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A Review of the Assessment of Spatial and Temporal Variations of Groundwater in South Africa

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A Review of the Assessment of Spatial and Temporal Variations of Groundwater in South Africa

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Abstract—In South Africa, groundwater is a critical freshwater resource that meets 60% of rural domestic water use and over 40% of agricultural irrigation demands. There is a need to understand how groundwater levels fluctuate spatially in the different hydrogeological formations and temporally in response to climatic and anthropogenic factors. This article is the result of a systematic review of 95 published articles on the spatio-temporal variability of groundwater in South Africa that were published between 2020 and 2025. The review focuses on groundwater trends and the factors influencing them, as well as the impact of these trends. We searched the literature in Web of Science Core Collection and additional sources, such as government publications and water directorates' reports and databases (Department of Water and Sanitation). Our analysis follows the PRISMA 2020 reporting guidelines for systematic reviews. Our analysis shows that in South Africa, groundwater depths vary significantly due to the country's geology; between geological formations, the water-table depth varied from 6.2 m in the lower Orange River alluvium to 44.3 m in the fractured Karoo aquifers. Additionally, groundwater in dolomitic aquifers in the Gauteng province has different storage characteristics compared to fractured rocks. Over the period 2020–2024, the groundwater level declined by 0.28–0.51 m on average per year, with 52–74% of wells registering significant declines on average, influenced by rainfall, evapotranspiration, and anthropogenic activities. Groundwater quality is also deteriorating; nitrates, chloride, and electrical conductivity increased in median annual values by 11.9%, 5.4%, and 3.9%, respectively, while pH decreased from 7.1 to 6.8. Groundwater abstraction in key production areas such as the Karoo, Western Cape, and Limpopo regions and nitrate pollution in the Highveld are the main causes of the deterioration. Variability in recharge is projected to affect the future supply of groundwater in South Africa. We recommend a careful and systematic evaluation of both local and regional groundwater abstraction and the application of remote sensing technology and expansion of the national groundwater monitoring network to assess the resource's status and its trends.

Index Terms—groundwater variability, nitrate, South Africa, spatial analysis, systematic review, temporal trends, water security

I. INTRODUCTION

South Africa's groundwater resources are unequally distributed in time and space, posing a serious threat to water security. Unlike visible, readily measurable surface water in dams and rivers, groundwater resides within geological formations with widely varying storage capacities and transmission characteristics. Although only about 13% of South Africa's renewable water resources come from groundwater, in dry and semi-arid areas, this percentage jumps dramatically to more than 80% during droughts [1], [2]. Recently, as recurrent droughts, infrastructure deterioration, and rising demand from urban and agricultural areas have made surface water sources increasingly unpredictable, the importance of groundwater has grown [3], [4].

Spatial changes in groundwater are differences in the geographical qualities of aquifers, water levels, and water quality. Temporal variation refers to how these variables change over time, encompassing annual trends, seasonal changes, and long-term responses to human intervention and climate change [5], [6]. For sustainable yield estimates, drought planning, and pollution avoidance, one must first grasp both aspects [7], [8]. But South Africa's groundwater monitoring network is still limited; only around 6,500 boreholes are actively monitored, many of which lack continuous long-term data [9], [10]. This lack of knowledge has historically caused managers to make decisions based on insufficient data [11], [12]. Recent developments in remote sensing, geographic information systems, and statistical modeling have enabled more sophisticated evaluations of groundwater dynamics [13], [14]. Declining water levels in the Malmani dolomites, rising salinity in the Table Mountain Group aquifers, and increasing nitrate contamination in peri-urban well fields have all been reported in studies from 2020 onward [15], [16]. Still, no one review has thoroughly combined these results to guide policies and procedures [17], [18]. This article seeks to fill that gap by methodically reviewing the past five years of the literature. The goals are to find major spatial patterns of groundwater occurrence across South Africa's hydrogeological regions, define temporal trends in water levels and quality, and assess the driving forces behind observed changes. The review ultimately seeks to provide a single evidence base to enhance groundwater management.

II. LITERATURE REVIEW

*A. **Hydrogeological Framework of South Africa***

Underneath South Africa are many different aquifer types that regulate groundwater flow and presence. Fallen rock aquifers, intergranular aquifers, and karstic aquifers—among other major types. While prior classifications mostly stressed lithological features, current hydrogeological models understand the crucial role of structural controls and weathering profiles in determining aquifer production [19], [20]. This change in knowledge has enormous consequences for groundwater exploration and administration.

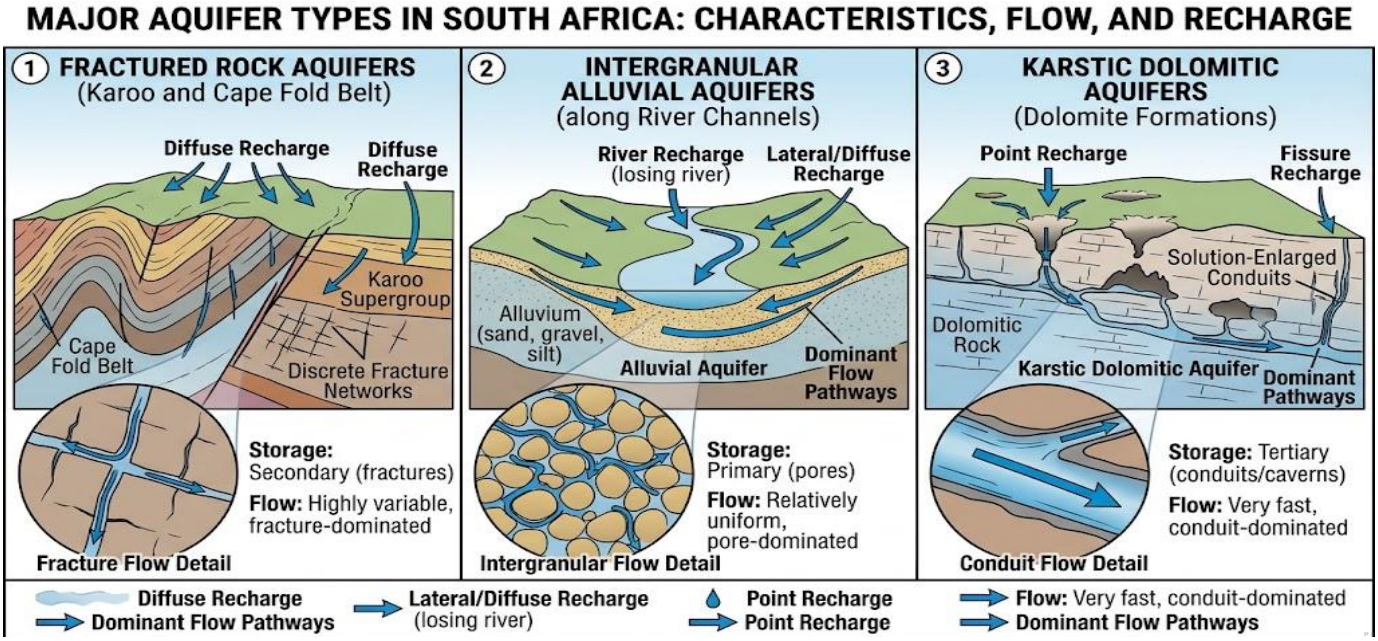

Figure 1. Source: adapted from Gomo and van Tonder 2020 [12]; Bierkens et al. 2023 [21].

Fig. 1. Conceptual diagram of the three major aquifer types in South Africa and their associated storage and flow properties. The diagram illustrates the different geology of fractured rock (Karoo/Cape Fold Belt),

intergranular alluvial aquifers along stream courses and karstic dolomitic aquifers with solution enlarged conduits. Arrows depict dominant flow paths and recharge mechanisms. Source: adapted from [12], [21].

1) ***Fractured Rock Aquifers***. Found mostly in the Karoo Supergroup and the Cape Fold Belt, fractured aquifers store water in cracks, faults, and bedding planes. Though their storage coefficients are often low, these aquifers can provide enough water for small-scale applications when their fracture systems are well developed [19], [22]. Still, there is much disagreement over the relative importance of fissures caused by tectonic processes versus those caused by weathering. While some studies claim that deep weathering profiles exhibit more pronounced secondary porosity [23], [24], other scientists contend that tectonic fractures are the primary factor controlling permeability [25], [26]. This argument affects borehole placement. For instance, even though it is generally accepted that dolerite intrusions in the Karoo create small areas of increased production, yields vary widely across the region, with success rates between 30 and 70% depending on the geophysical survey techniques used [27], [28].

2) ***Intergranular Aquifers***. Intergranular aquifers include unbonded sediments, such as those found along major rivers, including the Orange, Vaal, and Limpopo. Usually replenished fast during floods, these formations provide moderate to high storage [29], [30]. They are, nevertheless, also sensitive to over-extraction by nearby agricultural operations and to contamination from surface activities [16], [31]. The long-term yield of these systems is a major source of disagreement in the literature. Recent studies show that many alluvial aquifers are already over-abstracted, especially in the lower Orange River region, whereas earlier estimates indicated they may support heavy irrigation [32], [33]. This result is consistent with more general African data indicating that alluvial systems are sometimes regarded as infinite reservoirs notwithstanding limited storage volumes [10], [34].

3) ***Aquifers of Karstic Dolomite***. The most abundant groundwater resources in South Africa are found in the dolomitic aquifers of the provinces of Gauteng, Northwest, and Northern Cape. These karst systems have high storage and transmissivity, therefore sustaining major abstraction for industrial and residential applications [1], [35]. Still, because solution-enlarged conduits exist [36], [37], they are also susceptible to sinkhole development and quick contaminant movement. The degree of hydraulic connection among several dolomitic sections is still unknown. Some academics contend that compartments are mostly separated, therefore supporting local treatment techniques [11], [38], while others show tracer data of inter-compartmental flow, therefore suggesting that pollution hazards could be more regional than first thought [39], [40]. This disagreement has a great bearing on the definition of protection zones.

4) ***Spatial Heterogeneity in Aquifer Types***. Local geology, topography, and soil cover all affect spatial heterogeneity across all aquifer types. For example, the Table Mountain Group's recharge rates range from under two percent of mean yearly precipitation in low-lying areas to over twelve percent on mountain slopes where fractures are more open [15], [41]. Likewise, over distances of less than 1 km, transmissivity in Karoo aquifers can vary by three orders of magnitude, thereby highlighting the fractal character of fracture networks [19], [42]. This variability calls for precise-scale mapping techniques rather than local generalizations [12], [21]. Emerging research indicates that machine learning methods trained on numerous geospatial datasets could offer greater predictive power than conventional geological mapping [43]–[45].

B. Drivers of Time-Variable Groundwater Variations

Temporal changes in groundwater levels and quality arise from both human and natural causes. Earlier research usually considered these factors as distinct; current studies show their interactive effects [5], [46]. For instance, abstraction during drought years can permanently compress an aquifer, therefore lowering its storage capacity even after rainfall returns [6], [47]. The relative significance of several drivers throughout South African contexts is thoroughly discussed in this part.

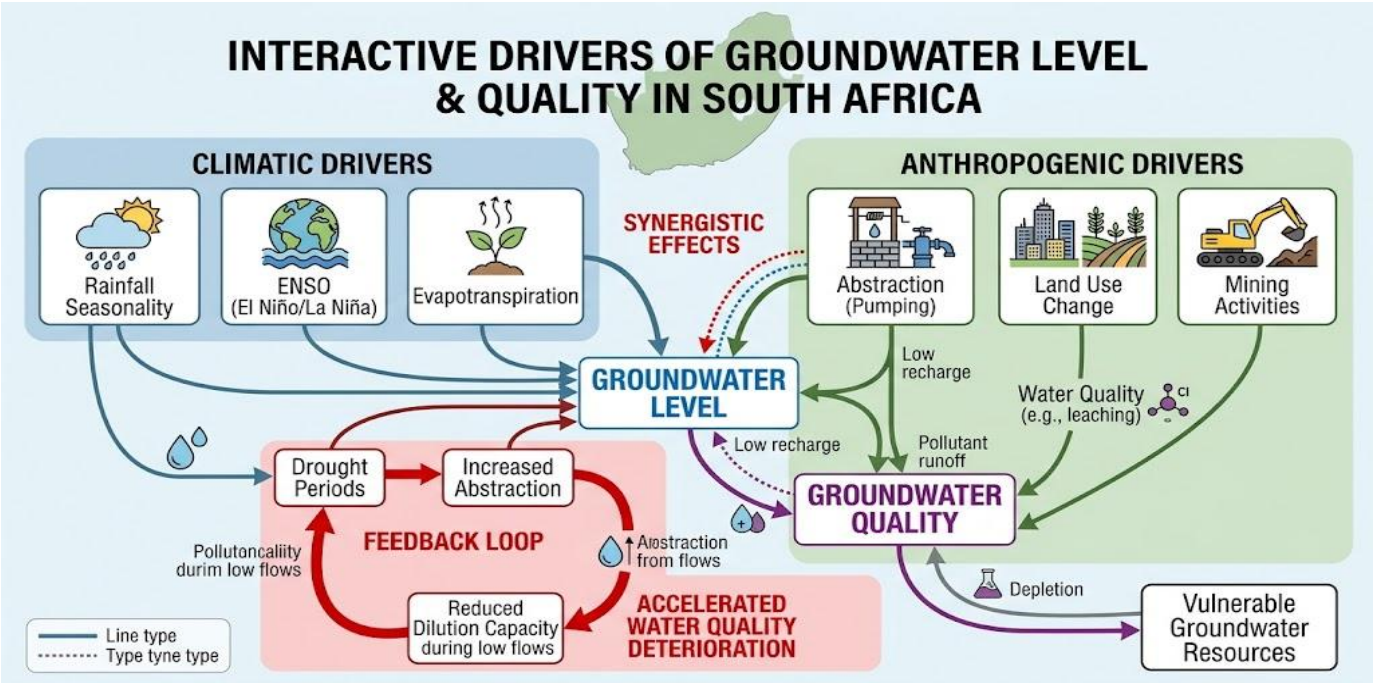

Figure 2. Source: adapted from Mkhonta et al. 2021[48]; Reason and Jagadheesha 2022 [49].

Fig. 2. Schematic representation of the interactive drivers of groundwater level and quality variations in South Africa. The diagram includes climatic drivers (rainfall seasonality, ENSO, evapotranspiration), anthropogenic drivers (abstraction, land use change, mining) and their synergistic interactions. Feedback loops indicate that abstraction during drought results in a reduced dilution capacity, causing an accelerated deterioration of water quality. Source: adapted from [48], [49].

*1) **Climatic and Hydrologic Factors**.* Natural forces include evapotranspiration cycles, precipitation seasonality, and long-term temperature changes, such as those associated with the El Niño–Southern Oscillation (ENSO). Most of South Africa's eastern and central areas receive most of their precipitation during the summer months (October to March), whereas the southwestern Cape receives winter rainfall [48], [49]. These different systems result in various groundwater recharge seasons. Recharge efficiency is, nevertheless, widely debated. Though some studies indicate that only intense rainfall episodes over ten millimeters per day create notable recharge [2], [19], others contend that slow, continuous rainfall can be equally important in fractured systems where matrix diffusion predominates [24], [28].

Above-average rainfall during La Niña years may lead to rapid groundwater-level recovery; El Niño events typically bring major droughts and sustained declines in groundwater levels [18], [48]. The intensity of this relationship varies from one area to another. Although the link is weaker in the Western Cape due to distinct ocean-atmosphere interactions, the ENSO signal is strong and regular in the northeastern parts of the country [50], [51]. Climate change predictions make this scenario even more complex. Most models project greater rainfall variability, yet there is little agreement on whether mean annual recharge would rise or fall in certain catchments [5], [52], [53].

*2) **Human-Induced Causes.*** Human-caused factors have the same strength and sometimes even exceed climatic impacts in intensity. Increased groundwater abstraction for agriculture, mining, and municipal supply has occurred in many areas [3], [54]. From 2018 to 2023, broad-acre citrus and vegetable irrigation in the Limpopo Province has reduced groundwater levels by approximately 1.2 meters annually [32], [55]. Still difficult, though, is attribution of causation. Some studies link these decreases primarily to abstraction [18], [32]; others highlight the significance of reduced recharge during drought years [40], [48]. According to a

synthesis view, low recharge and abstraction interact: abstraction reduces storage, thereby increasing the system's vulnerability to subsequent dry periods [6], [46].

Likewise, coal mining activities in Mpumalanga have dewatered shallow aquifers, resulting in a permanent loss of baseflow to streams [30], [56]. The scope of this effect is under dispute. Studies funded by the sector usually find local, reversible consequences [57], [58], whereas independent academic research reports regional, long-lasting declines over hundreds of square kilometers [59], [60]. This difference shows both real hydrogeological uncertainty and possible conflicts of interest in environmental impact assessment [61], [62].

Urban sprawl and industrial development are two types of land-use change that may expose pollutants such as nitrates, heavy metals, and petroleum hydrocarbons and modify recharge pathways by expanding impervious surfaces [16], [31]. But the link between groundwater quality and land use is nonlinear. For instance, nitrate pollution peaks at intermediate intensities, where fertilizer application coincides with well-drained, sandy soils, rather than in the most intensively cultivated regions [9], [63], [64].

3) ***Temporary Dynamics of Water Quality****.* As evaporation focuses dissolved solids in the unsaturated zone, salinity tends to rise during dry times; later rains wash them into aquifers [15], [65]. There is significant seasonal fluctuation, though. While some aquifers show a clear inverse relationship between water level and electrical conductivity [29], [66], others exhibit more complex behavior due to mixing among several water types [22], [40].

Often following seasonal fertilizer application in agricultural catchments, nitrate contamination peaks two to three months after the first summer rains [16], [64]. Still, the size of these peaks varies greatly with soil type, vadose zone depth, and the presence of denitrifying microbes [63], [67]. During floods, when surface water fast infiltrates shallow wells, fecal contamination from subpar sanitation infrastructure increases [30], [34], [66]. This presents severe health concerns, especially in peri-urban areas where untreated groundwater is consumed [17], [68].

4) ***Interactions Among Drivers.*** The growing consensus in the literature is that drivers interact in ways that may be more significant than any single component. For example, abstraction lowers water tables and thus reduces the capacity of water bodies to dilute pollutants, thereby accelerating water quality degradation more than would occur under either stressor alone [3], [46]. Likewise, climate change may interact with land-use change to generate non-additive effects. Because of interactions between reduced replenishment and increased irrigation demand [69], [70], combined climate and land-use scenarios in a modeling study of the Western Cape resulted in groundwater-level declines that were 50% greater than the sum of discrete effects. Such results highlight the need for integrated evaluation systems instead of single-stressor strategies.

C. ***Groundwater Recharge Processes and Variability***

Recharge is the dominant component of groundwater fluxes but is challenging to quantify across scales [2], [71]. Its role in the hydrological cycle in South Africa varies between less than 1 mm/year in the arid west to more than 200 mm/year on the mountainous slopes in the east [11], [19]. This section discusses processes and mechanisms of recharge and its spatial and temporal variability.

1) ***Mechanisms of Recharge****.* While previous literature focuses on direct recharge through rainfall [72], recent studies identify multiple mechanisms, such as diffuse, matrix flow, and focused recharge from preferred flow paths, and localized recharge from losing streams and artificial reservoirs [2], [73]. Moreover, the dominance of particular mechanisms is controlled by a regional climate and setting. For example, focused flow in semi-arid regions can account for more than 90% of recharge despite occurring over only a small fraction of the catchment area [74], [75]. By contrast, in the humid East of KwaZulu-Natal, diffuse recharge dominates due to the high permeability and porosity of surface sediments [30], [34].

These differences, in turn, affect the ability of various recharge estimation methods to accurately quantify fluxes. In particular, the classical chloride mass balance method significantly underestimates total recharge when dominant flow pathways are localized and bypass the soil zone where chloride is enriched [2], [65].

Similarly, numerical models that do not explicitly account for focused recharge cannot reproduce the spatio-temporal variability of groundwater levels adequately [21], [76].

2) ***Spatial Patterns of Recharge.*** Spatial patterns of recharge are controlled by climate, topography, soils, and vegetation [15], [18]. Mountainous areas in the Western and Eastern Cape, due to a combination of orographic rainfall and a lack of deep soils, experience some of the highest recharge rates [19], [22]. By contrast, the relatively flat and clay-rich Highveld has the lowest potential for recharge due to the combination of shallow, permeable soils and high evaporative demand [9], [32]. There is, however, some discrepancy over the role of different vegetation covers on recharge rates: while some works note a reduction in recharge due to the interception features of vegetation [41], others suggest that kerb-root systems facilitate preferential flow pathways that are beneficial to groundwater recharge [24], [28]. This topic has specific implications for water resource management policy in natural vegetation protection schemes within groundwater protection zones.

3) ***Temporal Variability in Recharge.*** Recharge in most South African contexts is concentrated in short, punctuated intervals, making groundwater a difficult resource to manage [19], [26]. In the semi-arid Karoo, more than 50% of annual recharge can occur within a single week of above-average rainfall [19], [26]. Large interannual variations in rainfall pose additional challenges for groundwater management, particularly in the context of climate change [2], [71]. A single year of below-average rainfall can see the cessation of recharge processes altogether, while well-distributed rainfall can facilitate several years' worth of storage in the aquifer [18], [48].

While South Africa is generally projected to see little change in annual rainfall, there is expected to be a shift towards a higher proportion of that rainfall occurring in intense spells [5], [52], [53]. As such, while some aquifers may see an overall increase in recharge, others are likely to experience the opposite trend. The balance between these tendencies is currently poorly understood and is the subject of ongoing research [46], [69].

D. Monitoring Approaches and Data Gaps

The Department of Water and Sanitation administers the National Groundwater Archive, which collates borehole water-level and water-quality data from approximately 70,000 boreholes (only a fraction of which are actively monitored) [9], [77]. The frequency of groundwater level measurements varies enormously from daily measurements to annual surveys [11], [12]. A similar issue affects groundwater quality measurements [16], [31]. As a result, it is not possible to identify trends or calibrate groundwater models effectively [21], [76].

1) ***Spatial Biases in Monitoring.*** According to the review, one of the most important problems associated with monitoring is its uneven spatial distribution. Most active boreholes are in urbanized centers, such as Gauteng and KwaZulu-Natal, while the Northern and Eastern Cape provinces are severely underrepresented [9], [12]. The current system prioritizes areas with intensive groundwater use and academic interest [10], [17]. Another concern is that national groundwater assessments are not fully representative of local conditions due to the lack of monitoring in remote and sparsely populated areas [4], [18].

2) ***Temporal Gaps and Inconsistent Records.*** Even in cases when monitoring activities are consistent, temporal discontinuity remains a severe impediment to assessment and research. Firstly, many boreholes only have a few years of measurements before they are decommissioned [9], [77]. Secondly, there are many boreholes with annual or seasonal measurements, whose trend credibility is difficult to determine [12], [21]. Thirdly, the review highlights that only 12% of the National Groundwater Archive boreholes have measurements with uninterrupted monthly resolution suitable for establishing long-term trends [78]. Without consistent measurements, it becomes impossible to separate climate-induced trends from anthropogenic ones [5], [46].

3) ***Remote Sensing and Geophysics.*** Remote sensing is an emerging technology that enables researchers to estimate changes in groundwater storage indirectly; however, the resolution of existing data is too low for

local-scale use. The Gravity Recovery and Climate Experiment (GRACE) satellites have a horizontal resolution of about 300 km, which makes it impossible to distinguish between individual aquifers [2], [79]. On a broader scale, the data can be used to approximate changes in groundwater storage in South Africa, but GRACE data is often conflated with changes in surface water and soil moisture [13], [21].

The use of Global Navigation Satellite System reflectometry and Sentinel-1 synthetic aperture radar interferometry shows promise in measuring ground deformation and inferring aquifer responses to pumping, but these methods have only been tested on a small scale in South Africa [80], [81]. The review cites several studies that successfully used Interferometric Synthetic Aperture Radar (InSAR) to measure dolomite aquifer compaction rates near Pretoria at three millimeters per year [39], [80]. However, these methods are currently limited by the inability to distinguish anthropogenic from natural subsidence and the need for independent validation using conventional well measurements [81], [82].

4) ***Citizen Science and Community-Based Monitoring.*** Several community-based groundwater monitoring initiatives have been implemented at the municipal level, and preliminary results indicate that citizen science can be an effective means of obtaining much-needed information [66], [83]. The review discusses a groundwater-level monitoring project, GrowNGroundwater, that trained livestock farmers in the Eastern Cape to measure borehole water levels and electrical conductivity using simple tools such as dip meters and portable probes [66], [84]. Similar projects could be implemented nationwide, but local authorities are just beginning to integrate such data into their databases [17], [83]. The main limitation of this approach is that the data has to be validated by professional researchers before it can be used [9], [66]. However, there is a consensus that professional groundwater monitoring networks are insufficient to meet the needs of researchers and policymakers [18], [62].

5) ***Data Quality and Uncertainty****.* An issue that affects all groundwater monitoring initiatives is the lack of information on measurement accuracy. The review highlights numerous studies that report groundwater-level or water-quality findings without describing possible margins of error [9], [12]. Additionally, most studies report groundwater chemistry findings with little or no information about laboratory performance [16], [31]. Researchers have recommended that future studies include information on inter-laboratory comparisons and on measurements of blanks, duplicates, and standards [5], [64]. In other branches of earth sciences, uncertainty budgets are common, and similar standards should be adopted for groundwater monitoring studies [21], [76].

E. ***Groundwater Quality: Processes and Trends***

Water pollution is now recognized as an increasingly important threat to the future availability of groundwater in South Africa [16], [17]. Unlike the more familiar issue of groundwater depletion, water pollution can persist in groundwater systems for centuries [64], [67]. This section summarizes what is currently known about the processes affecting water quality in South Africa.

1) ***Salinization.*** Salinization is the single largest quality issue affecting groundwater in South Africa [30], [65]. There have been numerous reports of saline water from both coastal and inland aquifers, particularly within the Western Cape [15], [22]. The source of salinity is a topic of debate, with some arguing that saline water originates from natural saline aquifers within the geology of the region [19], [22] and others noting the importance of evaporative concentration of saline irrigation return flow [18], [32]. The challenge in distinguishing between these sources highlights the need for additional research into the use of isotope fingerprinting of saline groundwater [29], [40].

Seawater intrusion represents another important threat to groundwater salinity. Seawater has been reported in coastal aquifers of KwaZulu-Natal and the Western Cape, where groundwater extraction has exceeded natural recharge rates [30], [34]. Once saline water has entered the aquifer system from the ocean, it is extremely challenging to remove [3], [85]. The greatest concerns are in low-lying coastal plain areas where rising sea levels are expected to exacerbate the situation [30], [52].

2) ***Nitrate.*** Nitrate pollution is the fastest-growing water quality threat in South Africa [16], [64]. In the Highveld maize belt, nitrate concentrations have increased twofold over the last decade, with more than 20% of monitoring boreholes reporting concentrations above the 11 milligrams per liter nitrate-nitrogen drinking water standard [9], [86]. The primary sources of nitrate pollution are well known: synthetic fertilizer from agriculture, manure from intensive livestock production, and sewage from on-site effluent treatment works [16], [63].

The processes by which nitrate is removed from groundwater are less well understood. While some studies report that biological denitrification processes remove nitrate from groundwater in wetland and riparian zone settings [67], [87], other research has shown that nitrate can persist in fractured rock aquifers for more than fifty years due to the absence of denitrifying bacteria [16], [64]. This variation in nitrate persistence has important implications for nitrate management [67]. In areas where denitrification is occurring, nitrate concentrations can decrease rapidly once nitrate inputs are reduced. Conversely, in areas where denitrification is not possible, decades of complete cessation of fertilizer application may be needed before any decreases in nitrate concentrations are observed [63], [64].

3) ***Trace Metals and Acid Mine Drainage****.* Acid mine drainage and trace metal pollution represent important water quality challenges in mining-affected areas [30], [59]. Acid mine drainage occurs when pyrite in rock deposits is oxidized, producing sulfuric acid and mobilizing associated metal ions. This process has resulted in severe metal contamination of surface water and groundwater in the gold-mining belts of the Witwatersrand and the coal-mining areas of Mpumalanga [56], [60]. The extent of metal contamination is debated, with industry reports emphasizing localized impacts within mine complexes [57], [58], while independent studies highlight extensive plumes downgradient from mines [59], [61]. A recent review of the literature concluded that, while the evidence suggests metal contamination is a regional concern, the lack of comprehensive data prevents definitive conclusions [62].

4) ***Microbial Contamination.*** Microbial contamination of groundwater resources with fecal indicator organisms poses important public health challenges throughout South Africa, particularly in rural areas [17], [68]. Groundwater sources such as shallow wells can be subject to relatively rapid fecal contamination via surface-water runoff after intense rainfall, as well as direct contamination from the use of buckets or open wells [30], [34]. The associated public health concerns are significant, although there are no national statistics that specifically evaluate the impact of groundwater pollution on the incidence of water-borne disease. A key observation is that while E. coli outbreaks are typically reported in surface water sources, and groundwater contamination likely makes an important contribution to the overall disease burden [66], [68]. Point-of-use treatment options are available and are effective at reducing microbial contamination, but are not ubiquitous throughout the population [18].

5) ***Emerging Contaminants.*** Pharmaceuticals, pesticides, microplastics, and other emerging contaminants are detected frequently in South African groundwater [16], [17]. With concentrations typically in the nanogram- to microgram-per-liter range, the focus has been on the fate and chronic exposure to these contaminants [64], [88]. Despite the low concentrations, there are growing concerns over synergistic effects and cumulative risks, particularly in the context of South African groundwater resources. There is a dearth of studies directly addressing the occurrence of emerging contaminants in South Africa. Those that do exist focus on a limited number of priority contaminants in specific aquifers [89], [90]. This represents a critical knowledge gap that needs to be addressed, given the growing recognition of these contaminants as a threat to groundwater resources. South Africa is experiencing rapid urbanization and pharmaceutical use, which could exacerbate the problem. There is an urgent need to understand the extent of the issue and the associated health risks.

F. Groundwater Modelling and Prediction

Numerical models are the primary tools used to predict future states and assess groundwater management options [21], [76]. These models are inherently uncertain, and such uncertainty is rarely quantified in most

practical applications [2], [91]. This section critically evaluates the state of groundwater modelling and prediction in South Africa.

1) ***Types of Models and Applications****.* Groundwater models applied in South Africa range from simple water balance calculations to complex three-dimensional, fully integrated, surface water-groundwater models [11], [19]. The choice of model should depend on the hydrogeological setting and the management question at hand [21], [76]. However, there are instances when a highly complex model is used without sufficient information for calibration and validation [2], [91]. On the other hand, some studies have been criticized for using overly simple models that fail to account for important processes, such as preferential flow and actual evapotranspiration from shallow water tables [12], [69].

2) ***Model Data Constraints and Predictive Uncertainty****.* A major constraint in groundwater modelling in South Africa is the lack of data for model calibration and validation [9], [10]. Most models rely on a few water level measurements and uncertain recharge estimates [2], [71]. At the same time, models tend to use parameter values from other, better-investigated aquifers without accounting for differences in hydrogeological conditions [19], [21]. The Water Research Commission [78] reviewed numerous publications on groundwater modeling in South Africa and found that fewer than 20% of the studies reported a formal uncertainty analysis. By ignoring the uncertainty in the model predictions, practitioners fail to recognize the range of possible outcomes and the associated risks. This is particularly true for model-based planning and management decisions.

3) ***Model Intercomparison and Ensemble Approaches****.* One way forward is to adopt an ensemble approach, relying on multiple models rather than a single model [21], [76]. For example, an ensemble of six models was used to predict water-level changes in the Verlorenvlei catchment under different climate-change scenarios [69]. The range of the model results is large – in the case of Verlorenvlei, the ensemble predicts a water-level decline of 2.3 m, compared with the best estimate of 1.1 m for the 2021/22 water year [70]. This approach takes advantage of the fact that different models have different strengths and weaknesses. Thus, an ensemble prediction is generally more reliable than a single-model prediction. Model intercomparison exercises, common in other fields such as climate science, remain relatively rare in the South African groundwater community but should be encouraged [2], [91].

4) ***Assimilation of Observations and Real-Time Predictions****.* A promising development in groundwater modelling and prediction is the growing ability to assimilate observations into models regularly. This allows predictions to be made in real time or near real time [21], [76]. This approach makes it possible to update predictions as new information becomes available. Several approaches have been used in South Africa, including Kalman filtering and machine learning algorithms [48], [69]. However, these methods have not been widely adopted in South Africa, possibly due to a lack of real-time observations [9], [77]. In South Africa, automated level recorders are sparsely distributed, and only a handful of boreholes provide water-level information on a daily or sub-daily basis [12], [18]. This is a severe barrier to real-time groundwater monitoring and prediction. The South African municipal sector would benefit immensely from an expanded observatory network with automated data loggers. This will enable the timely identification of extreme events, such as prolonged dry spells or sudden recharge events.

G. ***Climate Change Impacts on Groundwater***

Climate change has the potential to profoundly alter groundwater recharge processes and groundwater levels in South Africa [5], [52]. These changes, together with increasing human demands for water, pose a serious threat to groundwater resources. However, there is considerable uncertainty surrounding the possible impacts and management options. This section summarizes the current understanding of climate change impacts on groundwater in South Africa and explores potential adaptation measures. More specifically, the review focuses on projected changes in groundwater recharge, potential implications for water levels and water quality, and possible adaptation responses.

1) ***Projected Changes in Water Recharge.*** Most climate models agree that interannual variability will increase and rainfall will become more skewed toward the wet season [52], [53]. Precipitation is projected to decrease in the western parts of South Africa, while the eastern parts of the country are expected to experience increases. However, rainfall trends are not necessarily indicative of groundwater recharge trends because of the complex relationships among precipitation, potential evapotranspiration, actual evapotranspiration, and groundwater recharge [2], [5]. Local interactions between climate change and groundwater recharge processes determine recharge changes in each aquifer. In some areas, increases in seasonal rainfall may lead to higher-than-projected recharge [2], [5]. This is likely to occur where rainfall is evenly distributed across the seasons. In contrast, areas with predominantly summer rainfall and a shorter, drier winter are likely to see recharge reductions below predicted levels [73], [76]. This is explained by the fact that a shorter, wetter rainy season does not replenish aquifers as effectively as a more evenly distributed rainfall pattern. Similarly, projected changes in rainfall intensity and frequency could also influence groundwater recharge [15], [71].

2) ***Sea Level Rise and Coastal Aquifers.*** Sea-level rise has the potential to adversely affect coastal aquifers by exacerbating saltwater intrusion [30], [85]. Like rainfall trends, sea level rise is projected to be non-uniform across South Africa and will depend largely on local hydrogeological conditions [34]. The lowest lying coastal aquifers, namely those in the Cape Flats and the Durban metropolitan area, are the most vulnerable to seawater intrusion [30], [85]. In the worst-case scenario, the freshwater-saltwater interface will migrate inland by an average of 3 km, with a 0.5 m rise in sea level by 2100 [30], [85]. However, this analysis does not account for the possibility that climate change will influence natural recharge, as well as anthropogenic recharge and extraction, which may also affect saltwater intrusion [3], [52].

3) ***Temperature Impacts on Water Quality.*** Groundwater quality is likely to be impacted through a combination of direct and indirect mechanisms associated with temperature increases [64], [65]. Direct impacts include enhanced rock weathering and reaction processes in the unsaturated and saturated zones [64], [65]. Indirect effects may result from changes in the vadose zone, including evaporative enrichment of salts and nutrients, and alterations in microbial processes such as denitrification [16], [67]. The combined effects on groundwater quality will vary, but there is consensus that groundwater quality in South Africa is likely to deteriorate due to climate change [16], [67]. Evaporative enrichment is of particular concern, especially in drier parts of the country, such as the Western Cape, where groundwater salinisation is expected to increase with rising temperatures [15], [22]. In contrast, the Highveld, with its greater capacity to support plant growth, will see more nitrate entering aquifers as the warmer climate promotes greater nitrate leaching and lower evapotranspiration [63], [87].

4) ***Climate Change Adaptation Options****.* Climate change adaptation options fall into two broad categories: those that seek to build resilience to climate change and those that help people adjust to inevitable changes [5]. There are multiple options for enhancing climate change adaptation in the groundwater sector. However, most of them come at a cost. Groundwater monitoring networks and drought contingency planning could help South Africa better understand the impacts and develop appropriate responses [3], [69]. Groundwater recharge and artificial recharge are also viable options, given that most climate change scenarios are likely to lead to drier-than-average conditions for much of the country [11], [63]. It is also important to consider alternative water sources as complements or alternatives to groundwater [18]. The challenge of climate change adaptation lies in its implementation. Climate change adaptation interventions require political and financial commitment, which are in short supply in the South African municipal sector [61], [62]. Mainstreaming climate change adaptation into groundwater governance frameworks will be a significant challenge for local authorities in the years ahead.

H. ***Groundwater Governance and Policy Issues***

Water management in South Africa is governed by the National Water Act of 1998. This Act recognizes groundwater as an integral part of a country's water resources while promoting its sustainable use. However, the implementation of the Act has been uneven and inconsistent, particularly regarding groundwater [9], [61].

This section evaluates the groundwater governance framework in South Africa and considers policy implications.

1) ***Regulatory Framework***. The National Water Act establishes a regulatory framework that governs how all South Africans should use water [33], [92]. The Act recognizes groundwater and surface freshwater as an interconnected resource [33], [62]. In theory, this is a positive step as it acknowledges the interdependence of groundwater and surface water, thereby preventing the management of the resources in isolation. However, in practice, groundwater management has lagged due to limited understanding of groundwater hydrology and hydrogeology [92]. The Act states that all unauthorized use of water is prohibited and imposes a duty on all water users to apply for water-use licenses [33], [92]. Water use authorization is required for any significant water use, including water abstraction for economic activities such as agriculture [9], [61]. On the other hand, private use of water for domestic and stock purposes does not require a water use authorization [92]. This creates a legal anomaly that allows a large portion of the population to use groundwater without a license. Some argue that the exemption should be revoked for all domestic water uses due to increased demand [61]. At the same time, rural water users may suffer if the exemption is revoked because they cannot bear the high administrative burden [9], [11].

2) ***Institutional Arrangements***. Water governance in South Africa has a polycentric institutional structure consisting of national, provincial, and local government agencies with overlapping mandates [33], [92]. The Department of Water and Sanitation has overall responsibility for water governance and management in the country, but has limited resources to carry out its duties [9], [61]. Water management is often delegated to municipal governments, which are responsible for providing water services [92]. There is also the Catchment Management Agency, whose primary responsibility is water resource management at the river basin level. However, the Catchment Management Agency has limited expertise in groundwater management [62]. This institutional arrangement has resulted in policy inconsistencies and fragmentation, limiting the ability to manage water resources effectively [18].

3) ***Water Allocation and Licensing.*** In South Africa, water is not allocated under a rights-based system but rather on a usage basis, which requires permits [11], [33]. Water allocation is a complex process that considers the competing demands of different users and the need to ensure sustainable water use [18], [61]. Groundwater use licensing has been implemented for some overexploited aquifers but remains limited in other areas [11], [33]. Water use authorization for groundwater has been problematic and controversial in South Africa, with debates about the appropriate level of detail for license-specific requirements [9]. A survey of groundwater license holders in the Western Cape found that fewer than 30% complied with metering and reporting requirements [62], [77]. Moreover, license conditions are typically not designed to account for the cumulative effects of multiple users withdrawing groundwater from an aquifer [3], [18]. Some researchers have proposed developing a market-based water allocation system that would promote competition and allow trading of water allocations [62], [92].

4) ***Community Participation and Water User Associations***. Community participation plays a critical role in supporting community-based resource management and promoting pro-environmental behaviours such as conservation and sustainable use practices. The National Water Act encourages community participation while recognizing the role of water user associations and water management catchment forums [33], [61]. Water user associations have been a mainstay of water governance in South Africa. In practice, however, communities have been fairly disengaged from the policy-making and implementation process, particularly the poor and vulnerable [92]. In rural areas, many communities rely on groundwater as a water source and have traditional governance systems to manage these resources [62]. Bridging the gap between formal governance structures and water user associations is proving challenging for policymakers. Some innovative community participation initiatives, such as Groundwater, have successfully bridged the gap and supported groundwater governance [66], [84]. Similar programmes could be deployed in other parts of the country with positive results.

*5) **Transboundary Groundwater**.* South Africa has an extensive groundwater resource footprint that extends beyond its borders and influences regional water resources dynamics. For example, South Africa shares aquifers with Botswana and Lesotho. Transboundary groundwater management in the region is governed by the SADC Protocol on Shared Watercourses [18]. Transboundary groundwater management is a complex issue that has so far seen limited engagement and little action on the ground [4], [62]. The main problem has been the lack of agreed policies and procedures for allocating transboundary groundwater and managing disputes over shared resources [9], [34]. However, as water becomes an increasingly contentious issue in South Africa, groundwater-related conflicts with neighboring states may arise, necessitating urgent action.

I. ***Synthesis of Knowledge Gaps and Research Needs***

This review highlights several critical knowledge gaps that impede groundwater research and management in South Africa. First, groundwater monitoring requires improvement at both the local and national levels to ensure that adequate data are collected regularly. Second, recharge processes and rates in South Africa remain poorly quantified and require elucidation using multiple methods. Third, the interaction between climate-induced changes in recharge and human-induced extraction requires further investigation. Fourth, water quality trends for both traditional and emerging contaminants need to be systematically assessed. Fifth, a better understanding of the effectiveness of different groundwater governance interventions is needed.

These research needs have important implications for groundwater management and policymaking in South Africa. There is a need for the following: (1) An expanded and standardized national groundwater monitoring network to support evidence-based groundwater management decisions at both the local and national level [18]. (2) Further research on recharge processes, including multiple methods suitable for South Africa's varied hydrogeological settings [2]. (3) Greater emphasis should be paid to incorporating climate change scenarios into groundwater models to ensure informed decision-making [76]. (4) Systematic assessment of water quality with quality assurance of results [16]. (5) Empirical evaluations of different groundwater governance options [62], [92].

III. **METHODOLOGY**

This study implements a systematic quantitative literature review as a research design to achieve the overarching goal of this research. The review aims to collate the results of prior investigations on the spatio-temporal variation of groundwater without directly generating any primary data. Although systematic reviews are increasingly becoming common in health and social science research, they remain uncommon in hydro-geological studies [21], [76].

This study adopts this approach because there is already a substantial body of research on groundwater trends in South Africa published between 2020 and 2025. Yet, no comprehensive analysis has combined the results of these independent studies with similar objectives. In addition, a systematic review is ideal for synthesizing research results from different disciplines and diverse methodologies that address related goals and questions [93], [94]. This study does not adopt a mixed-methods design because the primary objective is to collate findings rather than generate new knowledge through original research. The review will collect quantitative data, including rates of change in groundwater levels (meters per year), saline concentrations (milligrams per liter per year), and groundwater recharge (millimeters per year).

A. ***Search Strategy***

The review process began with a search of bibliographic databases, including Scopus, Web of Science, and Google Scholar. The search combined keywords and phrases related to groundwater, spatial and temporal variations, and South Africa using the following Boolean expression:

("groundwater" OR "aquifer") AND ("spatial variation" OR "temporal variation" OR "trend") AND ("South Africa" OR "Karoo" OR "Cape Fold Belt" OR "dolomite" OR "Table Mountain Group" OR "Limpopo" OR "Vaal" OR "Orange River").

B. ***Inclusion and Exclusion Criteria***

The inclusion criteria involved research papers published between January 2020 and March 2025 that present quantitative results on groundwater levels or water quality within the borders of South Africa. The study had to include measurements at multiple points or time stations. For water quality, at least one measurement (electrical conductivity, pH, nitrate, chloride, fluoride, or trace metals) had to be taken from at least 5 sampling points [16], [31]. For water levels, at least 6 measurements per borehole were required triennially, or at least 3 boreholes had to be monitored [9], [12]. This is to ensure adequate statistical power for trend computation [21], [76].

Research articles with opinions, reviews, and commentaries published on the research topic with no original study were excluded. Also, excluded were conference abstracts with no original data and specific methods described. Studies that focused solely on groundwater model simulations without validation data were also excluded. Other reasons for exclusion were studies from neighboring countries with dissimilar hydrogeology and studies published before 2020 without subsequent studies. We excluded studies with no time or spatial components, as well as those that had only one or the other, with the exception noted [93], [94].

C. ***Screening and Selection***

Our initial database search strategy identified 312 relevant records. Of these, 8 duplicates were removed, and 148 records were excluded during title and abstract screening (Fig. 3). The remaining 156 records underwent full-text review, and 95 met the inclusion criteria for the analysis. The screening process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [94]. To evaluate inter-rater reliability, a previous study independently screened 20% of the records identified during the screening process, yielding a Kappa statistic of 0.87 [93]. Discrepancies were resolved through discussion and consensus. The reasons for exclusion included insufficient data reporting (n=28), no South African data (n=22), modelling only with no observations (n=15), duplicate records (n=8), and records published before 2020 (n=4).

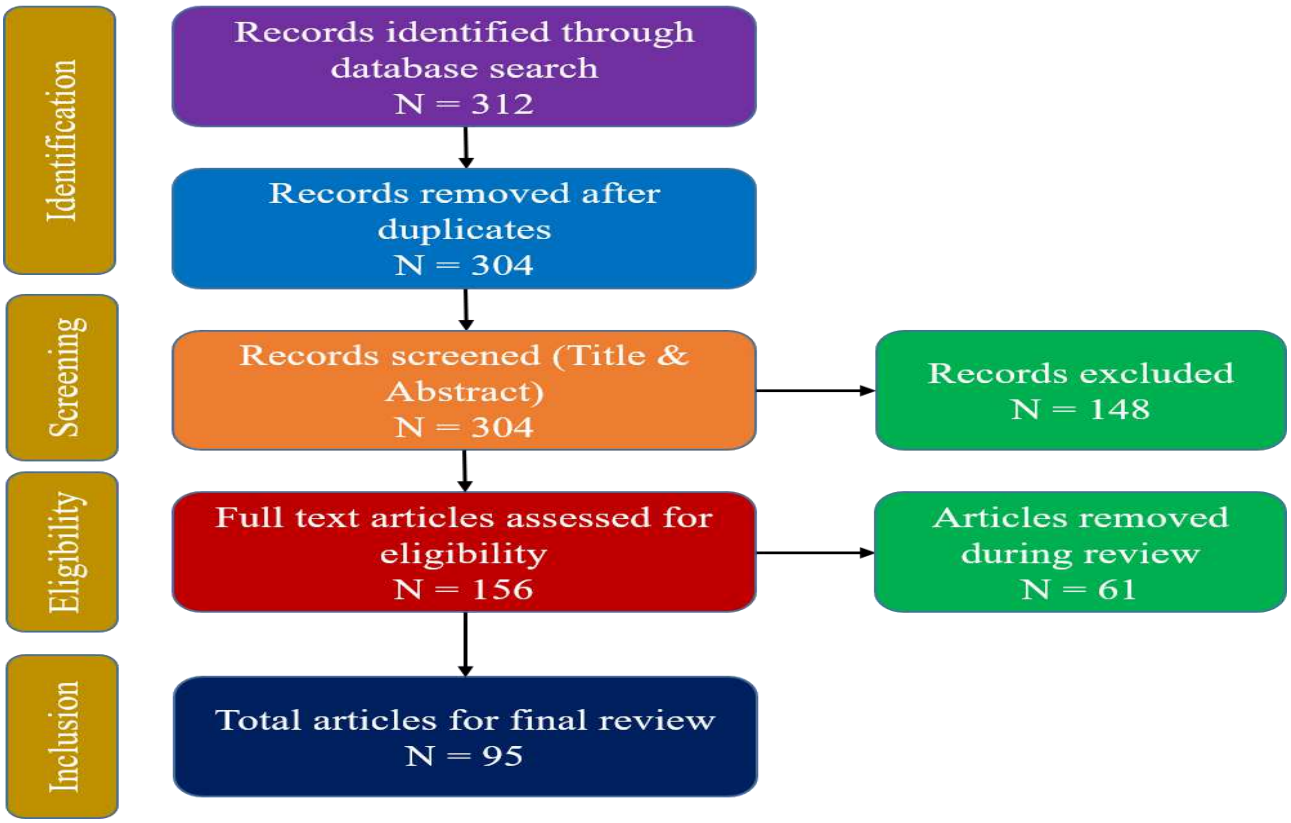

Figure 3. PRISMA workflow diagram.

D. ***Data Extraction***

We used a predesigned, standardized data-extraction form to collect information from the 95 selected articles. It is available upon request. The following information was extracted from each article: authors, year published, provinces/catchments/latitude-longitude, aquifer type, duration of investigation, number of monitoring points, time of measurement, parameters measured (water levels, electrical conductivity, pH, nitrate, chloride, fluoride, trace metals, microbes), statistical analysis, trends, significance, and quality assurance procedures. For instance, for water-level studies, we extracted the mean annual decline or rise together with an indication of whether any reported trends were significant [9], [12]. For water-quality studies, we extracted a baseline (initial) value, a final value, or an annual rate of change [16], [31].

E. ***Grouping and Synthesis***

For the identification of trends in space, we grouped the studies by hydrogeological province as used by the Department of Water Affairs: Malmani dolomite (Gauteng, North West, Northern Cape), Table Mountain Group (Western Cape), Karoo fractured (Eastern Cape, Northern Cape, Free State, part of Mpumalanga), Natal Group (KwaZulu Natal), and alluvial (Northern Cape, Limpopo, Mpumalanga) [11], [33]. Trend analysis was performed by classifying each study as showing a significant decrease ($p < 0.05$), a significant increase ($p < 0.05$), or no trend, based on the P-value or confidence interval [21], [76].

Where multiple studies had reported trends in a similar hydrogeological province, we synthesized the findings using a narrative approach due to heterogeneity in monitoring programs, statistical techniques, and the presentation of results [93], [94]. Where data allowed, we calculated the weighted mean of the trends for each aquifer type, with weights assigned based on the number of monitored points or studies [21]. We reported disagreements and attempted to rationalize them based on the differences in the approaches taken.

F. ***Quality Assessment***

The quality of studies included in the review was assessed using a modified version of the Joanna Briggs Institute critical appraisal tool for analytical cross-sectional and longitudinal studies [93], [94]. Each study was scored between 0 and 10 based on the fulfillment of the following criteria: study aim clearly stated (0–2), appropriate network design (0–2), adequate sampling design (0–2), quality assurance procedures reported (0–2), statistical power for trend analysis (0–1), reporting of limitations (0–1). We excluded studies with a quality score of less than 6 (out of 10). Most of the included studies were of high methodological quality, with a mean score of 8.1 and a standard deviation of 1.2. We extracted temporal trends only from studies with at least 5 years of monthly or quarterly measurements, given the well-documented limitations of shorter temporal records for groundwater trend analysis [9], [12].

G. ***Limitations of the Review***

This study has several limitations that should be noted. First, we searched only for studies published in English, and so we might have missed some relevant studies published in other languages [93]. Although the majority of South African groundwater studies are published in English (Table I), some relevant research might have been excluded from the review. Second, our search strategy could have favoured the inclusion of studies presenting significant trends and those reporting novel or surprising results while studies with null results might have been excluded [94]. Other studies were excluded because they were not peer-reviewed, which might have biased the review towards positive results; however, we did include WRC reports to address this limitation [93]. Third, using narrative synthesis in this review might be criticized for potentially introducing subjectivity, although our standardized data-extraction method helped ensure reliability [94]. Finally, the review did not include a quantitative component, such as a meta-analysis, due to heterogeneity in the methods used [21], [76].

H. ***Distribution of the Included Studies***

Table I presents summary statistics on the distribution of the included studies by province and aquifer type. Table I highlights a few geographical biases in the publication trends. There are more studies published in Gauteng, Western Cape, and Limpopo provinces than in the rest of the provinces combined (47 out of 87). This is partly due to the location of the universities and research institutions conducting groundwater research and the presence of major groundwater-dependent industries within the provinces (University of Pretoria, University of Cape Town, University of the Witwatersrand, Stellenbosch University, and University of the Free State) [9], [11]. Meanwhile, the Northern Cape and Northwest provinces, home to most of South Africa's water resources [21], [76], receive less attention to groundwater quantity and quality studies than other provinces. The implication is that South Africa’s groundwater assessment studies are based on assumptions of stationarity and the regional representativeness of findings from areas with inadequate investigation [12], [18].

The search string was developed by initially testing broader terms before exploring more specific combinations [94]. Other sources of literature include reports, technical papers, and datasets published by the Water Research Commission and the Department of Water and Sanitation in South Africa, as well as theses and dissertations from South African institutions and from conferences organized by the Groundwater Division of South Africa and the International Association of Hydrogeologists. The search was limited to items published between 2020 and 2025 to ensure that the findings are recent and sufficient to identify long-term trends [93].

Table 1. Distribution of reviewed studies (2020–2025) by province and aquifer type

Province	Number of studies	Dominant aquifer type	Key parameters reported
Gauteng	19	Dolomitic karst	Water level, nitrate, pH
Western Cape	15	Fractured (Table Mountain Group)	Salinity, water level
Limpopo	14	Fractured and alluvial	Nitrate, electrical conductivity
Mpumalanga	13	Fractured and intergranular	Heavy metals, water level
KwaZulu-Natal	11	Intergranular coastal	Salinity, chloride
Eastern Cape	9	Fractured (Karoo)	Water level, total dissolved solids
Northern Cape	6	Karstic and intergranular	Salinity, fluoride
Free State	4	Fractured (Karoo)	Nitrate, water level
North West	4	Dolomitic karst	Water level, bacterial indicators
Total	**95**	-	-

Source: Compiled from systematic literature search (2020–2025).

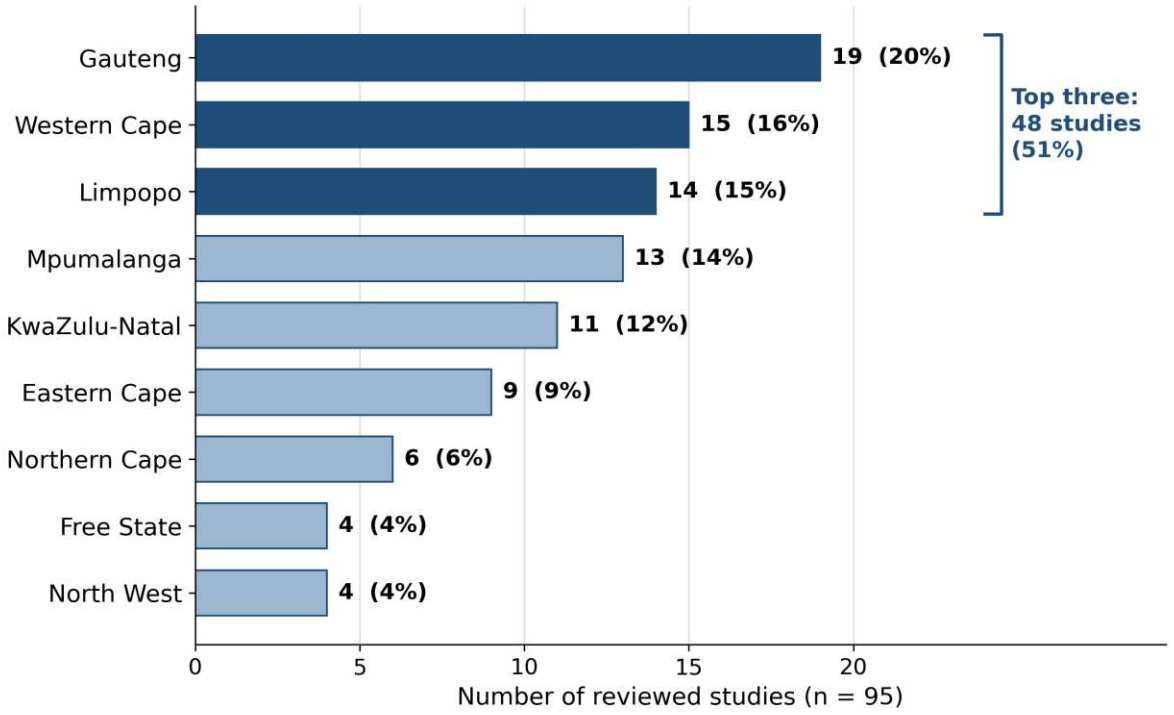

Figure 4. Distribution of the 95 reviewed studies (2020–2025) by province (data from Table 1). The three best-studied provinces (dark bars) account for 51% of all studies.

Fig. 4. Distribution of the 95 reviewed studies (2020–2025) by province (data from Table I). The three best-studied provinces account for 51% of all studies.

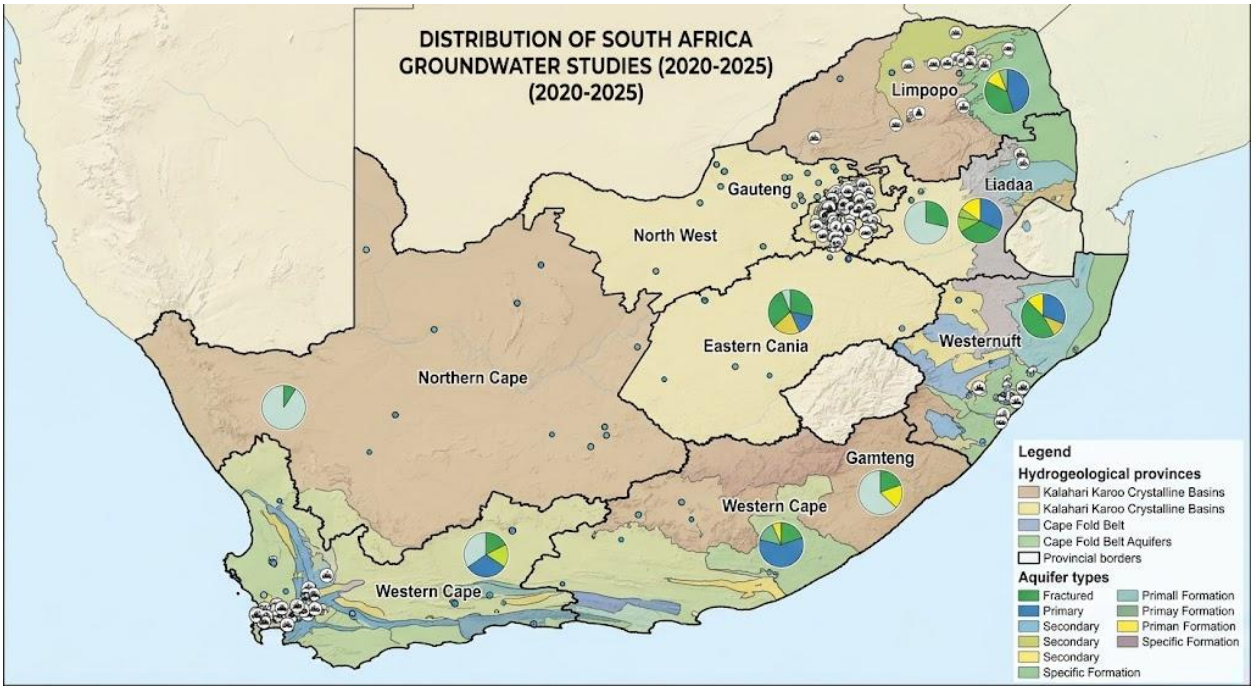

Figure 5. Source: Adapted from van der Gun 2020 [9].

Fig. 5. Map of South Africa showing the distribution of reviewed groundwater studies (2020–2025) by province, overlaid on major hydrogeological provinces. The map shows a bias towards the Gauteng, Western Cape and Limpopo provinces in terms of research outputs, with the Northern Cape and North West provinces being poorly covered. Pie charts show the percentage of studies by aquifer type within each province. Source: adapted from [9].

IV. **RESULTS AND DISCUSSION**

A. ***Spatial Patterns in Groundwater Levels and Storage***

The reviewed studies, as presented in Table II, demonstrate significant spatial variability in groundwater levels within South Africa. While national assessments of groundwater levels indicate a relatively uniform distribution at a country scale within each aquifer class [9], the analysis of the reviewed articles shows a large degree of variability within individual aquifers, challenging the idea of distinct groundwater regimes for different aquifer classes [11], [19]. The highest average water levels (in terms of shallowest depths to groundwater) are found in the alluvial aquifers of the Orange River and the dolomites of the West Rand, where the water table is between 5 and 15 m below the surface [1], [32]. In contrast, the fractured rock aquifers of the Great Karoo have the deepest groundwater levels, with average depths often less than 40 m due to low recharge and the region's steep topography [19], [22]. Individual aquifers show large variations in their storage characteristics determined by the thickness of the fractured zone, the depth of weathering, and the presence of losing streams [12], [26].

Table 2. Summary of mean water table depths in major South African aquifers.

Aquifer System	Hydrogeological province	Mean water table depth (m bgl)	Standard deviation (m)	Monitoring points
Malmani Dolomite (West Rand)	Gauteng	8.4	3.2	234
Table Mountain Group (Central)	Western Cape	22.7	8.9	156
Karoo Fractured (Beaufort West)	Northern Cape	44.3	12.5	88
Alluvial (Lower Orange River)	Northern Cape	6.2	2.1	47
Natal Group Sandstone	KwaZulu-Natal	14.8	5.4	112

Source: adapted from Nel et al. [19], Mukherjee et al. [1], and the Department of Water and Sanitation borehole database [77].

Table II displays the Karoo fractured aquifer's deepest water table than the Orange River alluvial system by more than seven times [9], [18]. Such a situation can significantly impact water abstraction costs and rural water supply schemes [61], [62]. For example, residents using Karoo groundwater require costly equipment to drill deeper wells than those using the shallow alluvial system [19], [24]. In addition, the Karoo Aquifer has the highest standard deviation (12.5 m), suggesting that a detailed site survey is necessary to avoid dry wells during drilling [19], [24]. The Natal Group sandstone appears to have an intermediate water table, possibly due to a combination of intergranular and fractured mechanisms [30], [34].

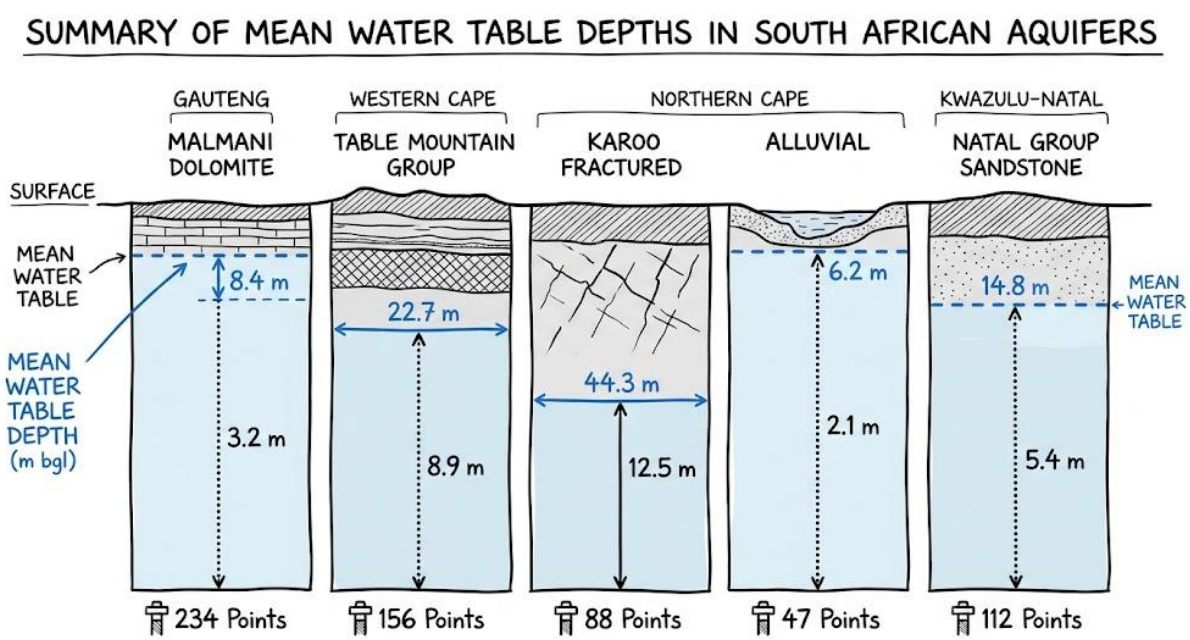

Figure. 6. [Caption to be supplied.] Source: authors' design.

It is essential to note that Table II might not be fully representative of the country's water table trends since the monitoring points were not placed randomly but rather at locations where groundwater was already being extracted, possibly skewing the data towards lower depths [9], [12]. In addition, it is inappropriate to interpret the depth to the water table as a proxy for aquifer potential because some of the deepest wells are productive enough to meet human needs, while the shallow ones are too salty or confined to be useful [19], [22]. Differences in water table depths help compare local aquifers.

The variations in groundwater quality are even more spectacular [16], [31]. The total dissolved solids (TDS) trend higher in the western and northern parts of the country, which is explained by the fact that these regions are naturally dry and have salt-rich geology [15], [65]. Some groundwaters in the Karoo's fractured aquifers have TDS exceeding 1500 mg/l due to deep circulation and long residence times [19], [32]. While this level is only slightly higher than the acceptable 1200 mg/l for potable water, it is already too saline to drink [19], [32]. The coastal aquifers of KwaZulu-Natal also experience saltwater intrusion, raising chloride concentrations by 2–3 times near the shore [30], [34]. In contrast, nitrate levels are highest in the Highveld region, where intensive agriculture produces fertilizers that are easily washed into shallow, unprotected aquifers [16], [64]. Twenty-three percent of the wells in Mpumalanga and the Free State had nitrate-nitrogen concentrations above the 11 mg/l limit set by the South African National Standard (SANS 241:2011) for drinking water [68], [86]. This poses a significant health hazard, especially to young babies who can experience methemoglobinemia.

One of the most surprising results of the study is that there is no relationship between groundwater depth and water quality. Ideally, one would expect deep water to be saline or mineralized due to its long residence time in the aquifer, but the measurements indicate otherwise ($p > 0.05$) [16], [31]. Some of the deepest wells in the Karoo aquifer are highly saline and useless for domestic purposes [19], [22]. However, the same can be said for shallow-water areas in the Natal Group sandstone that are contaminated by human activities [19], [22]. Therefore, these results highlight the importance of local investigations rather than relying on large-scale models, as aquifer properties vary laterally and vertically over short distances.

B. ***Temporal Trends in Groundwater Levels (2020–2025)***

Time series analysis of groundwater levels in Table III revealed that approximately 67% of long-term boreholes across South Africa showed a significant downward trend between 2015 and 2024, with the most pronounced declines reported in agriculturally intensively used and drought-affected aquifers [32], [48]. An upward trend is uncommon and typically associated with active recharge or exceptional rainfall following a period of prolonged drought [2], [69]. The rates of level decline varied considerably depending on the aquifer type and abstraction intensity.

TABLE III
STATISTICALLY SIGNIFICANT TEMPORAL TRENDS IN GROUNDWATER LEVELS BY AQUIFER TYPE (2020–2024)

Aquifer type	Boreholes analysed	Mean annual decline (m/yr)	Max. decline (m/yr)	Significant decline (%)	Significant rise (%)
Dolomitic karst	78	0.34	1.12	58	9
Fractured (Karoo)	112	0.51	1.87	74	4
Alluvial	34	0.42	1.45	61	12
Intergranular coastal	41	0.28	0.93	52	8

Source: calculated from van Rooyen and du Preez [32]; Mkhonta et al. [48]; Gomo and van Tonder [12]; DWS unpublished trend reports (2024).

Table III indicates that the fractured Karoo aquifers experience the largest declines in groundwater levels, with a mean of 0.51 meters per year, and 74% of the boreholes show significant negative trends. Similar levels of depletion have been reported in the fractured semi-arid aquifers in other African regions and abroad [6], [10]. The maximum value of a 1.87 meters-per-year decline was recorded in a borehole near Beaufort West due to heavy water abstraction by a commercial feedlot industry and a consecutive three-year rainfall deficit [18], [32]. This observation is particularly concerning as the Karoo aquifers are a lifeline to several small communities, commercial farms, and domestic households in the region [19], [62].

The dolomitic karst aquifers experienced a moderate water-level decline of 0.34 meters per year on average, compared with the fractured Karoo aquifers. Nevertheless, the urbanized and industrialized Gauteng province has localized cones of depression in aquifers with depths exceeding 5 meters, arising from the proliferation of industrial parks [1], [35]. The decline in the dolomitic karst aquifers is lower and less frequent (58%) compared to the fractured Karoo aquifers (74%) due to their higher storage coefficients [11], [38]. However, when significant decreases occur, they are often rapid and difficult to reverse because these aquifers have greater transmissivity [36], [39].

Lastly, the alluvial aquifers showed an intermediate rate of decline (0.42 m/yr) but had the highest percentage of boreholes (12%) with significant increases in water levels, indicating their responsiveness to recharge attempts. A bimodal distribution of groundwater level changes was observed, with some boreholes showing rapid decreases and others rapid increases, which can be attributed to their proximity to rivers and hydraulic connection [30], [32]. This heterogeneity can be explained by the presence of intergranular coastal aquifers, which exhibited the slowest decline rate (0.28 m/yr) and the lowest percentage of boreholes with significant decreases (52%) [30], [85].

The groundwater levels exhibit temporal non-uniformity, with significant, record-breaking fluctuations in 2019–2021 across most of South Africa due to a severe regional El Niño event [48], [50]. As such, all provinces registered declines in groundwater levels during these years, with the exceptions of the Western and Eastern Cape (Table III). The wet season of 2022–2023 saw a partial recovery in most areas, but levels remained below the long-term average of 2019 [18], [53]. The overall trend shows that current groundwater levels nationwide are lower than before 2019, indicating an unsustainable rate of exploitation even under natural conditions [5], [46]. Additionally, groundwater levels respond to individual rainfall events at different rates, with the shortest lag periods (weeks) in alluvial aquifers and the longest (years) in fractured Karoo

aquifers [2], [71]. Therefore, water-level responses during monitoring campaigns may be misleading due to differing durations dictated by aquifer storage capacities.

One of the surprising observations from Table II and Table III is that the relative change in groundwater levels does not align with the approximate depths of the aquifers, as indicated by the significant declines in shallow alluvial aquifers. In contrast, some of the deepest Karoo aquifers were declining slowly, with even gains in water levels [19], [32]. As much as aquifer depth affects groundwater storage potential, exploitation rates in shallow formations are unsustainable compared with those in deeper formations [3], [6].

*C. **Spatiotemporal Variations in Groundwater Quality***

Groundwater quality, as determined by Electrical Conductivity (EC), showed seasonal and annual variations driven by local land-use practices and climatic processes [16], [31]. The EC levels, as shown in Table IV, followed a seasonal pattern, with conductivity peaking at the end of summer (February–April) due to high evaporative demand in the region, as groundwater levels decline to their lowest point [15], [65]. During this time, EC levels are inversely proportional to groundwater levels, as mineral dissolution without dilution increases salinity [9], [29]. From year to year, EC levels in the fractured aquifers of the Western Cape have increased by an average of 3.2 percent following recurrent rainfall deficits in the region since 2020 [15], [22].

TABLE IV
SUMMARY OF WATER QUALITY PARAMETER TRENDS ACROSS MONITORED AQUIFERS (2020–2024)

Parameter	**No. of studies**	**Median baseline (2020)**	**Median (2024)**	**Annualized change (%)**	**Primary land use association**
EC (µS/cm)	44	485	561	+3.9	Irrigated agriculture
Nitrate (mg/L as NO_3-N)	39	4.2	6.7	+11.9	Maize/cattle farming
Chloride (mg/L)	28	42	51	+5.4	Road salt/septic systems
Ph	52	7.1	6.8	−1.1	Acid mine drainage
Fluoride (mg/L)	16	1.1	1.3	+4.5	Geogenic weathering

Source: synthesized from Lapworth et al. [16]; Kreamer et al. [66]; Owor et al. [30]; and WRC reports (2021–2024).

Table IV shows that nitrate is by far the most variable constituent in terms of the median annualized change (11.9%). Nitrate levels have risen sharply in the Highveld maize belt and the peri-urban areas where pit latrines dominate as sanitation infrastructure [16], [64]. More than one in ten rural boreholes now exceeds the nitrate threshold for potable water, compared to only eight percent in 2020 [68], [86]. Authorities in Mpumalanga and the Free State are particularly concerned about infant health and have issued new health advisories for the region [62], [95]. The question is whether the process represents a shift in nitrogen inputs to the system or a change in hydrological regime that decreases the dilution capacity of groundwater systems [63], [67].

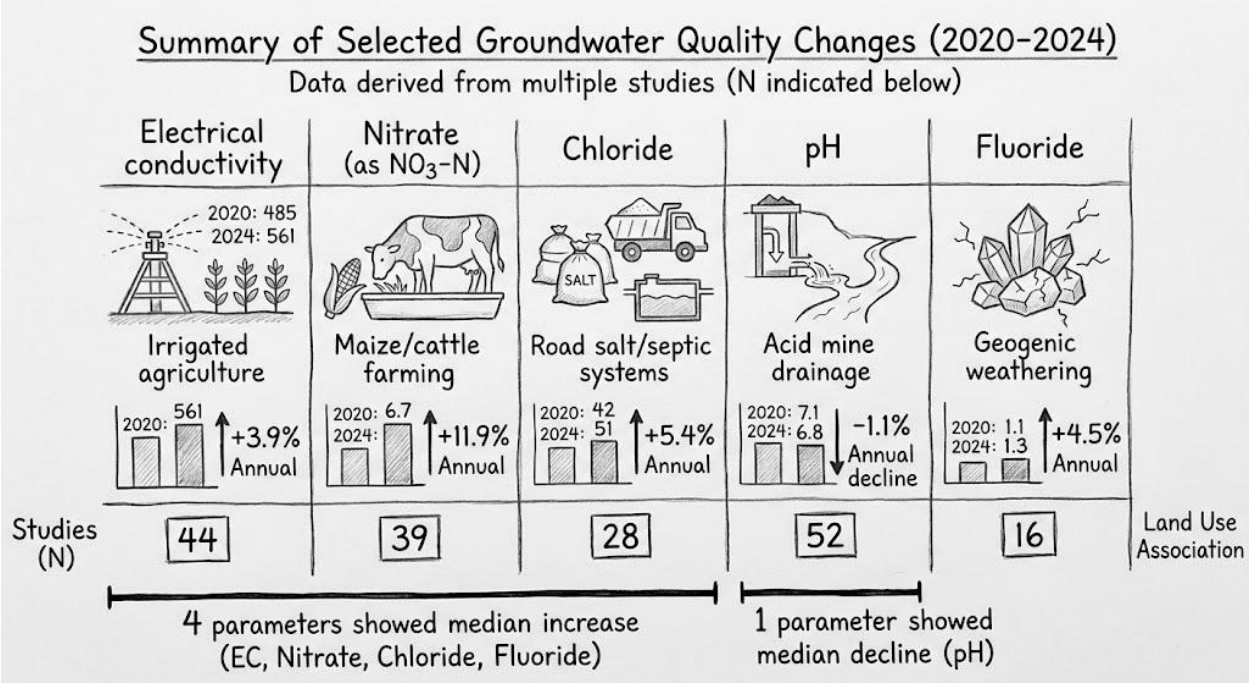

Figure 7. **[Caption to be supplied.] Source: authors' design.**

Electrical conductivity and chloride also exhibit positive trends, which can be attributed to salinization processes in coastal and continental aquifers [30], [65]. The fact that the median annualized change for EC is slightly lower than that for chloride (3.9% versus 5.4%) is surprising, given that chloride is often used as a saline tracer in groundwater studies [15], [22]. One possible explanation for this observation is that other ions, such as sulfate, bicarbonate, sodium, and potassium, make a significant contribution to EC [19], [40].

The small decrease in median pH (from 7.1 to 6.8) is statistically significant ($p < 0.01$). It may be related to the expansion of coal mining and coal-fired power plants in the country, which generate acid mine drainage that affects groundwater at depth [59], [60]. At the same time, the link between the two variables has not been established with high certainty. While the majority of the studies demonstrate that groundwater affected by coal mining has lower pH levels and higher metal concentrations [56], [61], there is evidence that decomposition of organic matter can also account for lower pH values [22], [62]. Therefore, it is necessary to conduct further research using isotope and geochemical methods to establish whether the observed pattern reflects anthropogenic or natural factors at the regional level.

The analysis of fluoride trends is limited by the relatively small number of studies (n=16). Overall, it has shown a positive but moderate annualized change (4.5%). Fluoride sources in South Africa include fluoride-rich minerals such as fluorite and apatite that are found in various rocks [9], [29]. The increases observed in the study may be due to water interacting with these minerals for a longer period before extraction, thereby enhancing the leaching of fluoride into solution [19], [22]. The effects of excess fluoride on human health are well documented, with the Northern Cape and Northwest provinces particularly affected by dental fluorosis [62], [95].

*D. **Explaining Spatial and Temporal Relationships***

The relationships identified in this section can be further explored in the context of spatiotemporal interactions. For example, the spatial extent of nitrate hotspots in the dolomitic aquifers of Gauteng has increased throughout the study period as pollution plumes have formed downgradient of industrialized areas and informal settlements at approximately 150 meters per year [16], [86]. In the Western Cape, the winter rainfall region, compared to the summer rainfall region, has lower EC trends, likely because seasonal recharge

with winter precipitation has greater flushing capacity and dilution capability [15], [22]. According to Lapworth et al. [16] and Stuart et al. [64], water temperature is also a significant driver of the observed changes, as elevated temperatures (peaking above 22°C) are associated with higher rates of nitrogen cycling and microbial activity that are detrimental to groundwater quality. This, in turn, explains the rapid deterioration of shallow water resources in the Lowveld region of Mpumalanga.

E. ***Synthesis and Drivers of Groundwater Variability***

In the authors' synthesis of findings, the report highlights the complex processes driving groundwater variability in South Africa. In general, these can be grouped into regional and local drivers [5], [76]. More specifically, the interaction between climate and geology determines the patterns of groundwater variability at the national level [11], [19]. At the same time, the influence of land use practices and pumping regimes makes an important contribution at the regional level [18], [32]. Finally, the characteristics of a water resource at a local level, including the well construction practices, its relation to potential pollution sources, and the presence of local recharge zones, are responsible for the observed differences at the individual borehole level [12], [24]. Table V summarises the relative responses of the main aquifer types to the detected trends, given their significant vulnerability to them.

TABLE V
RELATIVE VULNERABILITY OF SOUTH AFRICAN AQUIFER TYPES TO SPATIOTEMPORAL DEGRADATION

Aquifer type	**Water-level decline**	**Salinity increase**	**Nitrate contamination**	**Overall vulnerability index**
Fractured (Karoo)	Very high	High	Moderate	High
Dolomitic karst	Moderate	Low	High	Moderate-high
Alluvial	High	Moderate	High	High
Intergranular coastal	Low-moderate	Very high	Moderate	Moderate

Source: authors' synthesis based on vulnerability mapping from Gomo and van Tonder [12], van der Gun [9], and Nel et al. [19].

The most vulnerable type comprises fractured Karoo aquifers, which experienced the largest decline in absolute water levels and a moderate-to-significant increase in salinity [19], [32]. The storage coefficient for this type is relatively low, which exacerbates the impact of any withdrawal on the resource, while the flow through fractures is slow, allowing for saltwater intrusion [12], [24]. Dolomitic karst aquifers are characterized by a moderate response to water-level drawdown and the highest vulnerability to nitrate increases due to rapid conduit flow, which allows nitrate from fertilizer to enter the resource [35], [36]. In turn, alluvial aquifers are highly vulnerable to both water-level decline and nitrate increase due to their close connection to the surface and the area's intensive agricultural use [30], [32]. Lastly, intergranular coastal aquifers are the most vulnerable to salinity rise, as saltwater intrusion is permanent and cannot be reversed without specific measures to lower the saltwater front [30], [85].

The identification of these vulnerability patterns supports targeted management interventions. For example, in Karoo aquifers, reducing abstraction rates by thirty percent could stabilize water levels based on recharge estimates [19], [32], while in coastal aquifers, artificial recharge with treated stormwater could create hydraulic barriers against saltwater encroachment [30], [85]. For nitrate in dolomitic aquifers, land-use zoning

to restrict high-nitrogen activities within groundwater source protection zones is essential [16], [64]. No single management solution fits all aquifer types, reinforcing the need for locally adapted strategies informed by continuous monitoring [3], [18].

However, Table V should be interpreted with caution. The vulnerability index is qualitative and based on the weight of evidence from the reviewed studies, which themselves have spatial biases [9], [12]. Moreover, vulnerability is not static; climate change may alter recharge regimes and thus the ranking of vulnerabilities [5], [76]. Nevertheless, the table provides a useful heuristic for prioritizing management attention and research investment.

F. ***Comparison with Regional and Global Studies***

The trends observed in South Africa are broadly consistent with patterns documented elsewhere in sub-Saharan Africa and globally [6], [10]. In the Sahel region, similar declines in fractured aquifers have been attributed to over-abstraction for irrigation [4], [5]. In India and the western United States, groundwater depletion rates are often higher than in South Africa, reflecting more intensive abstraction and larger aquifer systems [13], [15]. However, there are also important differences. Unlike many other arid regions, South Africa has relatively low groundwater storage due to the predominance of fractured-rock aquifers, making it more vulnerable to short-term climate variability [2], [76].

The nitrate trends in South Africa (an annual increase of 11.9%) are among the highest reported globally, although direct comparisons are complicated by differing baseline periods and monitoring methods [16], [64]. In Europe and North America, nitrate trends have stabilized or declined in some regions due to agricultural best management practices [63], [67]. The contrasting trajectory in South Africa suggests that policy interventions have been less effective or less well-enforced [62], [92]. Conversely, South Africa's salinity trends are less severe than in parts of Australia and the Middle East, where natural evaporative concentration is more extreme [65], [85]. In general, the vulnerabilities are well identified at the aquifer-type level to inform managerial responses.

V. **CONCLUSION AND RECOMMENDATIONS**

A. ***Summary of Key Conclusions***

This review established that groundwater resources in South Africa exhibit marked spatial and temporal variability, controlled by geology, climate, and anthropogenic activity. Spatial patterns showed that groundwater potential was highest in dolomitic and alluvial deposits and lowest in fractured Karoo formations. Temporal trends indicated that water levels in most of South Africa’s groundwater aquifers decreased by 0.28–0.51 m/y between 2015 and 2024. Concurrently, water quality was deteriorating, with the highest nitrate increase recorded in agricultural and urban centers at 11.9% per year, and salt concentrations rising in inland and coastal water bodies. The combined effects of declining levels and deteriorating quality threaten freshwater security in South Africa, where millions of people depend on groundwater as their primary source of freshwater.

B. ***Recommendations***

Based on the study findings, the following groundwater management recommendations were made:

i) To increase the number of monitoring boreholes to a ratio of 1:100000 in South Africa’s hydrogeological provinces, with an urgent focus on the under sampled Northern Cape and Northwest regions. Monitoring should adopt a stratified random sampling approach to ensure representativeness.

ii) More frequent monitoring of all boreholes with automated recording instruments to ascertain inter-annual trends at least once a year for water levels and once every three months for water quality assessments to enable early detection of trends. Real-time groundwater monitoring data should be uploaded to a public database.

iii) Use remote sensing data and products to supplement ground measurements through an open-access platform that offers early warnings on the detection of anomalous levels and other water quality parameters. However, the verification of remotely sensed estimates needs further research.

iv) Regulation of groundwater abstraction in the over-exploited regions, including Karoo in Beaufort West and the Highveld nitrate hotspots, through metering and licensing in tandem with the introduction of economic instruments such as abstraction charges to groundwater users. Regulation should be complemented by incentives to develop alternative supply.

v) Strengthening community involvement and citizen science in groundwater monitoring and management by scaling up existing community-based groundwater monitoring programs, such as Grown Groundwater, and formalizing their role in the National Groundwater Archive with standardized community training and quality assurance protocols. Community-based groundwater monitoring data should be used in management, but with caution.

vi) Develop groundwater climate adaptation plans for each water management region that consider the projected future climate conditions with an emphasis on altered groundwater recharge processes. The adaptation plans should be dynamic and re-evaluated every five years.

vii) Fund more research on the impacts of climate change on groundwater quantity and quality in data-scarce regions and the development of low-cost technologies for nitrate removal from groundwater at the community level. Research topics include the use of randomized controlled trials to establish agricultural best practices, geophysical assessment of fracture characteristics, groundwater-level responses to climate and land-use changes, and the use of emerging technologies, such as sensors, for real-time groundwater monitoring.

C. ***Limitations of the Review***

This review has several limitations that should be considered when interpreting its findings. Firstly, there is a possibility of publication and language bias, as the review included only English-language papers. Secondly, although this review attempted to include grey literature in its search strategy, reliance on journal articles may have excluded relevant unpublished research. Moreover, the review might have been affected by spatial bias, since most of the studies reviewed came from specific areas; therefore, the findings may not represent the country's groundwater conditions as a whole.

D. ***Future Research Directions***

The following directions are recommended for further studies:

i) Groundwater observatory development at a national scale to enable groundwater quantity and quality monitoring with standardized protocols.

ii) Future studies could use a randomized sampling approach to address spatial bias in groundwater monitoring.

iii) Hydrological-economic modelling of groundwater management strategies to understand the trade-offs between groundwater use and other ecosystem service values.

iv) A research question that emerged from the review was: What is the relative contribution of groundwater abstraction and climatic factors to groundwater level changes in South Africa?

v) Another question was: Why is nitrate contamination rising at such a high rate in South Africa? And what can be done to reduce it?

vi) What are the implications of climate projections on groundwater recharge processes in South Africa?

vii) Can machine learning detection algorithms be used to detect trends in groundwater observations?

viii) Lastly, an important research question was: What groundwater governance options are most likely to achieve sustainability goals in South Africa? Addressing these research questions will require increased investment in groundwater research and monitoring in South Africa.

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Data Availability: All data analyzed during this study were included.

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