remediation should be a part of any proposed drought interventions or water supply plans in rural communities.

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