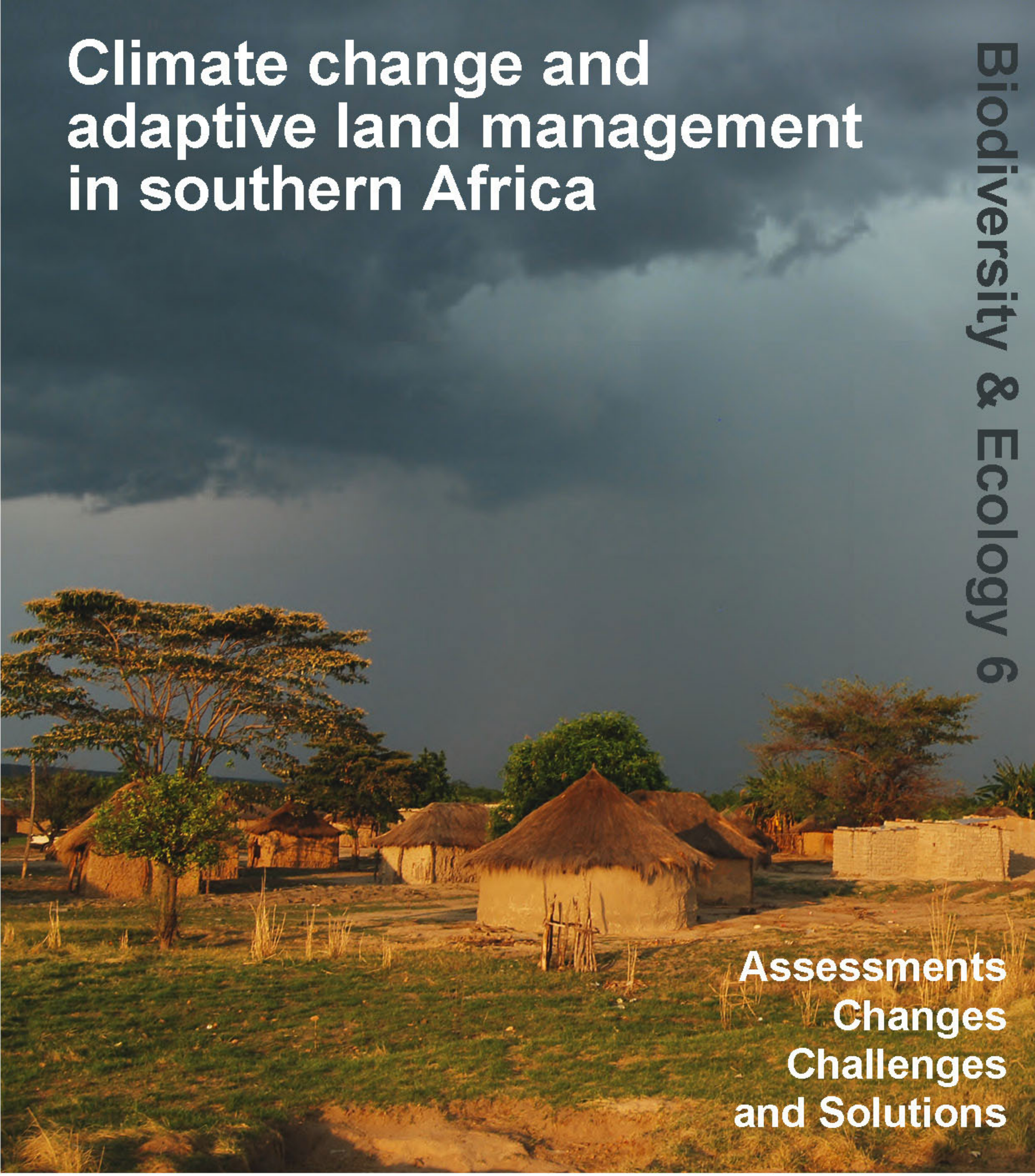

Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6

Assessments
Changes
Challenges
and Solutions

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Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

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Groundwater quality, quantity, and recharge estimation on the West Coast of South Africa

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Abstract: Along the west coast of South Africa, where precipitation rates are often less than 400 mm/year and rivers are mostly ephemeral, access to water is a critical limitation on development. However, west coast groundwater is variably saline in areas, can damage sensitive ecological systems, and is often not suitable for domestic or agricultural use. SASSCAL has installed weather and groundwater monitoring instruments along the west coast, with a focus on the RAMSAR-listed Verlorenvlei estuarine lake, to understand the interdependence of domestic, agricultural, and ecological water requirements. Groundwater modelling in the upper parts of the Verlorenvlei catchment intends to show that baseflow from the Krom Antonies tributary is a critical source of low-saline water that also supports economically important agricultural activities. Early results of the Krom Antonies groundwater model suggest that pumping regimes in the Verlorenvlei catchment are at or near maximum capacity. This would suggest that future changes in pumping regimes, through, for example, changes in land use patterns or precipitation patterns would need to be carefully managed to maintain sufficient baseflow supply to the tributaries feeding into the Verlorenvlei estuarine system. Lessons learned in this catchment will be applied to the data-poor Buffels River catchment further north to improve our understanding of west coast hydrology and how it will be affected by future climate change.

Resumo: Ao longo da costa Oeste da África do Sul, onde as taxas de precipitação são frequentemente menores que 400 mm/ano e os rios são essencialmente temporários, o acesso à água é uma limitação crítica para o desenvolvimento. Porém, a água subterrânea na costa Ocidental é variavelmente salina em determinadas áreas, pode prejudicar sistemas ecológicos sensíveis e muitas vezes não é adequada para uso o doméstico ou agrícola. O SASSCAL instalou instrumentos de monitorização meteorológica e de águas subterrâneas ao longo da costa Ocidental, com um foco no Lago Estuarino de Verlorenvlei (Sítio RAMSAR), de modo a compreender a interdependência das necessidades hídricas domésticas, agrícolas e ecológicas. A modelação de águas subterrâneas nas partes superiores da bacia hidrográfica de Verlorenvlei pretende mostrar que o escoamento base do afluente Krom Antonies é uma fonte crítica de água de baixa salinidade, a qual também apoia actividades agrícolas economicamente importantes. Os resultados iniciais do modelo das águas subterrâneas de Krom Antonies sugerem que os regimes de bombeamento na bacia hidrográfica de Verlorenvlei estão próximos ou já na capacidade máxima. Isto sugere que alterações futuras nos regimes de bombeamento, devido a, por exemplo, mudanças nos padrões de uso das terras ou de precipitação, necessitariam de uma gestão cuidadosa, de modo a manter um fornecimento suficiente de escoamento base dos afluentes que alimentam o sistema estuarino de Verlorenvlei. As lições aprendidas nesta bacia hidrográfica serão aplicadas à bacia do Rio Buffels mais a Norte, a qual é pobre em dados, de modo a melhorar a nossa compreensão sobre a hidrologia da costa Oeste e sobre como será afectada no futuro pelas alterações climáticas.

Introduction

The west coast of South Africa is semi-arid in nature, and therefore has very low yearly rainfall, often significantly less than 400 mm, which severely limits both natural recharge to aquifers and the availability of surface water. As a result, water supply for both agricultural and domestic purposes is largely derived from groundwater. Aquifers in this coastal region tend to be (1) primary alluvial aquifers, comprising coastal sands, gravels, and other unconsolidated material, overlying (2) secondary basement aquifers typically of either granitic material or low primary-porosity sandstones, both with relatively low permeability, where groundwater

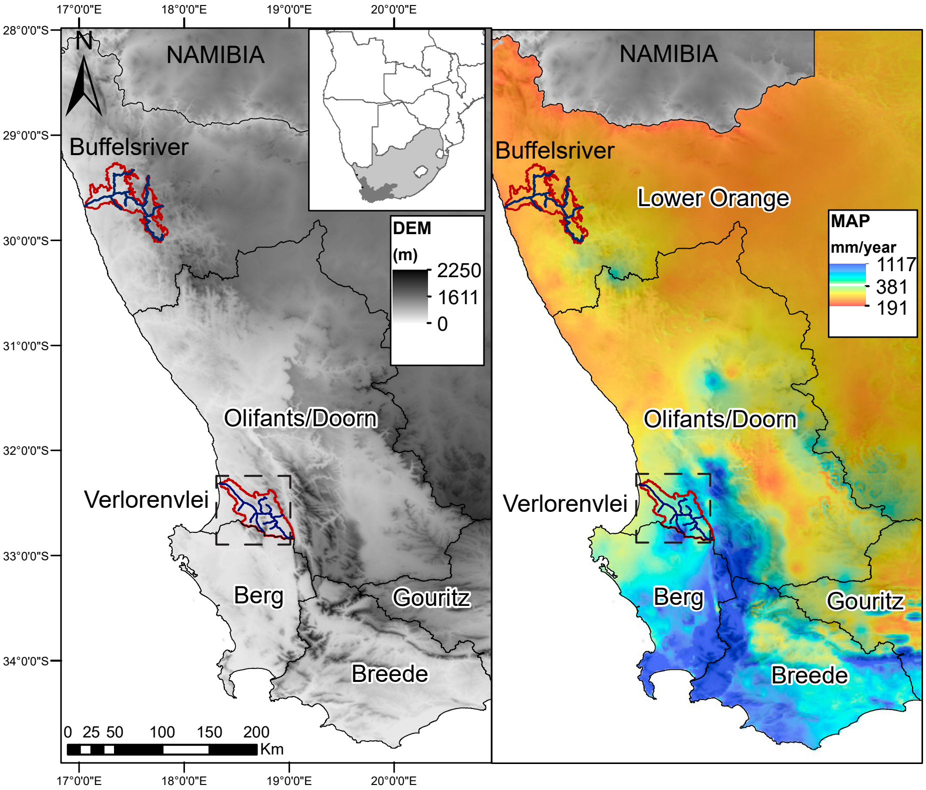

Figure 1: West coast of South Africa, showing catchment management areas for the Buffels, Olifants/Doorn, and Berg rivers as a function of topography (left panel) and mean annual precipitation (MAP) (right panel). Also shown in red are the Verlorenvlei and Buffels river drainage catchments and the location of the Sandveld region (black box) after Lewarne (2009). Inset map showing location of Fig. 1 within South Africa, with the Western Cape of South Africa shown as the darker grey shaded region.

movement is restricted to fractures. Although the unconsolidated, high-porosity nature of the primary aquifers theoretically facilitates rapid recharge, severe evaporative conditions generally result in mean annual recharge of less than 5% of mean annual rainfall (Adams et al., 2004). The net result is the development of moderately to severely saline groundwater associated with the alluvial aquifer systems, with potential contamination to the basement aquifers. The severity of salinization restricts the amount of groundwater that can be used in different regions. The only other viable sources of water are the three perennial west coast rivers, the Berg, the Oliphants, and the Orange rivers from south to north respectively (Fig. 1).

Despite the limitations in both the quantity and quality of available water resources, the west coast of South Africa is an important agricultural region and is host to a number of biodiversity hotspots. The most significant of these is the Verlorenvlei freshwater estuarine lake system, which lies to the north of the Berg River (Fig. 1). As part of the SASSCAL program, several weather and groundwater monitoring instruments have been installed in the Verlorenvlei catchment (Fig. 2) to better understand the interdependence of rainfall, groundwater recharge, as well as groundwater demand from the various stakeholders. In particular, a key objective is to place constraints on the ecological reserve (Hughes, 2001), the minimum amount of water needed to maintain the ecological health of the Verlorenvlei system. To this end, a detailed groundwater model is being developed. In this contribution, we outline the work that has been done to date in the Verlorenvlei system and discuss how the lessons learned in this catchment might be extrapolated to other west coast catchments with salinity problems, in particular the Buffels River catchment to the west of Springbok (Fig. 1), which is several hundred kilometres north of the Verlorenvlei catchment.

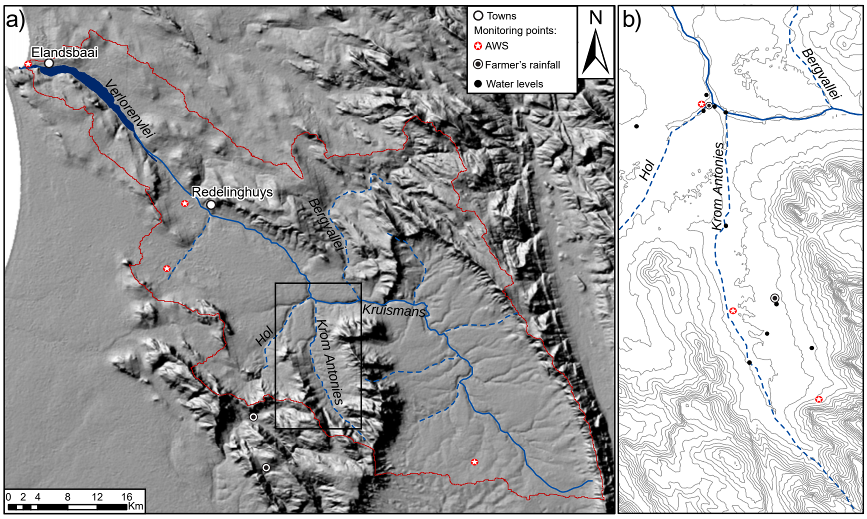

Figure 2: Detailed catchment map for the Verlorenvlei estuarine lake showing the locations of the different feeder tributaries and the regional weather stations. Right panel shows the location of borehole sensors installed as part of this project in the Krom Antonies subcatchment and their position relative to the two AWSs in the Krom Antonies subcatchment (after Watson et al., 2018).

The Verlorenvlei estuarine lake system

The Verlorenvlei estuarine lake system is located in the southern part of the Sandveld, a catchment along the southwestern coast of South Africa (Fig. 1). The area is dominated by sandy soils, and the major vegetation types are Strandveld and coastal Fynbos (Acocks, 1988). The environment has adapted to low rainfall conditions, where coastal rainfall rarely exceeds 400 mm/year, although at higher topographic elevations and further inland, rainfall may reach up to 800 mm/year (Lynch, 2004). The Verlorenvlei estuarine lake is a semi-freshwater lake with

Figure 3: The Verlorenvlei estuarine lake looking west towards the ocean. Photo courtesy of Brian Dyson.

an area of ~15 km^2 (Fig. 2). The lake's unique biodiversity, which is derived from its interaction between fresh and marine water, has resulted in the lake being RAMSAR listed. Rainfall distribution and volumes as well as groundwater abstractions in the catchment are thought to have a critical impact on the water quality and level within the lake (Sidigi et al., 2017; Watson et al., 2018). Decreases in the lake water level result in stagnant and saline conditions, favouring large algal blooms. Water levels have been recorded over the last 17 years, with critically low water levels recorded from 2003 to 2005 and more recently from 2015 to 2016 (Watson et al., 2018).

Hydrology

The estuarine lake is fed by four main rivers or tributaries. These are the Kruismans, Bergvallei, Hol, and Krom Antonies (Fig. 2). Previously, gauging stations existed along the Kruismans and the Hol rivers, but neither of these have been operational since 2009 although there is still active water-level monitoring within the estuarine lake close to Elandsbaai (Fig. 2). Despite no gauging stations currently operating on the Krom Antonies River, it is considered to be the most significant river in terms of both the quality and quantity of flow into the lake. The point on the Kruismans River where these three rivers join is termed the confluence. Below the confluence, the river is variably referred to as the Kruismans River or the Verloren River, but it essentially drains eastwards until the beginning of the actual lake west of Redelinghuis (Fig. 2).

Geology

The catchment geology consists of three major rock units. The oldest rocks in the area are the Neoproterozoic (~750–780 Ma) Malmesbury Group, represented by the Piketberg Formation composed of greywacke, sercitic schist, quartzite, conglomerate, and limestone (Rozendaal & Gresse, 1994). These rocks have been intruded by the Cambrian Cape Granite Suite. The youngest rocks in the catchment are the sedimentary rocks of the Cambrian Table Mountain Group, which overlie both the Malmesbury Group and the Cape Granite Suite. The Table Mountain Group in this area is dominated by three formations. The youngest of these is the Peninsula Formation, which is dominated by sandstones with varying amounts of conglomerate and quartz arenite along with minor shale and has an average thickness of 2000 m (Johnson et al., 2006). The Peninsula Formation is underlain by the Graafwater Formation, which consists of siltstone, shales, and minor sandstone, and has an average thickness of 430 m (Johnson et al., 2006). The Piekenierskloof is the oldest of the Table Mountain Group formations and is made up of coarse-grained sandstone, mudrock, and conglomerates (Johnson et al., 2006).

Hydrogeology

There are three aquifer units within the study area: (1) a primary alluvial aquifer, (2) a secondary aquifer made of shales that have some characteristics of a fractured rock aquifer, and (3) the Table Mountain Group aquifer, which is a fractured rock aquifer. The primary aquifer is made up of quaternary sediments dominated by coarse-grained, clean sand up to 15 m thick, suggesting a high-yielding primary aquifer. Previous recharge estimations for the primary aquifer are between 0.2 and 3.4% of rainfall (Conrad et al., 2004). The secondary aquifer, which underlies the primary aquifer, is made up of Malmesbury Group shales and has a transmissivity of between 0.07 and 7 m^2/day where the aquifer is around 70 m thick (SRK, 2009). The weathering zones, bedding, and fault planes are structural features that control groundwater flow in the secondary aquifer (Conrad et al., 2004). In addition to these two aquifer systems, the Table Mountain Group rocks, which make up the Piketberg Mountains in the hinterland to the Verlorenvlei lake, also constitute a fractured rock aquifer system, where estimates of transmissivity for the Peninsula Formation vary between 15 and 200 m^2/day (Weaver et al., 1999). Groundwater recharge is thought to occur primarily within the high-relief areas dominated by the Table Mountain Group aquifer (Conrad et al., 2004; Eilers, 2018; Watson et al., 2018), similar to other high-lying regions within the Western Cape.

Climate

In the Piketberg Mountains, where the Krom Antonies River originates, the mean annual precipitation (MAP) is around 537 mm/year (Lynch, 2004) (Fig. 3) but can be as high as 800 mm/year. Rainfall declines moving northeast from the Piketberg Mountains, reaching a low of 210 mm/year at the mouth of Verlorenvlei, which is around 50 m above sea level (Lynch, 2004). In summer, daily average air temperatures vary between 17 and 23°C with mean evaporation rates between 5.5 and 7.35 mm/day (Schulze et al., 2007). During winter, daily average air temperatures are between 8 and 13°C, resulting in lower evaporation rates of between 1.5 and 2.3 mm/day (Schulze et al., 2007).

Land use

Agriculture in the Sandveld is the major water user in the area, accounting for 90% of the total water requirements. Potatoes are the main food crop grown in the region, accounting for over 6,600 hectares and using around 20% of total annual recharge (DWAF, 2003). Potatoes in the Sandveld are usually grown in sandy soils, resulting in high yields but requiring high water and fertiliser usage. Tea is the second most grown crop in the catchment, making up around 5,000 hectares (DWAF, 2003), but the majority of the water used is during processing. These crops are also planted in sandy soils and are generally rainfed, and therefore have a limited impact on water resources. Other agricultural activities are citrus and viticulture, which are also high water users. Natural vegetation is also used for livestock grazing.

Data collection

As part of the SASSCAL program, physical infrastructure installed in the catchment was used to capture daily climatic fluctuations as well as groundwater and soil-water responses. Climatic conditions were measured at the confluence of the Krom Antonies, the Hol, and the Kruismans rivers using an Adcon Telemetry automatic weather station (AWS) (Fig. 4a; Muche et al., 2018) and at the foot of the Piketberg Mountains using a Mike Cotton Systems AWS (Fig. 4b). Groundwater was monitored and sampled in the primary and secondary aquifers. In the primary aquifer, 21 piezometers were sampled quarterly, while the water levels and the temperatures in four of these were monitored continuously using pressure transducers (Fig. 4c). In the secondary aquifer, 50 boreholes were sampled quarterly, while the water levels and temperatures in six of these were monitored continuously using pressure transducers. Soil moisture, temperature, and electrical conductivity were monitored at the top (Fig. 4d), middle, and bottom (Fig 4e) of a hillslope near the confluence using Hydraprobes that were installed at different soil textural horizons. Soil textural horizons were matched as best as possible between the three positions (top, middle, and bottom slope) such that different horizons could be traced between the three monitoring locations. Trenches were dug into the soil horizons, the soil moisture probes were installed in groups of three into three different soil horizons on the undisturbed faces of the trenches, and the trenches were subsequently backfilled. Quarterly field trips were undertaken to collect samples, download data, and maintain the instruments.

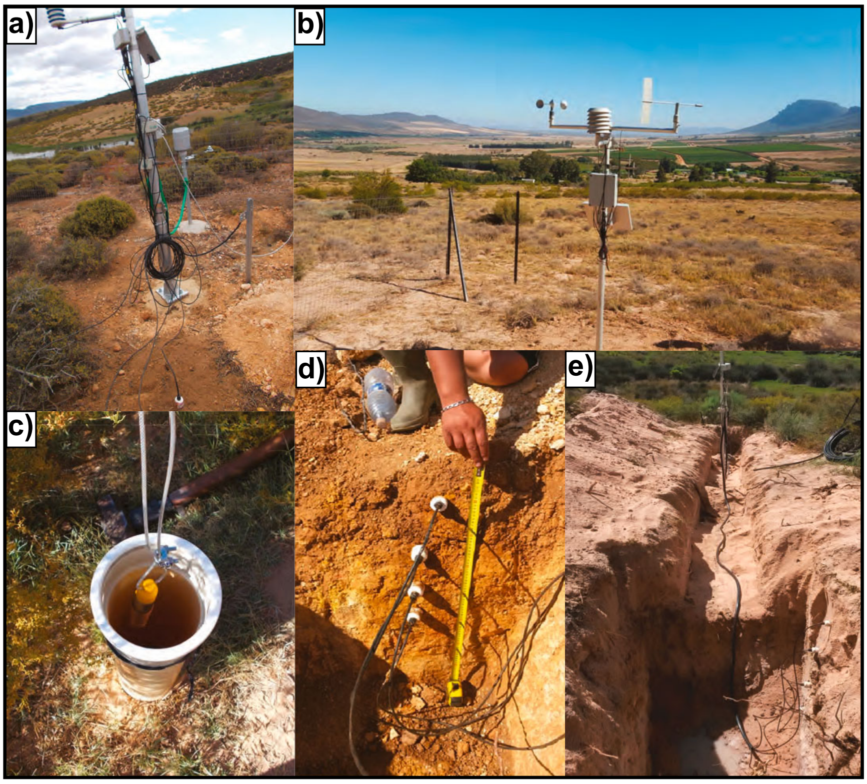

Figure 4: (a) and (b) examples of the AWSs installed in the catchment; (c) type of piezometer with pressure sensor installed in the tributaries to the Verloren River; (d) and (e) installation setup of soil moisture probes. See text for further description of soil moisture probes.

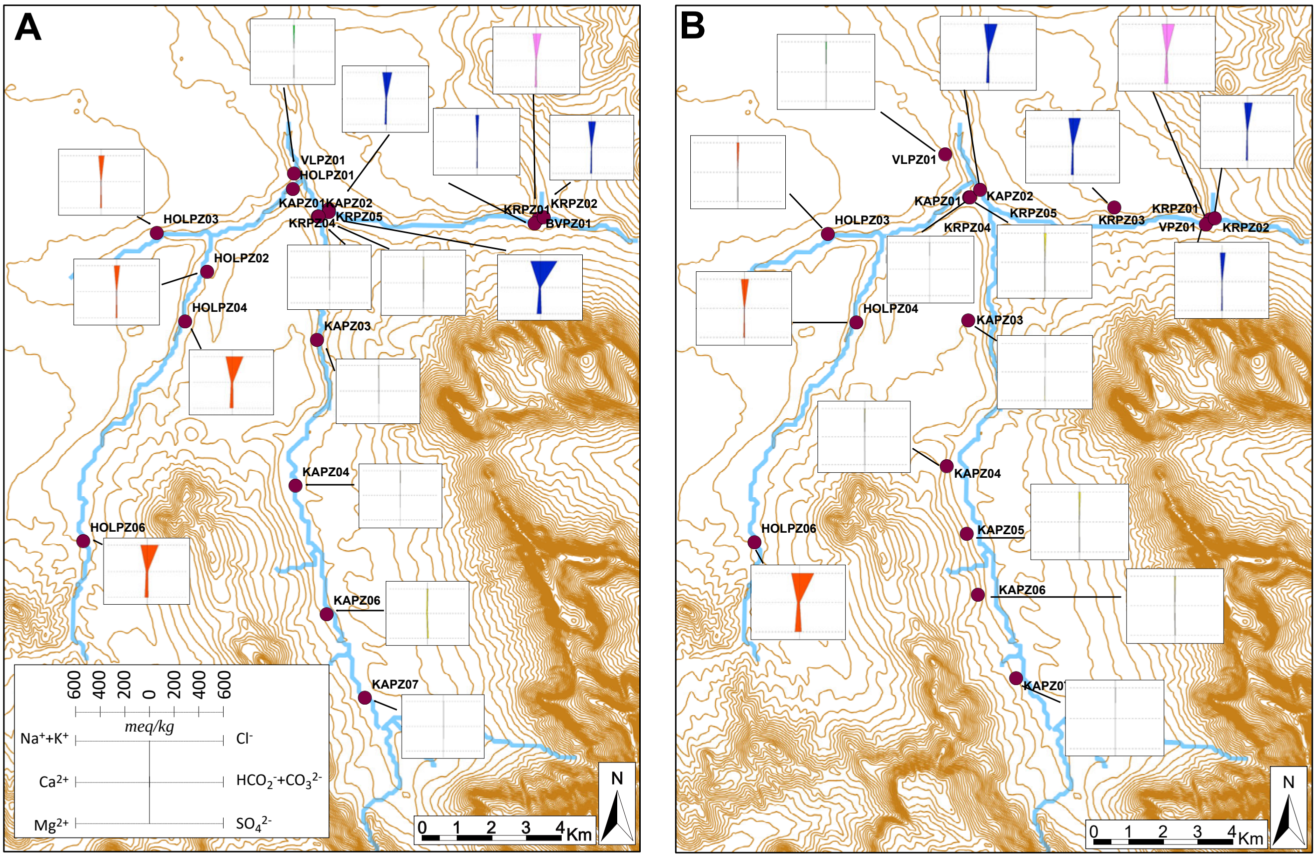

Figure 5: Stiff diagrams showing composition of the shallow groundwater system in the primary aquifer along the four tributaries examined in this study, where panel (a) is for November 2015 (dry season) and panel (b) is for June 2016 (wet season). Note that all stiff diagrams are plotted on the same scale so that relative differences in salt concentrations can be compared. Thus, the stiff diagrams for the Krom Antonies, for example, are very thin because of the low-EC nature of these waters. See lower left box for actual scale on stiff diagrams. HOL = Hol River; KA = Krom Antonies River; KR = Kruismans River; BV = Bergvallei River; VL = Verloren River (Confluence); PZ = Piezometer. Therefore KAPZ04 is piezometer number 4 in the Krom Antonies River. See Fig. 2 for locations.

Results

Surface water and shallow groundwater quality

Surface water and shallow groundwater have similar salinity characteristics in the Verlorenvlei catchment and are generally distinct from the deeper, fresher groundwater system. The Kruismans River has the highest electrical conductivity (EC), ranging from 200 mS/m to 500 mS/m. EC in the Hol River ranges between 400 mS/m and 1,500 mS/m, whilst the EC in the Bergvallei River is between 500 mS/m and 800 mS/m. The Verloren River along with the Krom Antonies River record the lowest salt loads, with EC values between 80 mS/m and 300 mS/m. EC decreases during the rainy season and increases during the dry season for both surface and shallow groundwater, but the surface waters show overall lower concentrations of major cations and anions in comparison to the shallow groundwater. Ions decrease in the order $Na^+ > Cl^- > Mg^{2+} > Ca^{2+} > SO_4^{2-} > HCO_3^- > K^+$ and were used to characterise the geochemical facies of shallow groundwater and surface water for each tributary in the Verlorenvlei catchment. Generally, surface water and shallow groundwater from the Kruismans, Bergvallei, Verlorenvlei, and Hol belong to the same Na-Cl water type. Some samples upstream from the Hol have a Na-Cl-SO_4 water type, while some shallow groundwater samples collected from the same tributary have a Na-Mg-Ca-Cl water type. The Krom Antonies surface water showed a Na-Ca-Mg-Cl water type although some samples had a stronger SO_4^- component and some a stronger HCO_3^- component. Stiff diagrams for all samples though showed a pattern indicative of saline groundwater (Fig. 5). These patterns are similar to the deeper groundwater system in the secondary aquifer underlying the primary aquifer, although the overall ionic strengths are considerably lower than in the shallow primary aquifer (Fig. 6). For the secondary aquifer, average EC values are 74 mS/m for the Kruismans, 123 mS/m for the Krom Antonies, and 147 mS/m for the Hol.

Recharge and groundwater modelling

As part of the goals of this project, a groundwater model will be constructed for the Krom Antonies subcatchment to assess the degree to which the ecological reserve is being met whilst pumping stresses are being applied to the system by the agricultural sector. This groundwater model is being developed based on a detailed analysis of the catchment, taking into account a variety of ranked factors that influence groundwater flow. Spatial and temporal estimations of recharge are essential to the development of this model. In this study, the J2000 rainfall/runoff model was used to estimate daily recharge for the Verlorenvlei catchment (Watson et al., 2018). Based on the results of the recharge modelling, a conceptual model for groundwater flow was developed.

Rainfall/runoff modelling

The J2000 rainfall/runoff model calculates percolation rates by means of simulating processes within the Verlorenvlei catchment. The model includes the following main process steps in calculating recharge: (1) the model subtracts the vegetation interception capacity from rainfall to get net rainfall, (2) runoff water is subtracted from net rainfall based on rainfall intensity and infiltration capacity of the soil, (3) evapotranspiration is supplied by soil moisture and the remaining water is routed further to interflow or recharge, (4) interflow is simulated based on slope factor and the maximum daily soil percolation, and (5) the remainder is allocated to simulated recharge. The J2000 model makes use of hydrological response units (HRUs) for distributed hydrological modelling (Flügel, 1995). The Verlorenvlei catchment was divided into HRUs based on homogenous physiological and topographical features. Soil and climate properties are assigned to each HRU based on available field and literature data. Climate data for the model, including air temperature, relative humidity, wind speed, solar radiation, and rainfall, were obtained from nine weather stations throughout the study catchment. Potential evaporation was calculated using the Penman Monteith evaporation equation, using the above climate data and including a vegetation crop factor. Potential evaporation is assigned to each HRU based on the closest climate monitoring station. To assign rainfall to each HRU, a rainfall correction factor was used, which correlated rainfall with elevation. Farmers' rainfall records were included to improve the rainfall network distribution. The model was calibrated using gauging records from station G3H001 using measured data from 1989 to 2006 (Watson et al., 2018).

Modelled percolation results

The percolation results suggest that simulated potential recharge is higher than that previously estimated (Conrad et al., 2004). Simulated potential recharge values within the catchment varied between

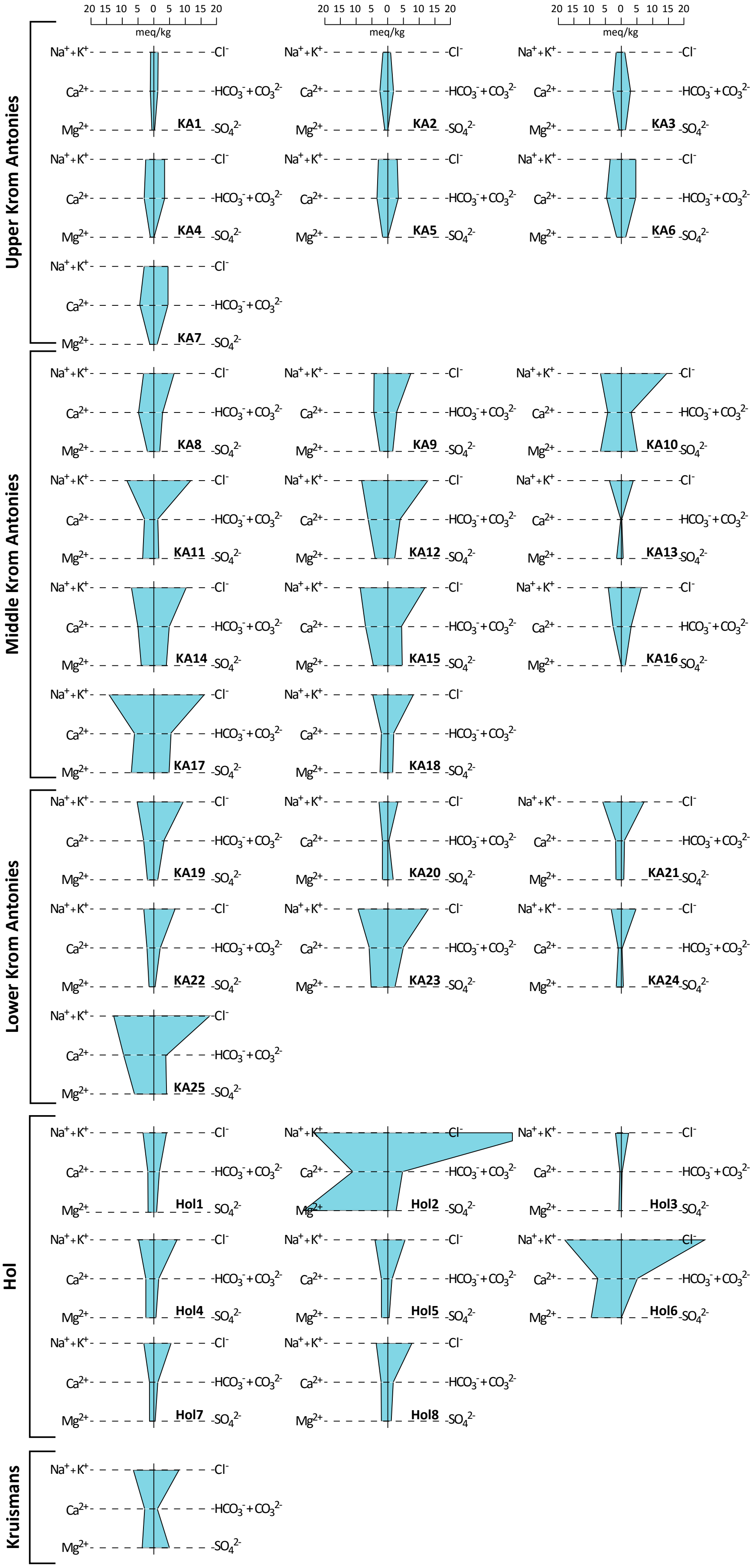

Figure 6: Stiff diagrams showing composition and concentration of cations and anions in the deeper groundwater system within the secondary aquifer. Sample number letters are as per Fig. 5. Low numbers indicate high up in the catchment and higher numbers indicate lower in the catchment towards the confluence.

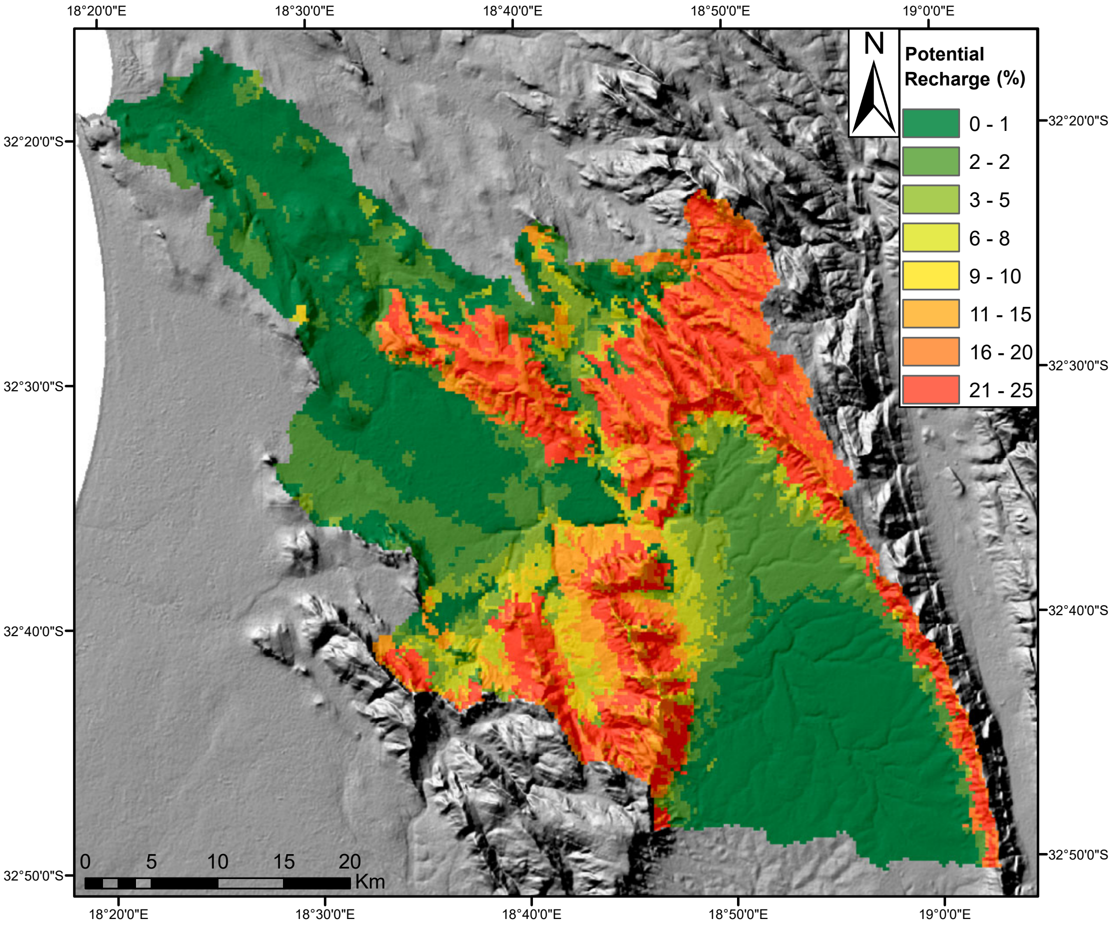

Figure 7: Daily percolation outputs as a function of % median annual rainfall (which equates to potential groundwater recharge rate) for the different hydrological response units (HRUs) defined in the Verlorenvlei catchment.

a median range of 0.7% to 25.12% of rainfall (Fig. 7; Watson et al., 2018). The daily timestep nature of the J2000 model, which incorporates a daily mass balance of evapotranspiration and rainfall, results in higher yearly estimates of potential recharge than from methods such as chloride mass balance or GIS approaches. Daily mass balances allow for higher recharge estimates during winter because of the abundance of rainfall and lower evaporation rates. This result is significant because it explains the apparent discrepancy between the very low calculated recharge rates in semi-arid catchments, through the application of yearly averaging approaches, and the apparent ecological sustainability of most semi-arid catchments.

Although the results above suggest that the system receives more recharge than previously estimated, groundwater abstraction volumes should take into account the needs of the environment. The ecological reserve, which defines the quality and quantity of water needed to sustain the environment, has both peak and low flow requirements. The most critical issue in Verlorenvlei is the impact that groundwater abstractions have on low flows, as these are supplied primarily via groundwater baseflow at times when recharge is low to negligible.

Defining the conceptual groundwater model

The modelled percolation results presented above were used to define a conceptual groundwater model. The main objective of the groundwater model is to understand the maximum pumping volumes possible that will still maintain the ecological reserve during low flow periods. The Krom Antonies catchment is considered to be the main source of groundwater and baseflow to the Verlorenvlei lake system and hence the groundwater model is being developed for this subcatchment of the Verlorenvlei first. The distribution of rainfall across the Krom Antonies catchment is such that the majority of rainfall (450–800 mm/year depending on location within the catchment) is received in the Piketberg Mountains, and the lowest rainfall (210–450 mm/year) is received in the valley of the catchment (Fig. 1b). As a result, the majority of recharge is generated in the Table Mountain Group aquifer in the Piketberg Mountains, where rainfall exceeds evapotranspiration. Very little recharge is received in the primary aquifer located in the valleys, where evapotranspiration exceeds net rainfall. The Table Mountain Group aquifer conveys recharge into the secondary aquifer, which thereafter supplies groundwater flow to the primary aquifer. During the wet season, streamflow is generated primarily from surface runoff in the mountains and valley. Rainwater that is unable to percolate through the Graafwater and Malmesbury shale aquitards also contributes to streamflow. During the dry season, groundwater baseflow is responsible for

Figure 8: The Buffels River catchment looking down from the edge of the escarpment about 50 km west of Springbok.

supplying water to the streams within the catchment. The Krom Antonies subcatchment behaves as though it is a gaining stream, where the groundwater levels in the primary and secondary aquifers allow for baseflow to be generated. When pumping stresses are applied to either the primary or the secondary aquifer, the lowering of the groundwater levels is likely to reduce groundwater baseflow.

Summary and future work

The installation of weather and borehole sensors to model potential recharge and baseflow from the Krom Antonies has facilitated an understanding of the maximum possible recharge volumes that this subcatchment can receive. The use of a daily timestep function in the recharge estimations from the J2000 model produces annual potential recharge estimates that are higher than previous estimates (by up to a factor of 3), with net recharge being less than previous estimates (by a factor of 2 in mountainous regions). Future groundwater modelling using these data, along with delineated aquifer hydraulic conductivities, aquifer storage properties, and localised and regional baseflow, will aim to provide quantitative estimates of the sustainable pumping regimes for the agricultural sector in this region. Because the Krom Antonies has been considered the primary recharge area for the Verlorenvlei catchment as a whole, groundwater modelling in this part of the catchment will also be used to determine the minimum water flow (based on lake water level) and quality thresholds (based on WHO water quality guidelines) for the Verlorenvlei estuarine lake. One important constraint is the contribution that baseflow from the Bergvallei River has to the total flows into the estuarine lake. Although this river was initially thought to be a minor contributor, daily flow rates from the J2000 model suggest that the Bergvallei might contribute up to 20% of freshwater inflows to the estuarine lake, although it is not clear whether these inflows are coming from the shallow (moderately saline) or deep (less saline) groundwater systems. Ongoing work focusing on O, H, and Sr isotopes indicates that there may be a contribution from a Table Mountain Group aquifer system within the Bergvallei subcatchment and that this system is also critical in balancing saline inflows into the lake. Future work will evaluate the relative contributions of all the tributaries into the Verlorenvlei system through the ongoing development of a comprehensive numerical finite-difference (MODFLOW) groundwater flow model coupled to the J2000 outputs and using stream discharge rates and isotopic tracers to evaluate the model results. By coupling these two models together, the fully integrated results generated will provide a comprehensive assessment of the groundwater surface water interactions and flow volumes in the upper parts of the Verlorenvlei catchment. The J2000 model will be used to translate potential recharge received from rainfall into the primary and Table Mountain Group aquifers, while the MODFLOW model will translate potential recharge into a yearly net recharge value based on geological hydraulic conductivities and aquifer drawdown.

The Buffels River catchment

As can be seen from the Verlorenvlei case study, the construction of a groundwater model to determine the sustainability of groundwater abstraction generally requires a network of monitoring boreholes and detailed weather data. Due to the associated costs, many catchments, particularly in Africa, are data poor, and consequently groundwater models are not constructed or are poorly calibrated. Whilst a primary objective of this work is to develop a groundwater model for the Verlorenvlei catchment, the secondary objective is to test how transferable the model results will be to catchments where there are fewer monitoring data available. The Buffels River catchment (Fig. 8) in the Northern Cape of South Africa (Fig. 1) shares many similarities with the Verlorenvlei catchment. Both are semi-arid to arid coastal catchments where the dominant land use is agriculture and where groundwater is variably saline. Each consists of a primary aquifer overlying a secondary aquifer system consisting of fractured or crystalline rock. However, whereas the Verlorenvlei catchment is relatively well monitored, the Buffels River catchment is data poor, with limited weather-monitoring data and rainfall records, no long-term monitoring of water levels within the aquifer system, and no discharge data (actual or modelled) for the river and tributary networks. In spite of these limitations, ongoing groundwater sampling in the catchment has established the hydrochemical and isotopic character of the groundwater. EC levels in the Buffels River are moderately to extremely high, with maximum EC levels of ~1,900 mS/cm. High EC levels are recorded mostly in the alluvial aquifer, and groundwater from the secondary aquifer tends to be fresher, whilst isolated springs present in the region have the lowest EC levels. Sr, O, and H isotope data from both the primary aquifer and the secondary aquifer allow some constraints to be placed on relative flow paths and the role of fluid rock interaction, particularly with the granitic basement gneisses. Once the groundwater model for the Krom Antonies subcatchment described above has been developed and calibrated, it is intended to apply this model to the Buffels River catchment to establish the boundary conditions of the ecological reserve and to better understand the origin and spatial distribution of the saline groundwaters.

Conclusions

Establishing the boundary conditions of groundwater flow and understanding the distribution and transportation of groundwater salts are critical to enable the construction of accurate groundwater models for the west coast of South Africa. The installation of weather and groundwater monitoring equipment in the Verlorenvlei catchment has been essential in the development of a comprehensive conceptual model that forms the foundation for development of a groundwater model for the Krom Antonies subcatchment. The most critical step in this process was the detailed characterisation of recharge through the calculation of daily percolation rates using the J2000 model. The paradox of low recharge rates but apparent sustainability of semi-arid and arid catchments can potentially be resolved by this daily timestep approach. However, groundwater models need proper geochemical and physical characterisation of the groundwater system in order to be accurately constructed and calibrated. In the Verlorenvlei catchment, modelled discharge rates for the different tributaries were combined with isotope characterisation of the primary and secondary aquifers to understand the role of each tributary. Preliminary results have indicated that although the Krom Antonies has historically been considered the primary source of freshwater inflows to the Verlorenvlei lake system, additional inflows from the Bergvallei tributary are more important than previously thought. Early results of the Krom Antonies groundwater model suggest that pumping regimes in the Verlorenvlei catchment are at or near maximum capacity. Thus, future changes in pumping regimes through, for example, changes in land use patterns or precipitation patterns would need to be carefully managed to maintain sufficient baseflow supply to the tributaries feeding into the Verlorenvlei estuarine lake system. The groundwater model developed for the Verlorenvlei region will be further evaluated by assessing the transferability of the groundwater model to the Buffels River catchment, where similar boundary conditions exist (mean annual precipitation, evapotranspiration rates, recharge rates, salinity profiles, etc.) and the same suite of isotopic tracers exist (O, H, Sr), but few monitoring data are available. Establishing the transferability of such a groundwater model would be a valuable step in understanding the groundwater dynamics in catchments that have even fewer data available, a situation that is still too common in large parts of Africa.

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References

Acocks, J. (1988) *Veld types of South Africa*, 3rd edition. Memoirs of Botanical Survey of South Africa 57.

Adams, S., Titus, R. & Xu, Y. (2004) *Groundwater recharge assessment of the basement aquifers of central Namaqualand*. Water Research Commission Report 1093/1/04, Pretoria, South Africa.

Conrad, J., Nel, J. & Wentzel, J. (2004) The challenges and implications of assessing groundwater recharge: a case study – northern Sandveld, Western Cape, South Africa. *Water SA*, **30**, 75–81.

DWAF (2003) *Sandveld preliminary (rapid) reserve determinations. Langvlei, Jakkals and Verlorenvlei Rivers. Olifants-Doorn WMA G30.* Surface Volume 1: Final Report Reserve Specifications. DWAF Project Number 2002-227.

Eilers, A. (2018) Deep groundwater characterisation and recharge estimation in the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Flügel, W. (1995) Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrological Processes*, **9**, 423–436.

Hughes, D.A. (2001) Providing hydrological information and data analysis tools for the determination of ecological instream flow requirements for South African rivers. *Journal of Hydrology*, **241**, 140–151.

Johnson, M.R., Anhauesser, C.R. & Thomas, R.J. (2006) *The geology of South Africa*. Geological Society of South Africa, Pretoria, 691

Lewarne, M. (2009) Setting up ARCSWAT hydrological model for the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Lynch, S. (2004) *Development of a raster database of annula, monthly and daily rainfall for southern Africa*. Water Research Commission Report 1156/1/04, Pretoria, South Africa.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: history, state of Measuring Network, database and online presentation, challenges & success. This volume.

Rozendaal, A. & Gresse, P.G. (1994) Structural setting of the Riviera W-Mo deposit, Western Cape, South Africa. *South African Journal of Geology*, **97**, 184.

Schulze, R.E., Maharaj, M., Warburton, M.L., Gers, C.J., Horan, M.J.C., Kunz, R.P. & Clark, D.J. (2007) *South African atlas of climatology and agrohydrology*. Water Research Commission Report 1489, Pretoria, South Africa.

Sidigi, N.T., Miller, J.A., Watson, A.P., Clarke, C.E., & Butler, M. (2017) Geochemical and isotopic tracing of salt loads into the RAMSAR listed Verlorenvlei estuarine lake, South Africa. *Procedia Earth and Planetary Science*, **17**, 909–912.

SRK (2009) *Preliminary assessment of impact of the proposed Riviera Tungsten Mine on groundwater resources*. SRK Consulting, Rondebosch, South Africa.

Watson, A., Miller, J., Fleischer, M. & de Clercq, W. (2018) Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa. *Journal of Hydrology*, **558**, 238–254.

Weaver, J., Talma, A. & Cave, L. (1999) *Geochemistry and isotopes for resource evaluation in the fractured rock aquifers of the Table Mountain Group*. Water Research Commission Report 481/1/99, Pretoria, South Africa.

References [CrossRef]

Acocks, J. (1988) *Veld types of South Africa*, 3rd edition. Memoirs of Botanical Survey of South Africa 57.

Adams, S., Titus, R. & Xu, Y. (2004) *Groundwater recharge assessment of the basement aquifers of central Namaqualand*. Water Research Commission Report 1093/1/04, Pretoria, South Africa.

Conrad, J., Nel, J. & Wentzel, J. (2004) The challenges and implications of assessing groundwater recharge: a case study – northern Sandveld, Western Cape, South Africa. *Water SA*, **30**, 75–81.

DWAF (2003) *Sandveld preliminary (rapid) reserve determinations. Langvlei, Jakkals and Verlorenvlei Rivers. Olifants-Doorn WMA G30*. Surface Volume 1: Final Report Reserve Specifications. DWAF Project Number 2002-227.

Eilers, A. (2018) Deep groundwater characterisation and recharge estimation in the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Flügel, W. (1995) Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrological Processes*, **9**, 423–436. CrossRef

Hughes, D.A. (2001) Providing hydrological information and data analysis tools for the determination of ecological instream flow requirements for South African rivers. *Journal of Hydrology*, **241**, 140–151. CrossRef

Johnson, M.R., Anhauesser, C.R. & Thomas, R.J. (2006) *The geology of South Africa*. Geological Society of South Africa, Pretoria, 691

Lewarne, M. (2009) Setting up ARCSWAT hydrological model for the Verlorenvlei catchment. MSc thesis, Stellenbosch University.

Lynch, S. (2004) *Development of a raster database of annula, monthly and daily rainfall for southern Africa*. Water Research Commission Report 1156/1/04, Pretoria, South Africa.

Muche, G., Kruger, S., Hillmann, T. et al. (2018) SASSCAL WeatherNet: history, state of Measuring Network, database and online presentation, challenges & success. This volume. CrossRef

Rozendaal, A. & Gresse, P.G. (1994) Structural setting of the Riviera W-Mo deposit, Western Cape, South Africa. *South African Journal of Geology*, **97**, 184.

Schulze, R.E., Maharaj, M., Warburton, M.L., Gers, C.J., Horan, M.J.C., Kunz, R.P. & Clark, D.J. (2007) *South African atlas of climatology and agrohydrology*. Water Research Commission Report 1489, Pretoria, South Africa.

Sidigi, N.T., Miller, J.A., Watson, A.P., Clarke, C.E., & Butler, M. (2017) Geochemical and isotopic tracing of salt loads into the RAMSAR listed Verlorenvlei estuarine lake, South Africa. *Procedia Earth and Planetary Science*, **17**, 909–912. CrossRef

SRK (2009) *Preliminary assessment of impact of the proposed Riviera Tungsten Mine on groundwater resources*. SRK Consulting, Rondebosch, South Africa.

Watson, A., Miller, J., Fleischer, M. & de Clercq, W. (2018) Estimation of groundwater recharge via percolation outputs from a rainfall/runoff model for the Verlorenvlei estuarine system, west coast, South Africa. *Journal of Hydrology*, **558**, 238–254. CrossRef

Weaver, J., Talma, A. & Cave, L. (1999) *Geochemistry and isotopes for resource evaluation in the fractured rock aquifers of the Table Mountain Group*. Water Research Commission Report 481/1/99, Pretoria, South Africa.