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Assessment of catchment scale groundwater-surface water interaction in a non-perennial river system, Heuningnes catchment, South Africa

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ABSTRACT

A significant proportion of the world's river networks are non-perennial rivers that are characterized by segments of dry, standing, and flowing water. However, the role of groundwater and the controlling elements governing the flow processes in these rivers is not widely documented. In this study, aquifer-river interaction was assessed using a combo of geological, hydrological, environmental stable isotope, and hydrochemical data in the Heuningnes catchment, South Africa. Results showed the depth to groundwater levels ranging from 3 to 10 m below ground level and aquifer transmissivity values of 0.17 to 1.74 m^2/day. The analytical data indicated that Na-Cl type water dominates most groundwater and river water samples. Environmental stable isotope data of river samples in upstream areas showed depleted $\delta^{18}O$ (-4.3 to -5.12 ‰) and $\delta^{2}H$ (-22.9 to -19.3 ‰) signatures similar to the groundwater data, indicating a continuous influx of groundwater into the river water. Conversely, high evaporative enrichment of $\delta^{18}O$ (1.13 to 7.08 ‰) and $\delta^{2}H$ (38.8 to 7.5 ‰) were evident in downstream river samples. It is evident from the local geological structures that the fault in the north-eastern part of the study area passing Boskloof most likely acts as a conduit to groundwater flow in the NE-SW direction thereby supplying water to upstream river flow, while the Bredasdorpberge fault likely impedes groundwater flow resulting in hydraulic discontinuity between upstream and downstream areas. Relatively low conductive formation coupled with an average hydraulic gradient of 8.4×10^{-4} suggests a slow flow rate resulting in less flushing and high salinization of groundwater in downstream areas. The results underscore the significance of using various data sets in understanding groundwater-river interaction thereby providing a relevant water management platform for managing non-perennial river systems in water-stressed regions. Overall, the study provides important insights into the need for maintaining moderately high groundwater levels in shallow and local groundwater systems for sustaining the ecological integrity of non-perennial rivers.

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Introduction

Over half of the total flows in the global river network are characterized as non-perennial rivers, [1], indicating the importance of non-perennial rivers in supporting the ecosystem as well as providing critical water supply. However, the potential of perennial rivers transforming into non-perennial rivers is likely to intensify due to the effects of climate change and water resource development [2]. Therefore, to ensure proper management of non-perennial rivers, it is essential to comprehend the main controls governing the flow behavior of non-perennial rivers. It has been confirmed that groundwater and the accompanied geological controls are some of the key elements that control the flow regime of a river system through the processes of groundwater-surface water interaction [3,4]. Adequate knowledge of these interaction processes is critical for managing water resources, and in particular, protecting groundwater-dependent ecosystems, which has become a requirement in different water resource legislation across the world [5–8].

Uys and O'Keeffe [9] presented convincing evidence that groundwater flowing into rivers is significant during dry periods as it supplies water to river discharge forming permanent or intermittent river segments through exchanges of water between the aquifer and surface water. Despite being largely ignored, groundwater input into streams is often subject to hydrogeological characteristics, which can influence flow variability and instream ecology [10]. Further, the biogeochemical processes as a result of aquifer-river interaction become more significant during dry or flow cessation periods than during flow continuous periods [11]. This is particularly true due to the dilution effect of high flow periods during rainy seasons which can mask the influence of groundwater, hence, there is a need for an all-year-round assessment of the interaction processes.

In non-perennial rivers, the interaction between an aquifer and the river affects the occurrence of flows, the existence of static pools, and the amount of water stored beneath and adjacent to the river channel [12]. The presence of pools and flowing water in non-perennial river systems are known to be linked to groundwater input, especially during dry or drought conditions [13]. However, Bestland, George [14] suggested that such a presumption may not always be true since some non-perennial rivers retain standing pools without having a direct connection with the underlying groundwater. It has been argued that pools are sometimes maintained by residual surface flows, irregular flow pulses, and perched streambeds [14]. Furthermore, Zimmer and McGlynn [15] showed that non-perennial rivers could act as focal areas of groundwater recharge and discharge mainly in headwater landscapes. Considering the importance of non-perennial rivers in supplying critical water supply needs to biodiversity and human use, thoroughly understanding the all-inclusive hydrogeological characteristics of local aquifers is critical to comprehensively assess the interaction processes and evaluate the role of groundwater in non-perennial river systems.

Several aquifer hydrogeological characterization methods in assessing the connectivity between groundwater and surface water bodies are commonly implemented. These include studies by Menció and co-authors [16–20], whereby hydraulic head, geological information, and hydrochemistry and environmental tracers have been applied. The spatial and temporal heterogeneities in aquifer-river interactions result in difficulties in the assessment, therefore, a combination of various techniques has to be used since the methods may work at different scales. For instance, catchment water budget methods are most useful at large-scale groundwater-surface water interactions [21] while environmental tracers can be applied at small-scale scenarios especially where there is sufficient difference in tracer concentrations [22].

Non-perennial rivers have been, historically, considered as systems of low ecological and economic value by scientists and policymakers [23]. Likewise, perceptions of non-scientists, for example, a study by Rodríguez-Lozano, Woelfle-Erskine [24] show that non-perennial rivers are less valuable and require little attention in terms of conservation compared to perennial rivers. Hence, in the past, most research works on aquifer-river interaction focussed on perennial river systems in which the methods used to assess the interaction mainly relied on the presence of flowing water. As such, the linkages between aquifer characteristics and non-perennial rivers and the role of groundwater in influencing the flows and quality of such rivers remains poorly researched in the global literature.

Yet, it has also been shown that non-perennial rivers are as ecologically important as their perennial counterpart, whereby groundwater usually has been a huge contributing factor to the ecosystem sustenance. For example, Larsen and Woelfle-Erskine [25] in a study in northern California observed that during the dry season groundwater inflow to the pools supplied fairly high oxygen enough for the survival of fish. The study showed that the long-term viability of the fish in intermittent streams may, therefore, depend on maintaining high groundwater levels during dry spells and in drought periods due to climate variability. Therefore, there is a need to perform comprehensive studies on all the river systems including the non-perennial ones in order to effectively manage water resources and fully understand their biodiversity and sustainability, particularly under land use and climate changes [26].

In South Africa, about two-thirds of the river networks are non-perennial [13], which signifies the relevance of undertaking this study. There are some previous studies focusing mainly on determining environmental flow requirements in non-perennial rivers [12,13,27,28]. These studies highlighted that groundwater-surface water interaction is critical in non-perennial rivers such that when assessing environmental flows there is a need to consider such groundwater-surface water interactions. However, the studies do not comprehensively explain the role of groundwater in influencing the flows and quality of non-perennial rivers. It is critical that the process of streamflow generation, changes in quantities of water flow, and the associated water losses be characterized to enhance the understanding of these non-perennial rivers.

This study, therefore, aims to assess the role of groundwater in non-perennial river systems by conceptualizing the groundwater flow system and qualitatively evaluating aquifer-river interactions using hydrogeological, hydrochemical, and

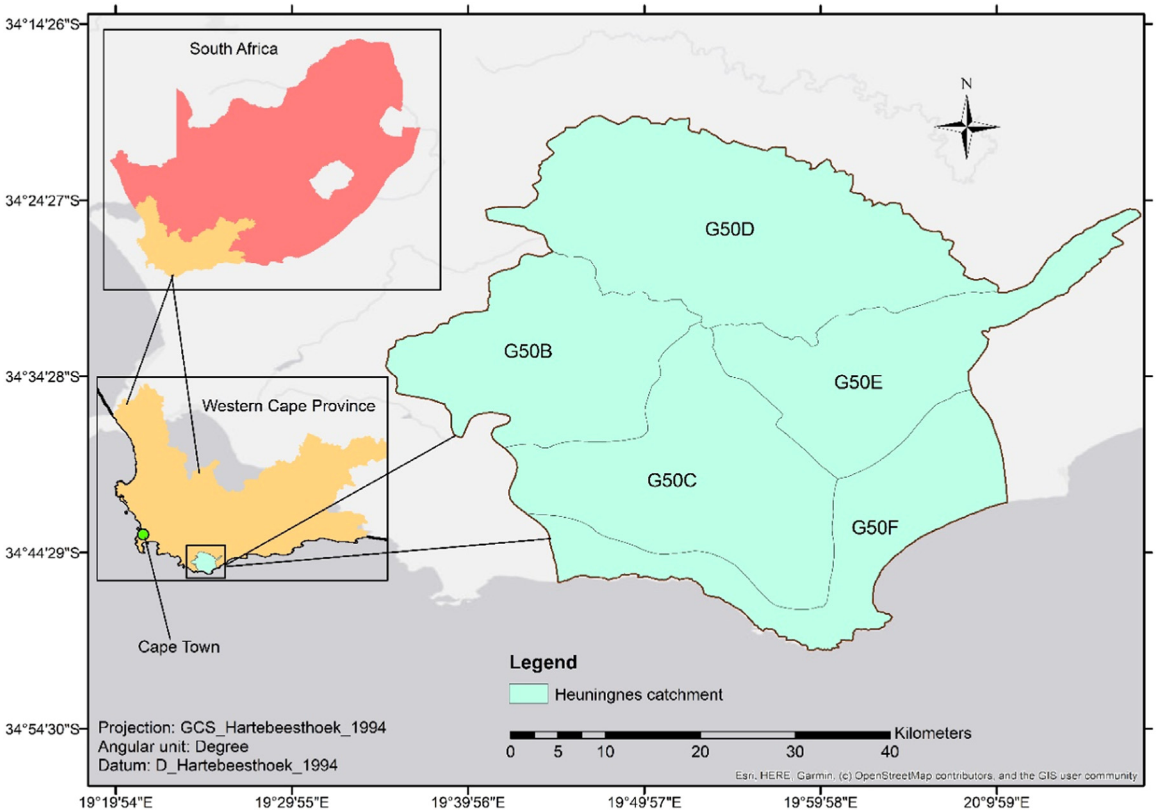

Fig. 1. Location of the study area.

environmental isotope tools. The study incorporates the characterization of aquifer properties and assessing the interaction between groundwater and a non-perennial river in the Heuningnes catchment, Western Cape Province of South Africa. The outcome of this study would provide a critical platform in designing implementation plans for using and managing water resources within non-perennial river systems.

Description of the study area

The study site is located roughly 220 km southeast of Cape Town in the Western Cape Province of South Africa (Fig. 1). The Heuningnes catchment lies between 34° 20′ and 34° 50′ S latitude and 19° 33′ and 20° 17′ E longitude. It has five quaternary catchments namely G50B, G50C, G50D, G50E, and G50F. A quaternary catchment is a fourth-order catchment in a hierarchal classification system structured from the primary drainage catchment, through to the secondary, tertiary, and quaternary levels [29]. The quaternary catchment forms the basic hydrological unit for water resource management in South Africa. This study was specifically experimented in the Nuwejaars River sub-catchment covering quaternary catchments G50B and G50C (Fig. 1), which has an effective area of approximately 760 km^2. The Nuwejaars catchment was selected due to its invaluable biodiversity located within the area. The Nuwejaars River, together with its floodplain wetlands surrounding it, offers a wide range of habitats such as wildlife, aquatic species, birds, and flora, resulting in this area having a wide range of biodiversity. The upper segments of the Nuwejaars River have been identified as priority areas for conservation initiatives due to their relatively unimpacted nature and high numbers of indigenous fish species [30]. Land cover in the Nuwejaars catchment area is largely natural vegetation with 41% of the area covered with fynbos. Agriculture is the second dominant land use comprising dryland farming (covering 39%) and livestock production. Urban development comprises only a small percentage of the catchment (3%), having Elim as its only town with an approximate area of 28 km^2. Hence, chemicals from farms, and animal and human waste are potential sources of water contamination in the area.

The topography of the study area varies considerably and is characterized by an undulating slope in the northern part while the southern and south-eastern part has a relatively flat area sloping gently towards the seashore (Fig. 2). The highest topographic elevation is in the northern and north-western parts of the catchment reaching approximately 250 m above mean sea level (amsl) while the lowest elevation is located in the southern part reaching 0 m amsl along the coastal line. Surface water drains towards the east and southeast in the upstream portion, and it becomes dominantly south flow in the mid and downstream area towards the coast. The relatively flat topography shows less than 35 m elevation difference over

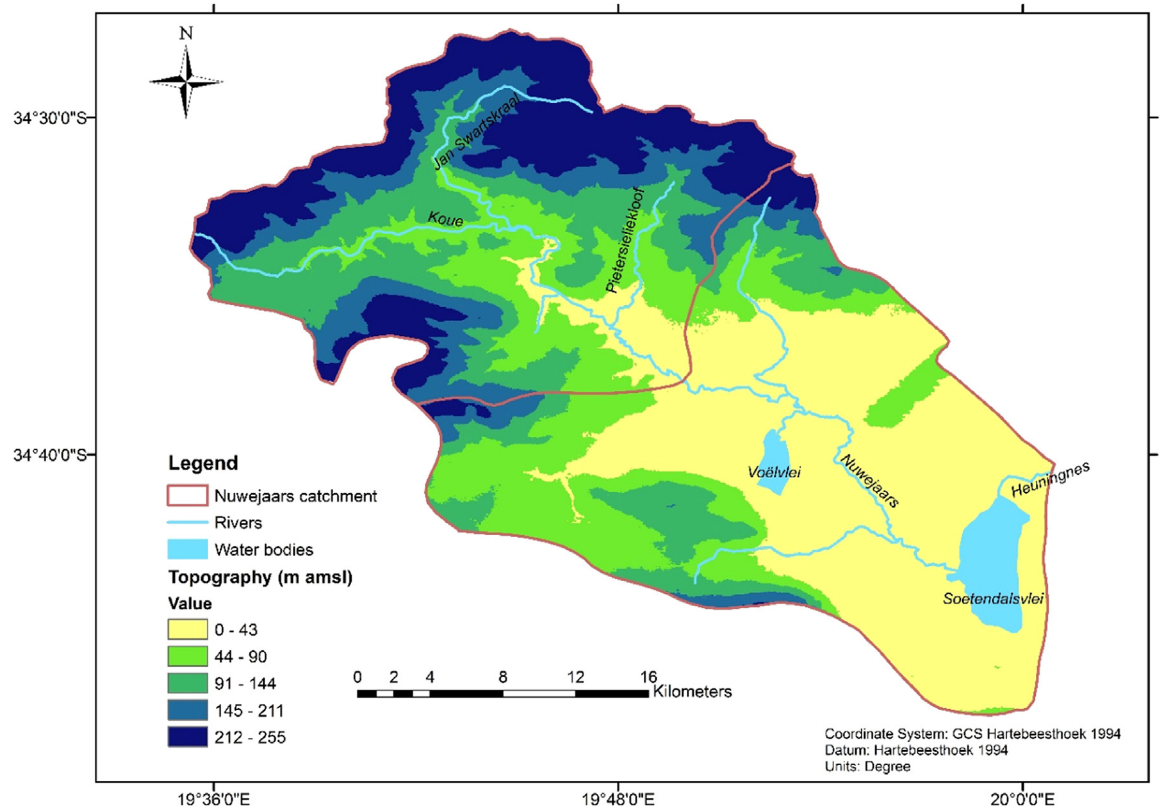

Fig. 2. Topography of the Nuwejaars river catchment.

a distance of approximately 30 km in the NW-NE strike (Fig. 2). Hence, based on the topography, the study area was divided into upstream and downstream parts of the catchment along the Nuwejaars River. The upstream part was demarcated as an area, on the Nuwejaars river stretch, having an elevation greater than 35 m amsl. Meanwhile, the Nuwejaars River has two key tributaries namely the Jan Swartskraal and Koue. The Nuwejaars drains into Soetendalsvlei, a small naturally freshwater lake, whose outlet joins the Kars River to form the Heuningnes River.

The study area falls within the Mediterranean climate with cold rainy winters and hot dry summers. Rainfall is mainly cyclonic with some orographic rainfall occurring in the upper parts of the catchment. It has been confirmed that rain-bearing winds are mainly from the west or southwest and rainfall originating from the southern slopes tends to be higher compared to the one emerging from the north-facing slopes of the study area [31]. Mean annual rainfall along the coast ranges from 445 mm in the east to 540 mm in the west and rises to about 650 mm on the low hills that form the region's northern boundary, with 60 – 75% of the precipitation falling in winter (May to October) [32].

The study area is largely composed of the following main geological formations: The Table Mountain, Malmesbury, Bokkeveld, Cape Granite Suite, and Bredasdorp Groups. Cape Granite and Malmesbury, a late Precambrian to early Cambrian in age are basement rocks consisting of coarse-grained granite which are overlaid by the Table Mountain and Bokkeveld Groups. The Table Mountain Group (TMG), of Ordovician to Silurian age (500 million years), comprises quartzitic sandstones derived from coarse sands deposited within the Agulhas Sea, and along its coastal plane. The Bokkeveld Group date back to the Silurian and early Devonian age and is composed of a cyclic alternation of fine-grained sandstone and mudrock units that conformably overlie the TMG in an off-lapping succession [33]. Bokkeveld strata consist largely of shales and thin interbedded sandstones derived from marine continental slope muds of early to mid-Devonian (400 - 370 million years old) age. Meanwhile, the Bredasdorp Bed is characterized by Tertiary to Recent alluvium, calcified dune sand, calcrete, calcarenite, and basal conglomerate.

The geology map (Fig. 3) shows a number of faults largely dominating the northern part of the study area. However, two major fault lines are present in the catchment running almost east/west. One fault line lies just south of the Bredasdorpberge and the other lies just north of Soetanysberg further south [31].

In general, the water-bearing formations in the study area are the TMG quartzite sandstone, the Bokkeveld shale as well the Bredasdorp alluvium. Largely, the TMG has high yields in areas where faulting and fracturing are prevalent due to its brittle and competent nature of the arenaceous deposits [34]. Meanwhile, the Bokkeveld Group is more argillaceous and therefore, less susceptible to brittle deformation and the sediments of the Bokkeveld Group normally have low groundwater

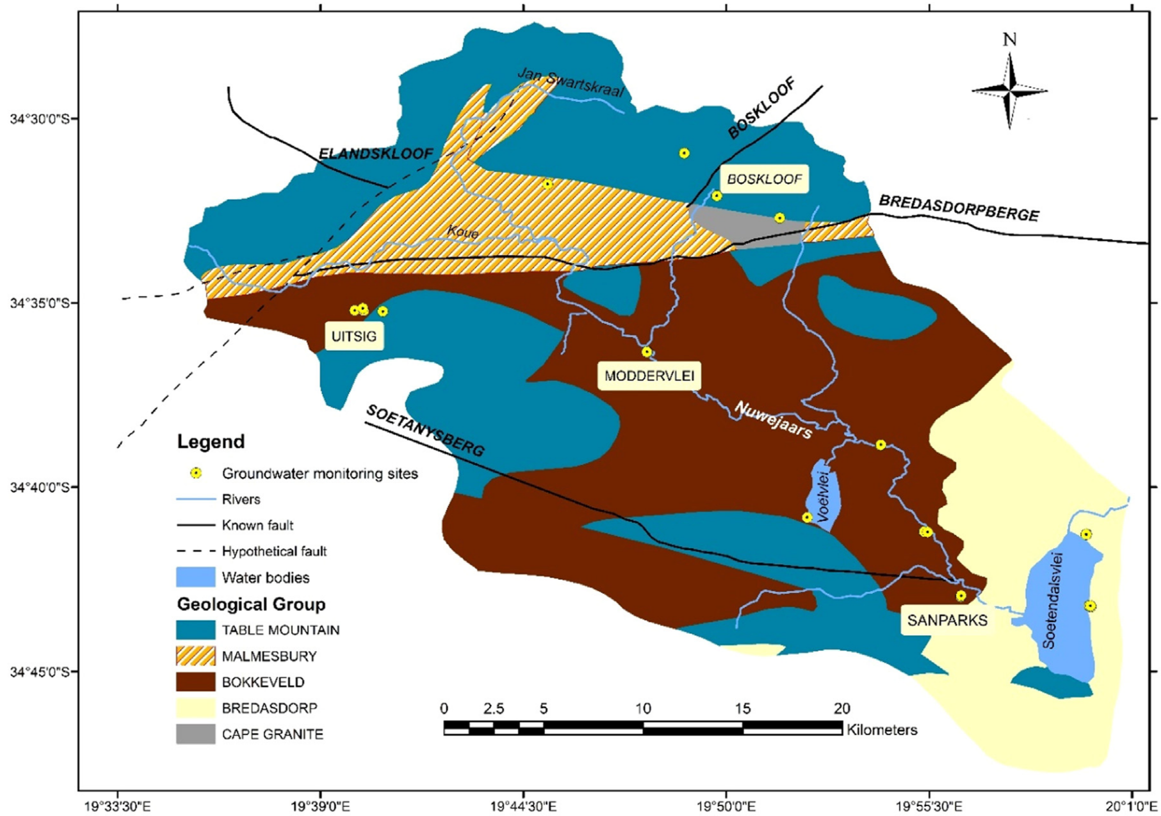

Fig. 3. Geological map of the study area.

potential and high saline water [35]. Groundwater movement is mostly associated with the secondary structures including faults and fractures, whereby the fault systems are likely to control the regional groundwater flow system. The clay and sandy clay of the Bredasdorp Group in the Nuwejaars River floodplain can result in a perched water table resulting in waterlogged conditions due to the flatness of the area.

Materials and methods

Borehole and piezometer installation and aquifer characterization

Investigation on the connectivity between the rivers of the Nuwejaars catchment and its underlying aquifer systems was carried out based on data from 17 boreholes, 7 shallow piezometers, and 12 surface water points including pools. The shallow piezometers range from 1.5 to 4 m below ground level and are located along the downstream part of the study area comprising alluvium and unconsolidated clay. The borehole depths range from 8 to 60 m, which were drilled in both the unconsolidated and fractured rock in order to have representative water samples from the different depths and geological formations.

The depths to groundwater levels from the shallow piezometers were monitored manually using an OTT KL 010 water level meter every month during the study period (June 2017 to July 2018). In contrast, Solinst™ automatic groundwater level loggers (Model 3001) with a 0.05% full-scale accuracy were used to collect the depth to groundwater levels in the boreholes on an hourly basis, providing a continuous record of water level fluctuations for the entire study period.

Pumping tests were conducted in 3 sites that were drilled prior to this study, each using a 0.37 kW (0.5HP) submersible pump and a 6.5 kW generator. Since the aim was to estimate the aquifer hydraulic parameters, a constant rate pumping test was performed at each site. The boreholes were pumped at a rate ranging between 0.24 and 0.35 l/s for an average time of 1 hour with the recovery period ranging between 2 – 3 h. These pumping rates were determined by conducting a trial pumping test, which gave an indication of the appropriate pumping rate based on the observed drawdown. The actual pumping test was finally performed after the aquifer had recovered from the trial test to its original groundwater level. The aquifer parameters (transmissivity and storativity) were calculated using AQTESOLV pro™ software.

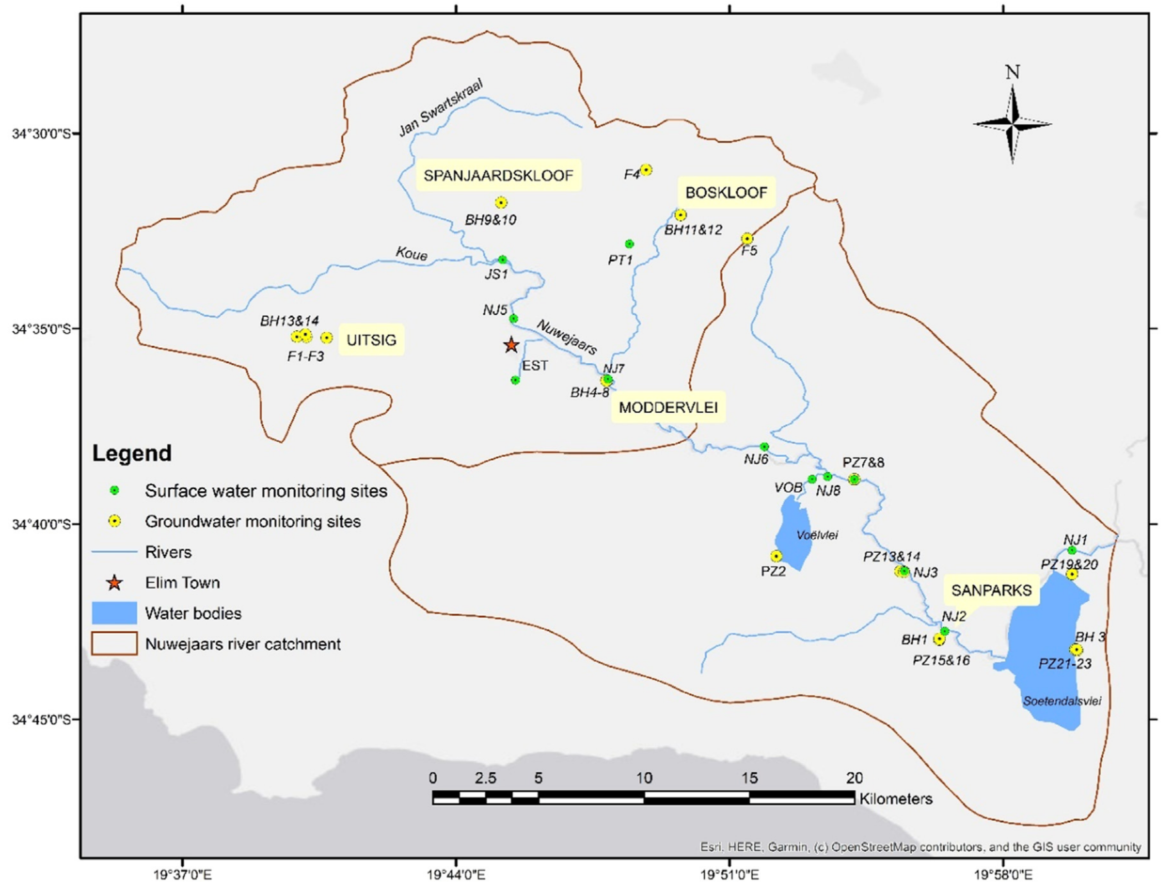

Fig. 4. Map showing locations of water sampling sites.

Sampling and analytical techniques

To capture the seasonal effects on aquifer-river interaction, groundwater and surface water samples were collected during both the rainy (October 2017) and dry (March 2018) seasons. Groundwater samples were collected from boreholes (labelled BH), piezometers (labelled PZ), and from privately owned boreholes (labelled F). The surface water samples were obtained from the Nuwejaars River and its tributaries. Meanwhile, during the dry season, other surface water samples were collected from segments of the Nuwejaars river having non-flowing water (pools). The locations of sampling sites and their names are presented in Fig. 4.

Groundwater samples were collected after purging boreholes with a portable water pump while surface water samples were collected either by dipping sample bottles in accessible sites or by scooping in deeper sites. Water samples for major ion analyses were collected in polyethylene water bottles of 200 ml capacity. Meanwhile, water samples for isotope analyses were collected in double-capped 50 ml polyethylene bottles to prevent isotopic fractionation due to evaporation. Electrical conductivity was measured in situ using a Hach^{TM} HQ40D portable multi-parameter probes. The EC parameter was only recorded when the meter had stabilized. The probes were calibrated before each field trip using standardized solutions within the EC ranges in the study area. Samples were properly labelled, transferred, and stored in a cool box at 4 °C until submission to the laboratory.

All water samples were analyzed for major ions including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), sulfate (SO_4^{2-}), and chloride (Cl^{-}). These parameters except bicarbonates were analyzed at the Western Cape's Department of Agriculture (Elsenburg) Production Technology Laboratory using Radial Inductively Coupled Plasma Spectrometer - Thermo Scientific Model number ICAP 7600. Meanwhile, alkalinity as bicarbonate was determined within 6 h after collection using the HACH burette titration method. Phenolphthalein indicator powder pillow, Bromcresol green-methyl red indicator powder pillow, and Sulfuric acid standard solution (0.020 N) were used as the reagents for the titration process.

Measurements for stable environmental isotopes of oxygen and hydrogen were done at the Earth Sciences Department of the University of the Western Cape using an LGR DLT-100 Liquid Water Isotope Analyzer (Model 908–0008–2010), manufactured by Los Gatos Research Inc. (Mountain View, California, USA). The results were represented as deviation from Vienna Standard Mean Ocean Water (VSMOW) in per mil (‰) difference using delta (δ) notation presented in Eq. (1):

$$\delta^{18}\left(\delta^{2}H\right) = \left(\frac{R_{sample}}{R_{standard}}\right) x\ 1000 \tag{1}$$

where by R is the isotope ratio of the heavy to the light isotope ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) in both the sample and the standard. The sample ratios were standardized using a range of standards (high and low) calibrated against VSMOW2 and SLAP2 standard reference materials. The measurement accuracy was below 0.6 ‰ and 0.2 ‰ for δ^2H and δ^{18}O, respectively. For reference purposes, the resulting stable isotope data were plotted along with the local meteoric water line (LMWL) and global meteoric water line (GMWL). The Cape Town data was used as the LMWL, which at the time of this study consisted of data collected for a period between 1995 and 2008, while the GMWL was derived from the [36] equation: $\delta_D = \delta^{18}O + 10$.

All field and laboratory-measured data were captured in Microsoft Excel 2016 spreadsheet for ease of calculation and graph plotting. Spatial data analyses including EC were visualized using ArcMap 10.3 whereas Surfer 11 was used to generate the potentiometric surface map and the hydrogeological conceptual model. Meanwhile, the Geochemist's Workbench version 12.0 software was used to produce Piper and Schoeller diagrams in order to present the major ions and classify the water types.

Results and discussion

Recharge and conceptualization of groundwater flow system

Data from the Department of Water Affairs Groundwater Resource Assessment (GRA) II [37] shows the recharge rates of 3.5 and 4.1% of mean annual precipitation in the G50B and G50C quaternary catchments respectively. G50B quaternary catchment covers mostly the upstream areas while G50C quaternary catchment covers the downstream areas. The slightly higher recharge in G50C quaternary catchment could likely be due to reduced runoff, which is in response to flat topography while the presence of dense vegetation and invasive alien vegetation in the G50B quaternary catchment could reduce groundwater recharge.

Understanding the characteristics of the water table is essential for conceptualizing groundwater flow systems and investigating the interactions between groundwater, surface water, and ecosystems [38]. The findings from groundwater head data showed that the study area has shallow water tables ranging from 3 – 10 m below ground level, both in upstream and downstream areas. An examination of the surface topography and groundwater level elevations showed that there was a strong correlation between the two parameters, with a coefficient of determination of 0.99, indicating that the water table is a subdued replica of the topography. Therefore, the study area was characterized to have topography-controlled water tables. Such water table characteristics are dominant in relatively low permeable aquifers and largely create a shallow and local groundwater flow system [39,40]. In essence, the connectivity between groundwater, surface water, and its associated processes is dependent on the nature and depth of the water table. Kollet and Maxwell [41] established that surface and subsurface processes are highly linked in shallow water tables, with a depth of less than 5 m being essential for the interaction processes. Hence, the shallow water table provides an initial understanding of the hydrogeological system in the study area, which helped in the conceptualization of the groundwater flow.

The available data on groundwater levels were used to construct a water table contour map to be used as a guide for deducing the general groundwater flow direction. Fig. 5 shows groundwater level contours and the general groundwater flow direction during the dry season. Only the dry season was plotted because it is during this period when the influence of groundwater on surface flows can be visible or not, unlike during the rainy season where runoff due to rainfall dominates. The results indicated that closely spaced contours were dominant in the upper high-elevation parts of the study area resulting in a relatively higher hydraulic gradient of 0.13. In contrast, widely spaced contours were found in the lower elevation areas of the catchment, whereby a relatively low hydraulic gradient of 0.0008 was determined. Generally, the potentiometric map showed the groundwater flow pattern mimicking the surface topography, largely flowing towards the southeast with local flows towards the Nuwejaars River. As shown in the water table map (Fig. 5), in the middle part of the study area contours are pointing up the river, suggesting increased groundwater–river interaction around this area.

Geological, hydrogeochemical, and environmental stable isotope data were further used to improve the groundwater flow conceptualization and assess the interaction between groundwater and surface water as well as evaluating the role of groundwater in non-perennial rivers. The findings are presented in the subsequent sections.

Aquifer characterization

Information from the geological maps, drilling of boreholes, and hand-augured piezometers demonstrated the presence of distinct hydrogeological boundaries, which influence the flow of groundwater and hence exhibiting evidence of interaction with the surrounding surface water bodies. The study area is comprised of both primary (intergranular) and secondary aquifers, whereby the intergranular aquifer (Quaternary Alluvial Aquifer) exists along the river flood plains and in areas where the Bredasdorp Group rocks dominate the geology. The secondary aquifers are mostly associated with fracture sets in the hard-consolidated sediments of the Bokkeveld and the TMG. Due to the faulting and fractures, in general, the TMG

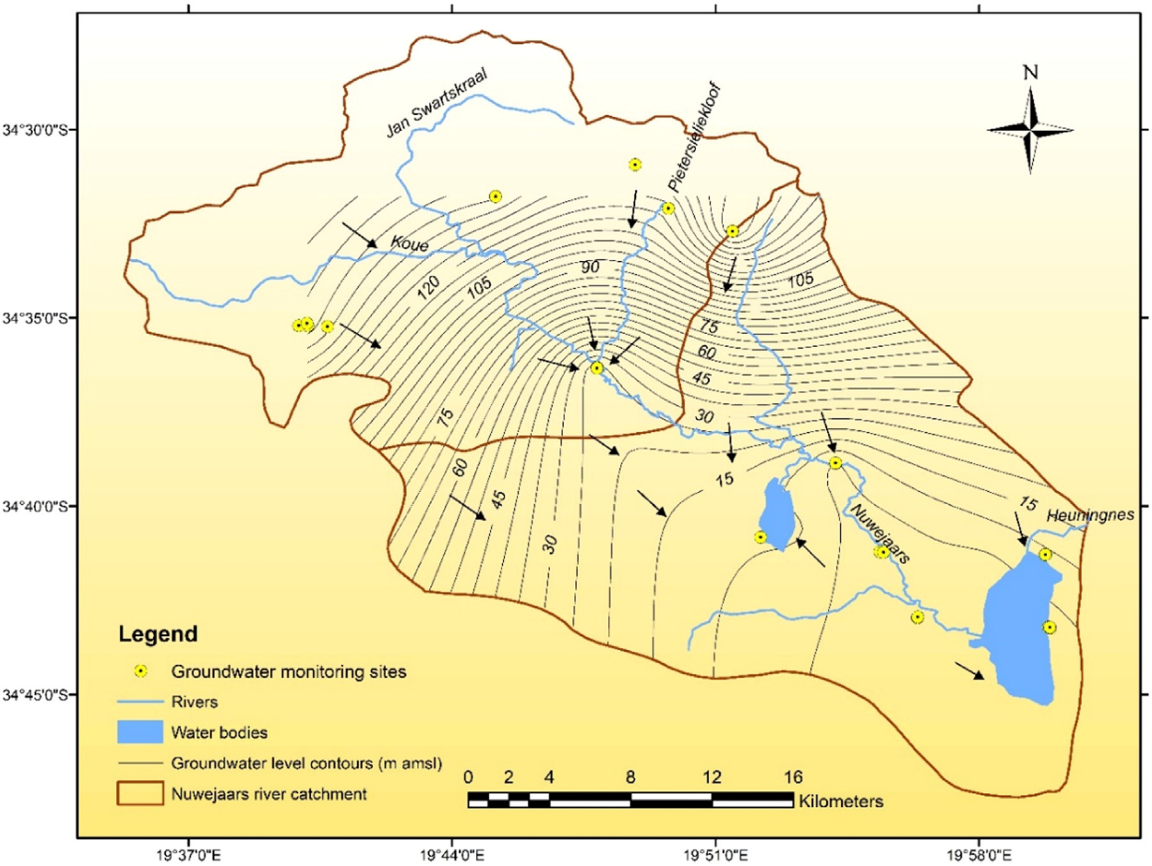

Fig. 5. Potentiometric surface map for the dry season. The arrows indicate the potential groundwater flow direction.

is considered a relatively high-yielding aquifer in most areas of its existence. The fracturing is prevalent within the TMG as a result of the brittle and competent nature of the arenaceous deposits [34]. However, the results of the pumping tests conducted in this study revealed low transmissivity values of 0.17, 0.24 and 1.74 m^2/day observed from boreholes at Uitsig, Spanjaardskloof, and Moddervlei sites, respectively (Fig. 4). Boreholes at Uitsig and Spanjaardskloof are within the TMG while those at Moddervlei are drilled in the Bokkeveld Formations. The low transmissivity values in the TMG are likely to be a result of changes in the structural properties of the sandstone quartz rock in this part of the study area due to fewer occurrences of rock fractures and a high prevalence of fine-grained materials. The fine-grained materials, which were detected from the drilling formations, were in boreholes near the fault lines as observed from the geological maps. Such fine-grained matrix of smaller particles tends to act as cementing agents restricting the flow of water. Although fault zones are primarily considered areas of increased groundwater permeability due to extensive fracturing, the presence of breccias and cataclasite results in reduced and low permeability of the fault zone [42]. Xu, Lin [43] noted that the most important single factor controlling groundwater flows in the TMG aquifers is the connectivity of fractures. Meanwhile, Xu, Lin [43] concurred that breccias available in fault core materials are common in the TMG formation such that they often serve as groundwater barriers. In addition, Newton, Shone [44] reported that most fault zones developed in the TMG sandstones and siltstones get cemented such that they may act as aquicludes in some cases.

Meanwhile, in the downstream part of the study area, the presence of a clay-rich regolith laying above the fractured Bokkeveld shale implies that it restricts the downward movement of water and facilitates the formation of a perched aquifer. Thus, the low hydraulic properties of the formation surrounding the river channel suggest slow groundwater movement and eventually the low rate of groundwater discharge to the river. Nevertheless, the local flow systems as a result of the shallow depth to water levels facilitate a relatively quick discharge to the river despite the low hydraulic conductive formation. These findings provide useful information on how the physical properties of aquifers influence groundwater flow, its discharge, and its interaction with the surrounding surface water bodies.

Table 1
EC concentration levels (µS/cm) during both the rainy and dry seasons.

Groundwater	Rainy season	Dry season	Location	Surface water	Rainy season	Dry season	Location
BH9	300	362	Upstream	**PT1**	561	646	Upstream
BH10	348	399	Upstream	**JS1**	501	909	Upstream
BH11	635	712	Upstream	**EST**	301	355	Upstream
BH12	712	907	Upstream	**NJ1**	9980	22,000	Downstream
BH13	388	447	Upstream	**NJ2**	1069	25,900	Downstream
BH14	436	466	Upstream	**NJ3**	1038	5380	Downstream
F1	516	584	Upstream	**NJ4**	833	1975	Downstream
F2	460	–	Upstream	**NJ5**	683	8220	Downstream
F3	241	336	Upstream	**NJ6**	787	1538	Downstream
F5	274	408	Upstream	**NJ7**	598	947	Downstream
BH1	10,230	29,900	Downstream	**NJ8**	876	3080	Downstream
BH2	–	60,800	Downstream	**VOB**	1352	13,110	Downstream
BH3	–	20,690	Downstream				
BH4	12,240	17,070	Downstream				
BH5	13,290	22,700	Downstream				
BH6	3190	4550	Downstream				
BH7	6530	12,840	Downstream				
BH8	3020	3040	Downstream				
PZ 2	27,600	31,000	Downstream				
PZ8	48,200	54,100	Downstream				
PZ14	57,400	66,200	Downstream				
PZ16	28,800	33,000	Downstream				
PZ26	64,600	64,300	Downstream				

The dash (-) signifies the period when no data was collected.

Hydrochemistry

Use of electrical conductivity (EC)

To understand the general extent of mineralization in the water, EC was measured in all the water samples during both rainy and dry seasons. In this study, EC values were used as a proxy for salinity and the degree of mineralization to describe the hydrochemical characteristics. Ordinarily, it is expected that there will not be much changes in the EC run along a river, unless where the river gets contaminated from anthropogenic activities or due to the input of groundwater of different chemical characteristics. Consequently, the use of the EC in assessing groundwater-surface water interaction is based on the notion that there are differences in the ionic strengths of groundwater and surface water.

The results of the EC values for both groundwater and surface water samples are presented in (Table 1). During the rainy season, groundwater salinity values range from 274 µS/cm to 64 600 µS/cm with a clear distinction of groundwater between upstream and downstream areas. In general, there is a correlation between the potentiometric surface and groundwater salinity such that groundwater in upstream areas is fresh and salinity increases in downstream areas.

During the dry season, there is a noticeable difference (increase) in the groundwater EC values in reference to that during the rainy season. The EC values for groundwater range from 274 to around 900 µS/cm in the upstream and from 3000 to 66 000 µS/cm in the downstream part (Table 1), with a remarkable increase in salinity levels during the dry season.

Similarly, for surface water samples, salinity levels increase from the catchment headwaters to downstream areas of the river (Table 1, Figs. 6, and 7). The Nuwejaars River tributaries located in the upstream and intermediate parts of the study area have the lowest EC values, between 300 and 900 µS/cm. EC levels in surface water also increased during the dry period, with a greater increase in the middle and downstream areas of the Nuwejaars River (Figs. 6 and 7). The origin of high levels of salinity in groundwater is well documented, as it is influenced by processes such as weathering from evaporite formations, evaporation at the land surface before recharge, mixing with other highly mineralized water, and saltwater intrusion [45–49]. On the other hand, higher EC in surface water may be due to mixing with seawater in estuaries [50] and other human-related causes such as irrigation return flow, discharge of industrial wastewater, and domestic effluent [51,52]. In the sampled areas, there was no evidence of direct mixing between the seawater and that of the Nuwejaars River as the river is not closer to or in contact with the seawater. Again, the study area is dominated by rainfed dryland agriculture, thereby omitting the possibility of irrigation return flow during the dry season, which also exhibited elevated EC.

Considering that the results show the EC trend of river water is similar to that of groundwater, such an agreement can be used as evidence of a hydraulic connection between groundwater and the river. The increase in salinity in the river was, therefore, attributed to saline groundwater discharge and partly evaporation. In general, the EC in groundwater is expected to be high than in surface water due to increased total dissolved and resultant higher ionic strengths in groundwater [53]. As such, areas in the river that are supplied by groundwater are identified by their amplified EC values in proportion to the expected surface water values. This was particularly the case in the study area because there were no major anthropogenic activities closer to the surface water sampling points that could have vastly increased the EC levels. The only exception where high EC during the dry season could be attributed to anthropogenic activities was at site NJ5 (Fig. 4), which is near

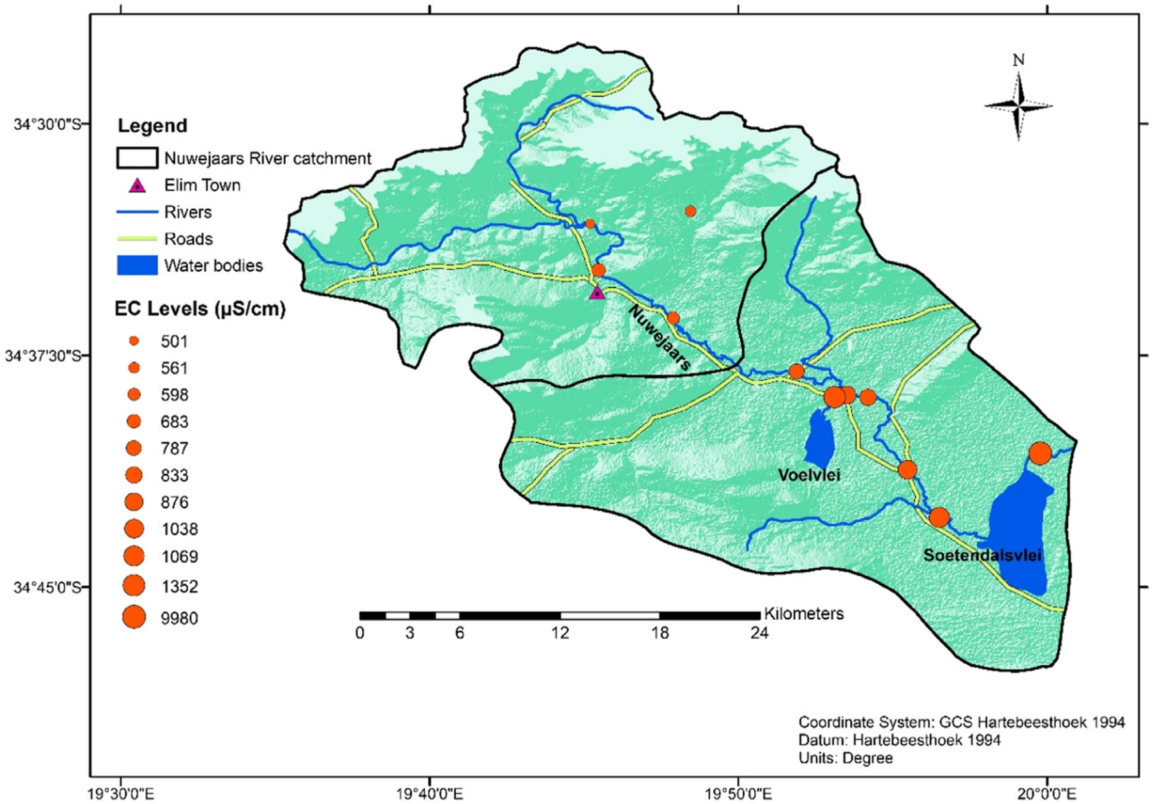

Fig. 6. EC levels for river samples during the rainy season.

Elim town (Fig. 7). The site is downslope Elim town and closer to a dairy farm, which may increase the concentration of nutrients and other ions, eventually raising the EC.

Use of major ions chemistry

Major ion data exhibit that there is a noticeable dominance of Na^+ and Cl^- in both groundwater and surface water samples confirming the elevated salinity in the water. The NaCl waters and the high salinity in groundwater are understood to be due dissolution and leaching of the Bokkeveld shale, which dominates the middle and lower part of the basin. The Bokkeveld is known to yield high saline groundwaters including in studies closer to this study area [54–56]. During both the rainy and dry periods, the dominant major cations are in the order of $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ for both groundwater and surface water samples. Meanwhile, major anions data show concentrations range from high to low in the order of $Cl^- > SO_4{}^{2-} > HCO_3{}^-$, again for both groundwater and surface water during the sampled periods. Generally, there are noticeable variations in the concentrations of parameters in upstream and downstream areas signifying different hydrogeochemical processes in the study area as shown in Tables 2 and 3. Meanwhile, the concentrations of chemical constituents including sodium and chloride were higher in some surface water sampling sites (e.g. NJ5, Fig. 4) than in groundwater. As earlier indicated, this could be a result of anthropogenic pollution from residential and farmland areas around Elim town, which is facilitated by the runoff from this area towards the river.

A Piper diagram (Fig. 8) also shows that there are two groups of similar water chemistry for groundwater samples, which are Na-Cl (86%) and Na-Mg-Cl (14%) type waters. It is shown that Na-Mg-Cl type water comes from shallow groundwaters in piezometers (PZ8, PZ14, and PZ26) which are close to the Nuwejaars River. In general, compositionally the groundwater samples are Na-Cl type water. Meanwhile, during the same rainy season, the Piper plot for surface water samples (Fig. 9) is again composed of two similar groups of water chemistry; Na-Mg-Cl (73%) and Na-Cl (27%) type waters. These results are supported by the findings made by Apedo [57] where it was found that surface water bodies in the Agulhas plain, which covers this study area, are characterized by the Na-Cl and Na-Mg-Cl water types. Generally, the results of this study show that both groundwater and surface sources have Na^+ and Cl^- as dominant ions with some river samples having a mixture of Mg^{2+}. Sodium and chloride contributed to 80% and 81% of the total analyzed chemical species in groundwater and surface water, respectively. The similarity in the major ion characteristics for both groundwater and surface water confirms the presence of connectivity between the two water sources.

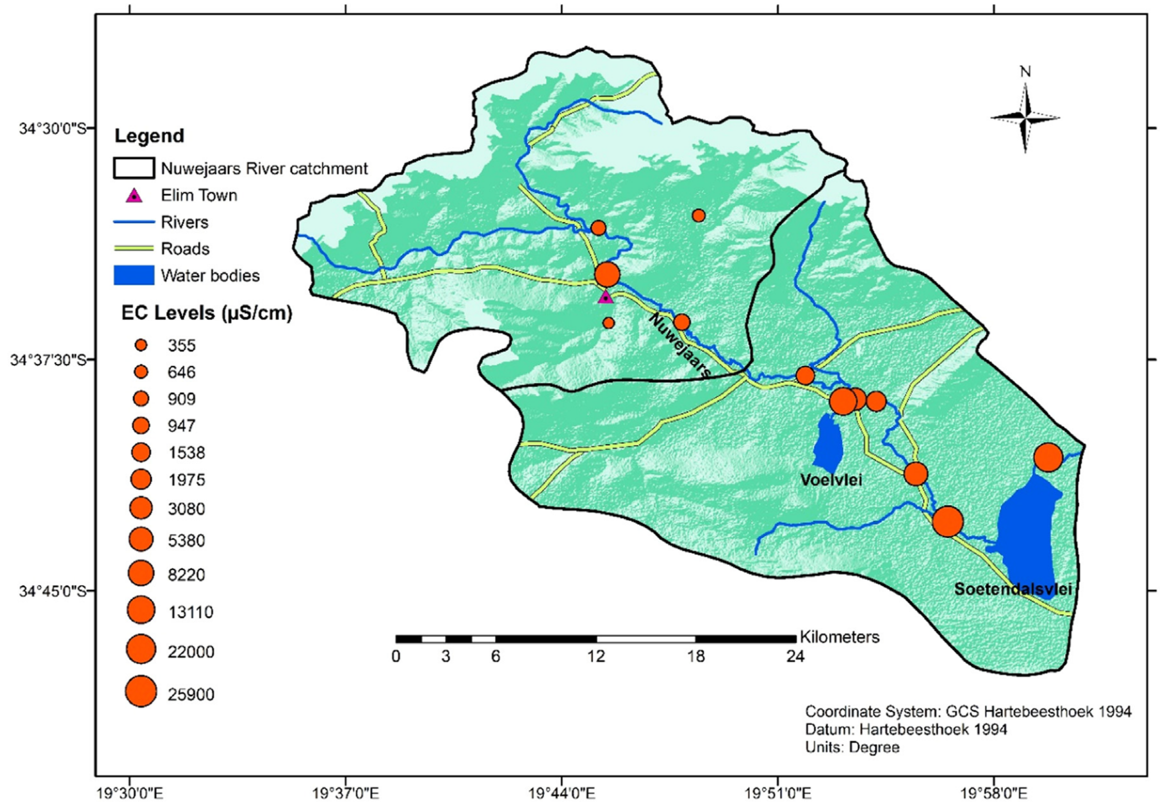

Fig. 7. EC levels for river samples during the dry period.

Table 2
Descriptive statistics of major ions for samples collected during the rainy period. Units are in mg/l.

	Ca^{2+}	Na^{+}	K^{+}	Mg^{2+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
River - upstream							
Minimum	8	109	2	18	210	23	12
Maximum	21	518	9	71	985	167	18
Mean	14	313	5	44	598	95	15
Standard deviation	9	289	5	37	548	102	4
River - downstream							
Minimum	8	113	1	18	213	1	12
Maximum	98	2200	32	170	3696	413	392
Mean	28	485	9	54	959	105	76
Standard deviation	34	729	13	63	1388	164	122
Groundwater - upstream							
Minimum	3	41	1	5	85	1	6
Maximum	17	115	5	15	389	32	80
Mean	7	71	3	10	148	18	24
Standard deviation	5	26	1	3	91	9	21
Groundwater - downstream							
Minimum	13	418	4	32	881	41	122
Maximum	431	6675	77	300	27,480	2381	310
Mean	140	1447	30	169	8778	842	182
Standard deviation	138	1756	26	107	9372	853	61

To confirm whether groundwater chemistry influences surface water chemistry and therefore the presence of a hydraulic connection, Schoeller diagrams were plotted for groundwater (mostly piezometers) and river samples located closer to the piezometers. The Schoeller diagrams for the rainy and dry seasons are indicated in Fig. 10 and Fig. 11, respectively.

The data indicate that the concentration of major ions is higher in groundwater during both the rainy and dry seasons. It is also evident that wherever there is a rise in the concentration of a particular ion in groundwater there is also such a rise of that particular ion in surface water. The fall in the ion concentration is also similar for groundwater and surface

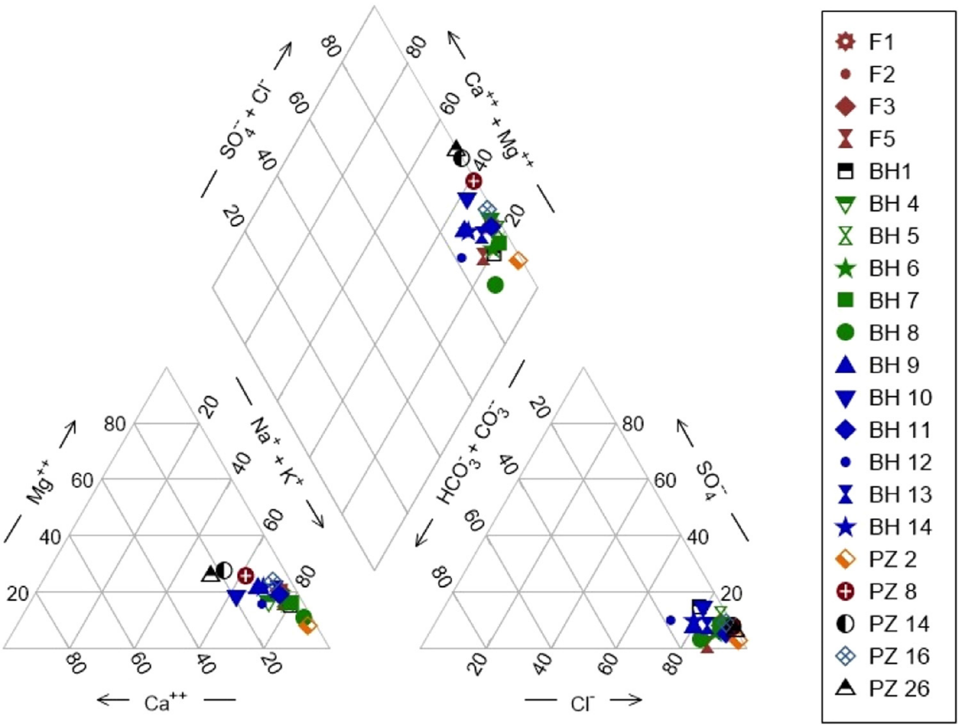

Fig. 8. Piper plot for groundwater samples.

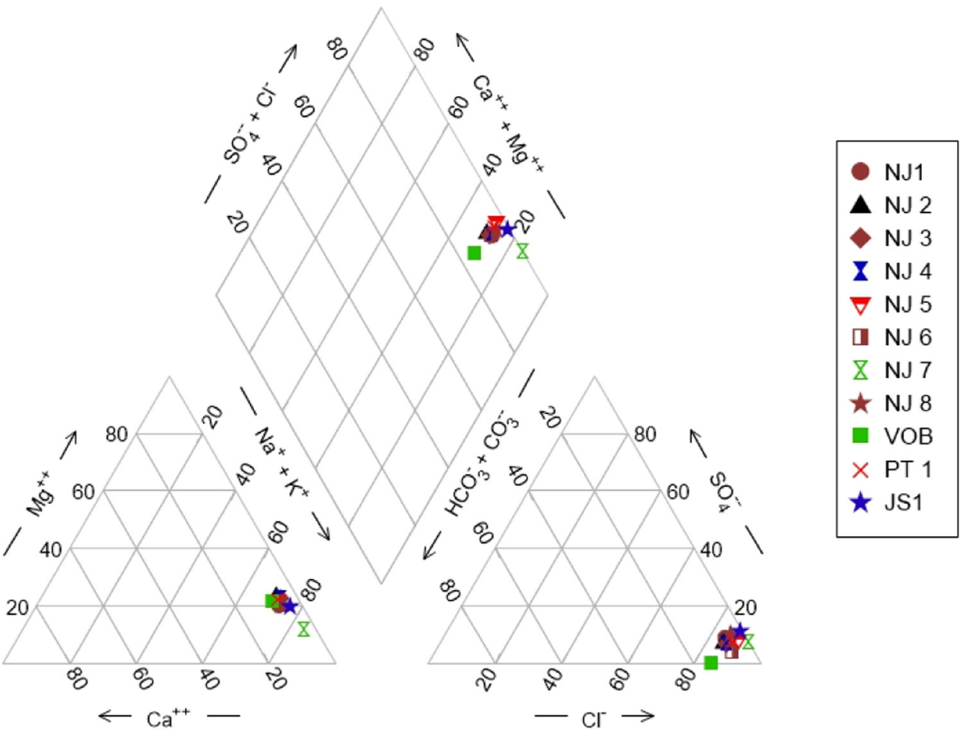

Fig. 9. Piper plot for river samples.

Table 3
Descriptive statistics of major ions for samples collected during the dry period. Units are in mg/l.

	Ca^{2+}	Na^{+}	K^{+}	Mg^{2+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
River - upstream							
Minimum	3	57	1	8	101	4	6
Maximum	15	130	3	28	245	20	110
Mean	8	98	2	17	178	12	41
Standard deviation	6	37	1	10	72	8	59
River - downstream							
Minimum	10	142	1	24	257	12	30
Maximum	152	1285	52	240	10,089	836	474
Mean	64	678	17	113	3070	229	200
Standard deviation	57	482	19	84	3772	284	172
Groundwater - upstream							
Minimum	3	42	1	5	90	3	10
Maximum	32	122	16	13	187	33	104
Mean	9	67	3	8	120	16	45
Standard deviation	10	26	5	3	35	9	34
Groundwater - downstream							
Minimum	18	30	2	14	562	19	136
Maximum	555	11,534	88	550	22,085	2515	466
Mean	186	3269	19	245	7779	1013	260
Standard deviation	178	3577	22	190	7092	832	107

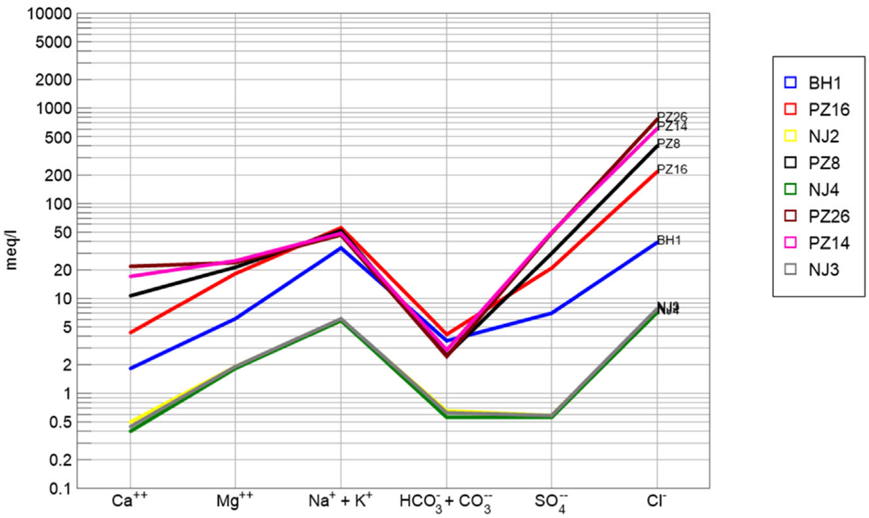

Fig. 10. Schoeller showing the relationship between groundwater (BH1, PZ8, PZ14, PZ16, and PZ26) and surface water (NJ2, NJ3, and NJ4) during the rainy season.

water. The same type of variation in major ion concentration between the two water sources, therefore, implies possible interaction between groundwater and surface water. In general, both water sources have high concentrations of Na and Cl. Therefore, it was concluded that the chemical composition of river water in the sampled area is generally influenced by groundwater chemistry.

Environmental stable isotopes

The stable isotopes of δ^2H and δ^{18}O were used to infer the potential interaction between groundwater and the Nuwejaars River and its tributaries. When characterizing the isotopic composition of water, it is important to have local precipitation data in order to identify the relative depletion or enrichment of the sampled water. As such, the results of this study were plotted relative to the Cape Town local meteoric water line (LMWL), which is the closest LMWL to the study area, as well as relative to the global meteoric water line (GMWL). The GMWL is defined by the equation $\delta^2H = 8\delta^{18}O + 10$ [36]. The GMWL can be a suitable reference for determining the possible rainfall compositions in cases where there is not enough local data to create a representative LMWL [58]. For this study, Cape Town Metro Area and the Heuningnes catchment have similar Mediterranean climate patterns, indicating the suitability for using the Cape Town LMWL in this study. The results for the isotopic composition of the water samples during the dry season are presented in Fig. 12. Only the dry season results are

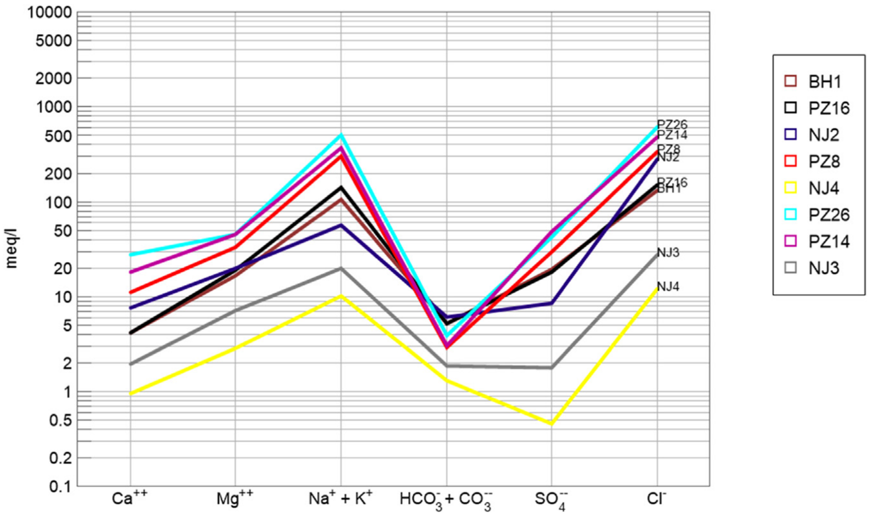

Fig. 11. Schoeller showing the relationship between groundwater (BH1, PZ8, PZ14, PZ16, and PZ26) and surface water (NJ2, NJ3, and NJ4) during the dry season.

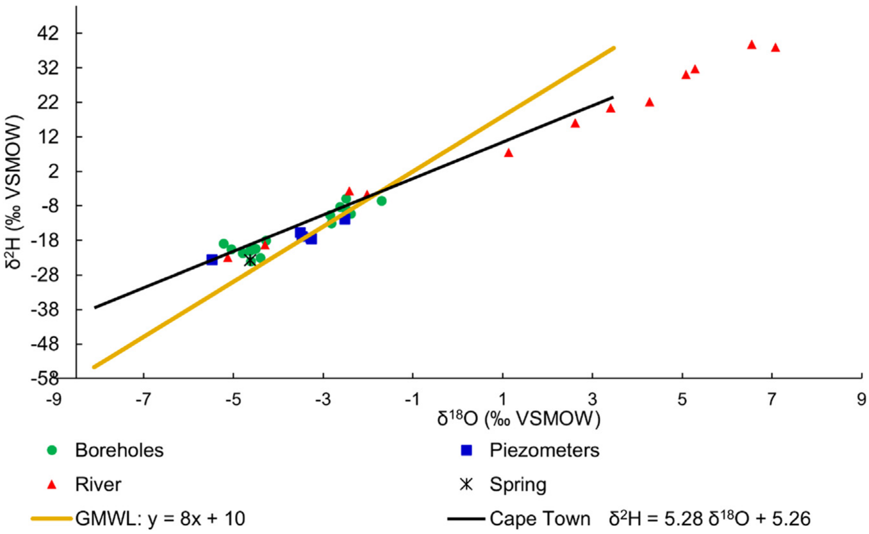

Fig. 12. Plot of stable isotopes of groundwater and surface water samples in relation to the LMWL and GMWL.

presented because it was hypothesized that the dry season data would provide a better understanding of the potential role of groundwater in the interaction process.

Results showed that during the dry season, the δ^{18}O values of groundwater range from −5.48 ‰ to −1.7 ‰ while δ^{2}H values range from −24 ‰ to −5.9 ‰. In contrast, δ^{18}O values for surface water (rivers) range between −5.12 ‰ and −7.08 ‰ while δ^{2}H values range between −22.9 ‰ and −38.8 ‰.

The heavy isotopes for all the groundwater samples plot at the depleted (negative) portion of the LMWL in comparison to the surface water samples whose majority of samples plot to the enriched (positive) portion (Fig. 12). This confirms that groundwater in this study area is a result of recharge from winter rainfall experienced in the study area. As earlier mentioned, the study area is characterized by the Mediterranean climate with cold, rainy winters and hot, dry summers. Rainfall samples collected during the winter period tend to be more depleted than summer rainfall related to cold polar air masses [59,60]. Further, the plot shows that the majority of the groundwater samples (shallow groundwater from piezometers, relatively deeper groundwater from boreholes and spring water) plot on and slightly below the LMWL suggesting the water experienced quick recharge, absence, or minimal evaporation and diminished fractionation from the meteoric water [61,62].

Results also revealed that most of the river samples are enriched (more positive) with heavy isotopes indicating evaporative signatures. However, river samples on upstream sites JS1, ETS, PT1, and NJ7 are depleted with oxygen and hydrogen isotopes suggesting the elevated contribution of groundwater to the river waters. Similar results were found by Menció, Galán [16] in a study on stream-aquifer relationships in the Mediterranean environment, whereby water samples from a

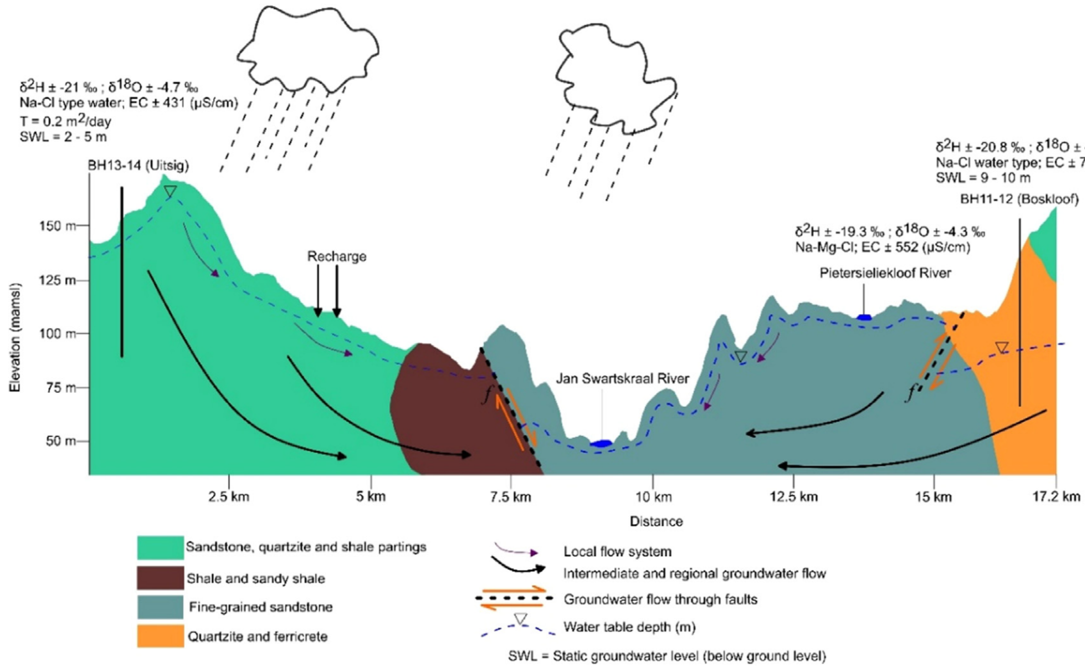

Fig. 13. Conceptual model of aquifer-river interaction in the upstream area.

river pool during the dry period showed depleted isotopic signatures. The study found that there was no clear shift of isotopic signatures from the meteoric line that could be attributed to evaporation and the pools were thought to be originating from groundwater [16]. Meanwhile, in the current study, all groundwater samples from shallow piezometers including those close to the river show depleted signatures demonstrating no evidence of the contribution of recharge from the river water, which is normally characterized by heavily enriched isotopic signatures.

It is important to note that evaporation results in the removal of lighter isotopes and a concentration of heavier isotopes in water [63]. Therefore, only such river samples which were not exposed to higher evaporation, for example, due to canopy cover or reduced temperatures, would provide a better indication for groundwater contributing to such rivers. This was evident in the catchment headwaters (upstream areas) which have considerable canopy cover and water flows relatively fast due to the permitting topography. Hence, surface water samples remained depleted having similar signatures to the groundwater samples. In contrast, the middle and lower segments of the Nuwejaars River have slow-flowing water due to a small topographic gradient, hence, despite evidence from other approaches showing groundwater contributing to the rivers, most of the samples in this region were enriched signifying high evaporation. This highlights the need for using suitable tracers and multiple approaches for better understanding the flow paths and interpreting the groundwater-surface interaction processes.

Relationship between groundwater and surface water: the conceptual model

The main source of recharge water to Nuwejaars River is the winter rainfall occurring between May and October, the groundwater-fed tributaries as well as groundwater discharge in the alluvial plains. The shallow groundwater in the study area appears to flow to the nearest discharge point including the rivers in the Nuwejaars sub-catchment. Hydrogeological conceptual models for the Nuwejaars river sub-catchment are presented in Figs. 13 and 14 for the upstream and downstream parts of the study area, respectively. The models, developed based on the hydrological, geological, hydrochemical, and environmental stable isotope data, show the major hydrogeological units of the study area and possible flow path within the local aquifers. Data on the catchment water balance is not available to provide an accurate quantitative description of the flow regime but the conceptual model avails an approximate groundwater flow path of the study area. However, with more data, the conceptual model can be refined so that it is used for any future numerical modeling.

In the downstream areas, there is a prevalence of clay intercalation in areas along the Nuwejaars River, which are mostly of low conductivity and potentially restrict vertical groundwater movement to the shale bedrock. This would result in greater lateral groundwater movement toward the river [18]. The exchange fluxes not only influence the quantity but also the quality of water in the river. Due to the geologic heterogeneity and the presence of faults, it is hypothesized that the shallow water table in the downstream areas may be disconnected from the regional groundwater flows, resulting in the dominance of the local flow system and perched groundwater. Perched groundwater can act as a partial substitute for regional groundwater by limiting seepage loss, and providing base flow and bank storage [64], thereby maintaining the ecosystem functioning of

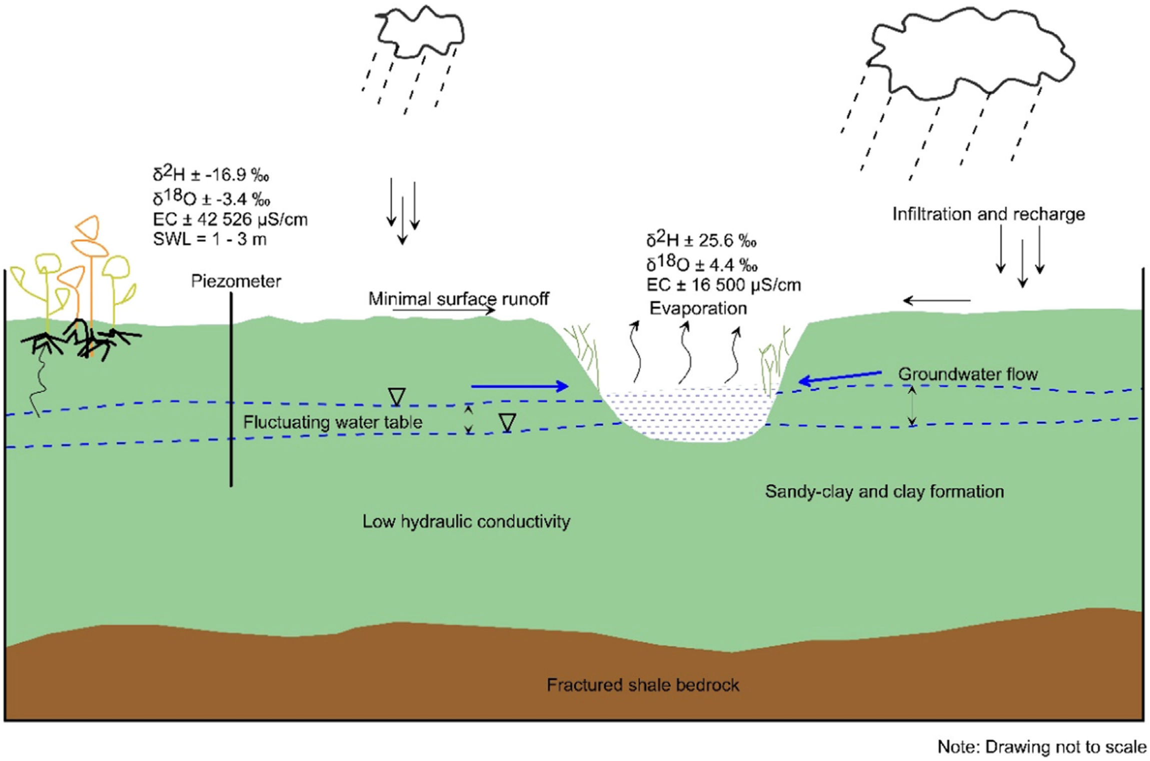

Fig. 14. Conceptual model of aquifer-river interaction in the downstream area.

rivers. In the downstream area, the river is connected to a saline shallow aquifer having low conductance clays overlying a deep fractured aquifer resulting in elevated salinity in the surface water bodies, especially during the dry season. However, the connectivity is to a limited extent as evidenced by the river being characterized by segments having continuous flows, pools, and some that are completely dry. Meanwhile, the upstream rivers are supplied by regional groundwater flow from the fault within the TMG formation maintaining the base flow with fresh water throughout the year. The North East – South West (Boskloof) fault present in the north-eastern part of the study area seems to act as a conduit to groundwater flow thereby supplying water to the upstream rivers while the Bredasdorpberge (East-West) fault in the northern part seems to act as a barrier to groundwater flow resulting into a hydraulic discontinuity between upstream and downstream areas (Fig. 3). Further, the Soetanysberg fault appears to act as a conduit for groundwater flow supplying water to the Nuwejaars river region around SANParks (Fig. 3).

The conceptual model would help in the development of the proposed optimum management of non-perennial rivers including the effects of groundwater abstraction on the river flows. To ensure river connectivity, it is therefore critical to maintain the river flows in the upstream areas (catchment headwaters). For a river system, which is connected to a groundwater system, managing groundwater abstraction in the upstream areas is crucial in maintaining the river flows. Reducing such losses in the headwaters would result in the river flowing longer distances to its downstream segments thereby providing a reliable supply of water to the aquatic organisms throughout the course of the river. Additionally, to maintain the required high groundwater levels for providing water to the rivers or pools in the downstream areas, regulating shallow groundwater abstraction is recommended for sustaining river functioning. Although results from the conceptual model are not quantitative, it provides a relevant water management platform in arid and semi-arid regions and therefore for managing non-perennial river systems.

While understanding the controlling processes governing the flow in non-perennial rivers, it is also worthy to mention the impact of climate change on the hydrological regime in such rivers, including the Nuwejaars River. Climate change impacts, particularly reduced rainfall and increasing temperature have important ramifications on water resources in general, but also the sustainability of riparian ecosystems. It is argued by other researchers, for instance, [65], that lack of precipitation is largely felt in non-perennial rivers because streamflow in such rivers is largely dependent on precipitation amount. However, the implications of reduced rainfall on the river flow regime could be intensified in a non-perennial river or its segments fed by groundwater. Natural groundwater recharge from rainfall replenishes the aquifers thereby raising the water table, thus, climate change would affect the timing and magnitude of potential recharge. Meanwhile, it has been established in the current study area that the aquifer-river interaction is dominated and facilitated by the shallow and localized groundwater flow systems. It is such shallow groundwater systems that are likely to be more and instantly sensitive to climate-driven changes [38]. Again, the hyporheic zone where the interaction of groundwater and surface water occurs will be directly or indirectly affected by climate change, for example, through increased evapotranspiration in the vadose zone. This would result in a lowered water table and reduced overall groundwater contributions to the river. As this study has largely established the spatial interaction between groundwater and surface, it is important to determine how climate change influences the temporal patterns in such interactions and eventually the sustainability of groundwater-dependent ecosystems.

Conclusions

The assessment of catchment scale connectivity between groundwater and non-perennial river systems and the processes governing their connectivity has not been widely documented. Knowledge of the interaction processes at different spatial and temporal scales is essential for water resource management and particularly, the protection of groundwater-dependent ecosystems. This study demonstrated the efficacy of using an integrated approach of combining different data sets for assessing the role of groundwater in non-perennial rivers. Aquifer hydrology, hydrochemical, isotopic, and geological data were used to describe the hydrogeological system of the Nuwejaars River sub-catchment. Groundwater in the study area is mainly characterized by shallow water levels and Na-Cl, and Na-Mg-Cl water types dominate both groundwater and surface water. Deeper groundwater and spring water in the upstream parts of the study area exhibit the isotopic signatures of rainwater indicating direct recharge without significant evaporation. Vertical mixing occurs in the TMG quartzite formations in the upstream areas as demonstrated by the similar chemical and isotopic signatures of water samples.

On a catchment scale, upstream areas are deemed to have high groundwater recharge rates and the downstream areas are discharge zone. Groundwater recharge is mainly from rainwater infiltration with no evidence of river seepage. Low surface elevation (gradient) and poor hydraulic conductivity in the downstream portion of the study area cause slow groundwater flows resulting in less flushing and high salinization of groundwater in the downstream areas. The slow flows result in steady and minimal groundwater discharge to the river resulting in groundwater failing to maintain the river flows or pools in such river segments. Based on the hydrogeological conceptual model developed from this study, it is hypothesized that groundwater is connected to surface water in the upstream parts of the study area while there is limited connectivity in the downstream parts. NE–SW fault passing Boskloof in the northeastern part and the Bredasdorpberge fault in the western part of the study area play an important role in the groundwater flows. The faults act as a conduit to groundwater flow by supplying water to the upstream rivers which feed into the Nuwejaars River. In general, rivers of the study area largely gain water from groundwater although the amount of groundwater discharge varies from one river segment to another in both upstream and downstream parts.

This study has provided qualitative information on aquifer-river connectivity at the catchment scale and identified river segments where interaction is occurring. Site-specific measurements provided strong evidence of aquifer-river interaction. In addition, the assessment from upstream to downstream areas provided reliable and valid evidence on the role of groundwater in non-perennial river systems at a sub-basin scale. It is recommended that such areas identified in this study are targeted for more detailed quantitative assessments so that the contribution of the water sources (groundwater, river, and precipitation) to each other are quantified, for instance, using the mass balance approach.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Vincent Dzulani Banda: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft. **Haile Mengistu:** Conceptualization, Supervision, Validation, Writing – review & editing. **Thokozani Kanyerere:** Conceptualization, Supervision, Resources, Writing – review & editing.

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