Understanding of Surface Water-Groundwater Interactions from Headwaters to Lowlands or Catchment Scale Sustainable Water Resources Management

Report to the
Water Research Commission

by

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WRC Report No. 2855/1/22
ISBN 978-0-6392-0492-5

October 2022

Obtainable from
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EXECUTIVE SUMMARY

BACKGROUND

An integrated water resources management (IWRM) approach has been adopted by most countries, and this is reflected in their policies and legislation. This approach requires that despite water occurring in various forms in a catchment, allocation and utilisation of this resource should reflect that the different forms of water are linked. This includes the integration of management of both surface water and groundwater in a catchment. Management may entail abstraction, diversion, storage, or modification of water quality. In those parts of the world where the use of either surface water or groundwater has had adverse effects on the other, consideration of the linkages between these two has been enforced as a result of litigation by those adversely affected. This has been particularly the case where unregulated use of water from both rivers and connected alluvial aquifers occur. In catchments or countries where there is limited knowledge about the nature of connectivity between rivers and aquifers, an integrated approach to the management of surface water and groundwater has been embraced but without implementation.

There is generally limited knowledge about the nature and spatiotemporal dynamics of interactions between surface water and groundwater, especially in areas with fractured aquifers. Several studies have been carried out about these interactions at the river reach scale. However, extrapolating site-specific results to different parts of the river from headwaters, midslope, to lowlands often leads to an inaccurate representation of the interactions. Changes in topography, the composition of the hyporheic zone, riparian vegetation, and hydrogeological characteristics along a river affect surface water-groundwater interactions. In regions with distinct wet and dry seasons, these interactions may vary at event-, seasonal- and annual time scales. Knowledge about the nature of the interactions, and factors accounting for their spatiotemporal dynamics at the catchment scale is required to inform integrated water resources management approaches. Without this knowledge, water managers embrace IWRM but are constrained from translating policy into practice. This study aims to contribute knowledge about the spatiotemporal dynamics of surface water-groundwater interactions at the catchment scale from headwaters to lowlands along the Nuwejaars River in Cape Agulhas.

AIMS

The following were the aims of the project:

1. To establish the nature of surface water-groundwater interactions from headwaters to lowlands.
2. To determine how surface water-groundwater interactions influence the spatial and temporal variations of available water resources in terms of quantity and quality at the catchment scale.

3. To examine how surface water-groundwater interactions influence ecosystems from headwaters to lowlands.
4. To explore options for managing surface water-groundwater interactions at the catchment scale, and how these options can be integrated in a catchment management plan.

METHODOLOGY

The study was carried out in the Nuwejaars Catchment located within the Cape Agulhas area. The catchment area is 784 km^2 with altitude varying from 100-654 m above sea level in the headwaters or uplands, 41-100 m in midslopes, and 7-40 m in lowlands. The study used a combination of hydrological, hydrogeological, hydraulic, hydrochemical and isotopic methods. Hourly weather data were collected from fiver automatic weather stations. These data were used to estimate inputs (rainfall) into and outputs (evapotranspiration) from surface water and groundwater. Spatial and temporal variations of river flows were determined from measurements of river water levels at 5 stations. River discharges were estimated using a rating curve established for a gauging station in the lowlands. Analysis of seasonal patterns of river flows gave an indication of possible groundwater contribution to river flows. Baseflow separation using a digital filter and conductivity mass balance methods was then carried out to give an indication of the possible order of magnitude of groundwater contribution to river flows.

Six sites, each close to a stream, were selected for detailed investigations of surface water-groundwater interactions. At each site electrical resistivity and gravimetric surveys were conducted to infer possible occurrences of aquifers along a transect sloping towards a stream. Based on the results of the geophysical survey, 2 to 8 monitoring boreholes with different depths were drilled at each site, with the total being 25 boreholes. Depending on the underlying formation, monitoring boreholes for shallow aquifer had depths of 6-20 m, while 50-100 m was for deep aquifers. The lithology at each site was determined from drilling logs. Water level loggers collecting data at an hourly interval were installed in some of the monitoring boreholes at each site. For boreholes without loggers, monthly static water level measurements were done. Changes over time of water table depth enabled an assessment of the response of both shallow and deep groundwater to rainfall. A comparison of the altitude of the water table with that of the nearest river bed was used to assess the potential for groundwater discharging into a nearby river, or the river recharging groundwater.

Surface water samples for hydrochemical analysis were collected monthly at 24 sites along tributaries and the Nuwejaars River. Rainwater for hydrochemical analysis was also collected at 3 weather stations. Similarly, water samples were collected monthly from 25 monitoring boreholes and 3 springs. Water temperature, pH, dissolved oxygen, and electrical conductivity were measured in the field. All the water samples were analysed for major ions in order to determine possible interactions between surface water and groundwater. The same river sites and monitoring boreholes were used for collecting monthly samples for stable isotope analysis (H2 and O18) and radon analysis.

The potential effects of invasive alien plants, especially the *Acacia longifolia*, occurring in riparian and non-riparian zones on surface water-groundwater interactions were investigated at four sites, representing lowlands, midslope and headwaters. The Moddervlei site with altitude of 21 m is a lowland site about 10 from Nuwejaars River. Another riparian site had an altitude of 66 m and located about 3 m from the Jan Swartskraal River. Other sites are located on hillslopes; Spanjaardskloof, altitude 145 m, and Sandfontein at 228 m. At each of these sites, water use was monitored on selected trees using the heat pulse velocity of the heat ratio method Monitoring of water use by the indigenous fynbos was done using an eddy covariance system installed at Tussenberge, with an altitude of 217 m.

RESULTS AND DISCUSSION

River flows

The Nuwejaars Catchment receives rainfall throughout the year, however 51% of the rainfall occurs during the May to August period. The December to March period is the driest and on average receives 21% of the annual rainfall. While rainfall can occur anytime during the year, 67% of the days are dry and rainfall only exceeds 10 mm/day during 5% of the days. The catchment received 437 mm/yr in 2018 and 818 mm/yr in 2020. The average annual reference evapotranspiration rate is 1140 mm/yr which is greater than the rainfall as expected in this semi-arid region. During summer, December to February daily reference evapotranspiration rates average 5.0 mm/day, while in the wet winter, May to July, this is 1.5 mm/day.

River flows are highly variable in both space and time. Streams in the headwaters are perennial an indication that they benefit from groundwater discharge, while in the midslope region, the river becomes non-perennial with no flow for 60% of the time particularly during the December to May period. Pools along the Nuwejaars River within the Moddervlei floodplain have water throughout the year except during severe droughts (e.g. 2017-2018). At the end of the floodplain, the lowland Nuwejaars River dries for about 35% of the time especially during the January-May period. Baseflow separation suggests that subsurface water contributes about 21% to 35% of the river flows. The occurrences of in- and off-channel pools within the floodplain in the lowland and from which water can drain back into the main channel leads to an over-estimation of baseflow contributions.

Water table

All the monitoring boreholes in the headwaters were drilled through sandstone. At the midslope site, adjacent to the Jan Swartskraal River, shale occurred 1-50 m. At Moddervlei, the lowlands site, clay occurred at the top up to 20 m and underlain by shale. The depth to the water table varies seasonally at all the sites. Water tables generally rise by about 1.0-3.0 m from July to October as a response to the winter rainfall, and then decline during the November/December to May/June period. Water tables of deep boreholes (50 m) in the headwaters (Tussenberge, Sandfontein) were above those of shallow boreholes (6-20 m), and became artesian during the wet season which suggests that they recharge zones located upslope. However, at each location all boreholes have similar variation over time of the water table depth and without any lagging. Within the headwaters, the water table was always above nearby river beds indicating a potential for the streams to gain from groundwater. In the midslope sections of the Nuwejaars River, the water table is below the river bed, and thus the river cannot benefit from groundwater discharge. In the lowlands the water table was higher than the river bed during the wet season but lower during the dry seasons.

Hydrochemistry

Streams in the uplands have acidic water while this changes to alkaline conditions in the lowlands. The major cations in both surface water and groundwater are Na>Mg>Ca>K, and anions are $Cl>SO_4>HCO_3$. Hydrochemical characteristics of surface water are influenced by groundwater discharge into streams in the uplands, while this is reduced in the lowlands. Stable isotopes revealed rainfall being the major source of groundwater recharge. In the uplands isotopic signatures of surface water and groundwater are similar indicating groundwater discharge. Radon data showed that groundwater discharged into upland streams while in the lowlands, the contribution is minor.

Aquatic fauna

The objectives of the faunal study were i) to identify instream faunal assemblages in the Nuwejaars River and from this, ii) find diversity patterns matching identified sections of the stream where ground- and surface waters interact. The project was compromised by the drought, during which time we were unable to sample. The following conclusions can be reached, however.

- Forty-two families of invertebrate, and three species of native fish, were collected, demonstrating the considerable biodiversity of a river and its tributaries in an area experiencing increasing aridity as a result of climate change. Some of these taxa will be useful indicators of ecosystem condition as changes in climate accelerate.
- A relatively short cessation of flow had little demonstrable effect on the invertebrate community, suggesting that numerous species of aquatic invertebrates and fish can survive in pools even in non-perennial systems.
- Sampling of the hyporheos might prove useful for investigating groundwater-surface water interactions in rivers like the Nuwejaars. A report is appended on the potential of using hyporheic invertebrates in further assessment of these interactions.

Tree water use

Fynbos shrubs and cultivated lands are the dominant land covers in the catchment. The extent of IAPs has declined from 25% to 11% as a result of clearing activities such as the “Working for Water” and the Nuwejaars Wetland Special Management Area forum in the catchment. Water use by *Acacia longifolia* was quantified along a topographic gradient. The results showed riparian *A. longifolia* stand consumed 41% (1 537 mm) more water than the non-riparian *A. longifolia* stand (914 mm). The differences among the non-riparian *A. longifolia* were also observed, where transpiration rates from the stand on the headwaters (Sandfontein) were higher than transpiration rates at Spanjaardskloof (non-riparian upland). These differences were attributed to the differences in depths to the water tables and soil water contents. Thus, it was evident that water use patterns by riparian and non-riparian *A. longifolia* stands were driven by water availability. Even though *A. longifolia* trees are shallow-rooted, but diurnal variations in the water tables from the borehole close to the sap flow monitoring stations were observed. Thus, suggesting the rate of water use by *A. longifolia* was faster than groundwater inflow, hence, affecting the water table.

The impact of IAPs on the water resources was observed by upscaling and comparing water use by riparian and non-riparian *A. longifolia* with that of indigenous fynbos stand. The upscaled results showed riparian and non-riparian *A. longifolia* used 38% and 12% respectively more water than the fynbos. Thus IAPs have higher rates of water use than the indigenous fynbos. High rates of use by IAPs were also observed through remote sensing. Actual evapotranspiration (AET) estimated using the SEBS model revealed spatial variation across the different land covers; with areas dominated by IAPs having higher water use rates than the other land cover types.

GENERAL

The study achieved the main objectives as river stretches with significant groundwater contributions were identified, and the nature of these contributions established.

CONCLUSIONS

The study area receives most of the rainfall during the winter period from May to September, and hence river flows and water tables rise during this period. Streams draining upland areas that form headwaters on the north-western and northern parts are perennial. With minimal rainfall occurring during the relatively dry period, December to April, flows during this period are due to groundwater discharge in the form of springs and diffuse discharge. Hydraulic analysis of water tables and river beds in uplands, hydrochemistry, stable isotopes and radon analyses results confirmed groundwater discharge to streams in uplands.

The Jan Swartskraal River, which is within the midslope region, has low to no flow during the dry season despite receiving perennial discharges from tributaries draining uplands. Water use by think stands of invasive alien woody plants along and within the channel of Jan Swartskraal River contribute to reduction of flows. The water table was 1.5 to 4.5 below the river bed. The 7 m borehole at this site dried up during summer which indicates that the river was not recharging groundwater within the midslope region. Results of hydrochemical, stable isotopes and radon analysis confirmed that the Jan Swartskraal River is not a gaining stream.

Lowlands have very low gradients. During the wet season groundwater may have positive head of up to 1.8 m with respect to the river bed. However, during the same period, high river water levels occur and discharge of groundwater may be minimal. In addition, the river bed has clay with may clog surface water-groundwater interactions. The analysis of stable isotopes and radon confirmed minimal surface water-groundwater interactions in lowlands.

The spatial extent of IAPs in the catchment has declined by 14% from 1973-2021. *A. longifolia* was used as a case study to quantify water use by IAPs along the topographic gradient which illustrated that riparian *A. longifolia* used more water than non-riparian *A. longifolia*. Furthermore *A. longifolia* used more water than the indigenous fynbos.

The diurnal variations in the water table adjacent to sap flow monitoring stations showed that transpiration by *A. longifolia* caused decline in the water table during the day. Thus the IAPs investigated had an impact on groundwater, which eventually affects groundwater discharge to rivers.

An integrated analysis of data on river flows, water tables, hydrochemical characteristics, stable isotopes and radon has identified stream in the uplands graining water from groundwater through spring discharges, diffuse seepage into channels, and diffuse seepage onto the surface. The midslope zone of the Nuwejaars River seems not gain groundwater as the water table was below the river bed. Surface water-groundwater interactions are spatially and temporally dynamic in the lowlands. Groundwater discharge to rivers may be possible during the wet season, while this will be limited to certain parts during the dry season. Low gradient and existence of clay may limit groundwater discharge to the river on some locations.

RECOMMENDATIONS

Spring discharge to rivers has been found to be important in contributing to river flows. However, very little specific information exists about factors accounting for locations of springs, rates of discharges, recharge areas, and how land cover and land uses including invasive alien woody plants influence spring discharges.

A study to improve understanding of springs is therefore recommended.

ACKNOWLEDGEMENTS

The project team wishes to thank the following people for their contributions to the project.

Reference Group	Affiliation
W Nomquphu	Water Research Commission (Chairperson)
MA Dippenaar	University of Pretoria
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TABLE OF CONTENTS

EXECUTIVE SUMMARY iii

ACKNOWLEDGEMENTS ix

TABLE OF CONTENTS x

LIST OF FIGURES xiii

LIST OF TABLES xvii

ACRONYMS & ABBREVIATIONS xviii

BACKGROUND 1

1.1 INTRODUCTION 1
1.2 PROJECT AIMS 2
1.3 SCOPE AND LIMITATIONS 2

CHAPTER 2: METHODS 4

2.1 INTRODUCTION 4
2.2 STUDY AREA 4
2.3 COLLECTION OF WEATHER AND RIVER FLOW DATA 5
2.4 HYDROGRAPH SEPARATION 5
2.5 GROUNDWATER DATA 6
2.6 SURFACE AND GROUNDWATER CHEMISTRY 7
2.6.1 Laboratory analysis of water samples 8
2.6.2 Data Analysis 9
2.7 AQUATIC FAUNA AND TREE WATER USE 10

CHAPTER 3: SPATIOTEMPORAL VARIATIONS OF RIVER FLOWS AND GROUNDWATER 11

3.1 INTRODUCTION 11
3.2 RAINFALL AND EVAPOTRANSPIRATION 11
3.3 RIVER FLOWS 14
3.4 GROUNDWATER RESPONSE TO RAINFALL 17
3.4.1 Tussenberge 17
3.4.2 Sandfontein 19
3.4.3 Jan Swartskraal 21
3.4.4 Spanjaardskloof 23
3.4.5 Boskloof 25
3.4.6 Moddervlei 26
3.4.7 Uitsig 27
3.5 HYDROCHEMISTRY OF SURFACE WATER 28
3.5.1 pH 28
3.5.2 Electrical Conductivity 30
3.5.3 Rainwater 32

3.6 CHARACTERIZATION OF GROUNDWATER CHEMISTRY 33
3.6.1 pH 34
3.6.2 Electrical conductivity (EC) 35
3.6.3 Major ion distribution 37
3.6.4 Water types 37

CHAPTER 4: AQUATIC FAUNA ALONG THE NUWEJAARS RIVER 39

4.1 INTRODUCTION 39
4.2 METHODS 40
4.2.1 Nuwejaars River and Catchment Characteristics 40
4.2.2 Description and location of the sampling sites 41
4.2.3 Data collection 41
4.2.4 Data Analysis 42
4.3 RESULTS 42
4.3.1 Fish 42
4.3.2 Spatial and temporal distribution and trends of macroinvertebrates in the Nuwejaars River 44
4.3.3 Biodiversity indices for the Nuwejaars River sites during the dry season 46
4.4 DISCUSSION 48
4.5 CONCLUSIONS 49

CHAPTER 5: TREE WATER USE 50

5.1 INTRODUCTION 50
5.2 METHODS 50
5.2.1 Assessment of the spatial extent of different land cover and land use types 54
5.2.2 Estimation of spatial variations of actual evapotranspiration at catchment scale 55
5.2.3 Site descriptions 56
5.2.3.1 Moddervlei 56
5.2.3.2 Jan Swartskraal 57
5.2.3.3 Spanjaardskloof 58
5.2.3.4 Sandfontein 59
5.2.3.5 Tussernberge 59
5.3 RESULTS 61
5.3.1 Spatial extent of land use and land cover types 61
5.3.2 Water use rates by IAPs along a topographic gradient: *A. longifolia* case study 62
5.3.3 Water sources used by riparian and non-riparian *Acacia longifolia* trees 65
5.3.4 Actual evapotranspiration rates of fynbos 69
5.3.5 Actual evapotranspiration of riparian and non-riparian *Acacia longifolia* stands. 69
5.3.6 Spatial variations of actual evapotranspiration within the Nuwejaars Catchment 71
5.4 DISCUSSION & CONCLUSION 73
5.4.1 The extent of IAPs in the Catchment 73
5.4.2 Transpiration dynamics by riparian and non-riparian A*. longifolia* stands along the topographic gradient 74
5.4.3 Comparative water use by invasive *A. longifolia* stands and the indigenous fynbos stand 75
5.4.4 Actual evapotranspiration at the catchment scale 75
5.4.5 Implications of IAPs stands on GW-SW interaction 76

CHAPTER 6: surface water-groundwater interactions 77

6.1 HYDROGEOLOGICAL ASSESSMENT FOR SW-GW INTERACTION 77
6.2 SPRINGS 80
6.3 INFERENCE ON SW-GW INTERACTIONS 82
6.3.1 Hydrograph separation 82
6.3.2 Hydrochemical analysis 84
6.3.3 Comparison of water tables and riverbed levels 86
6.3.3.1 Tussenberge 86
6.3.3.2 Sandfontein 87
6.3.3.3 Jan Swartskraal (mid catchment) 88
6.3.3.4 Boskloof 89
6.3.3.5 Moddervlei 90
6.3.4 Stable isotope analysis 91
6.3.5 Radon data 94
6.4 DISCUSSION 95

CHAPTER 7: CATCHMENT MANAGEMENT 96

7.1 INTRODUCTIONS 96
7.2 INVASIVE ALIEN PLANTS 97
7.3 IMPOUNDMENT AND ABSTRACTION OF WATER 98
7.4 WATER RESOURCES MANAGEMENT OBJECTIVES FOR THE NUWEJAARS CATCHMENT 99
7.5 CATCHMENT MANAGEMENT TO ACHIEVE RESOURCE QUALITY OBJECTIVES. 101
7.5.1 Control of invasive alien plants 101
7.5.2 Water abstractions 102
7.5.3 Balancing utilisation of green and blue water 102
7.5.4 Management of riverine habitats 102

CHAPTER 8: CONCLUSIONS & RECOMMENDATIONS 104

8.1 CONCLUSIONS 104
8.2 RECOMMENDATIONS 105

REFERENCES 106

APPENDIX 1: Boreholes for groundwater monitoring 116

LIST OF FIGURES

Figure 2.1: Location of the Nuwejaars Catchment in the Cape Agulhas and variation of altitude within the catchment....4

Figure 3.1: Monthly rainfall from 1 January 2015 to 31 August 2021 within the Nuwejaars Catchment. 12

Figure 3.2: Average monthly rates of reference evapotranspiration during the 2015-2021 period. 12

Figure 3.3: Nuwejaars Catchment, annual evapotranspiration rates estimated by the MOD16A3GF product (Running et al., 2019). 13

Figure 3.4: Temporal variation of river water levels along Nuwejaars River and the tributaries from June 2020 to September 20201....15

Figure 3.5: The Nuwejaars River at Moddervlei showing part of the 8 km long and about 0.5 km wide floodplain with a meandering channel and off-channel pools. X marks the site with boreholes and river water level measurement. Source: Google Earth Image of 1/2014. 15

Figure 3.6: Nuwejaars River at Elandsdrift – daily flows (May 2015-Oct 2021) (top), mean monthly flows (bottom right), and flow duration curve 16

Figure 3.7: Variations of the water table depth below ground level (top right) and above sea level (bottom right) in Tussenberge boreholes, and the layout of boreholes. The nearest stream is at 192 m above sea level and 100 m from BH15 on the south-western part. 18

Figure 3.8: Temporal variations of groundwater temperature at Tussenberg 18

Figure 3.9: Variation of electrical conductivity of groundwater in the 12 m borehole at Tussenberge. 19

Figure 3.10: Temporal changes in the water table depth in Sandfontein boreholes, and the layout of boreholes with the stream (RIV-500, Riv-501) being at a distance of 55 m on the northern side and altitude of 222.82 m above sea level. 20

Figure 3.11: Water temperature in the Sandfontein borehols. 21

Figure 3.12: Changes of electrical conductivity of groundwater in the 11 m borehole at Sandfontein.21

Figure 3.13: Responses of water tables to rainfall for boreholes next to Jan Swartskraal River. Riv-400 is the location of the river 22

Figure 3.14: Variations of the water table and water temperature in boreholes at Jan Swartskraal, and the layout of boreholes. 22

Figure 3.15: EC variations of groundwater in the 7 m borehole next to Jan Swartskraal River. 23

Figure 3.16: Temporal variations of depth to water table at Spanjaardskloof, and layout of boreholes. Boreholes at the southern part are at 145 m while northern boreholes are 179 masl 24

Figure 3.17: Water temperature and electrical conductivity in the Spandjaardskloof boreholes 24

Figure 3.18: Water table fluctuations in the Boskloof boreholes, and the layout of boreholes along the valley slope with Boskloof River (Riv-201) on the western part. 25

Figure 3.19: Water temperature changes for the Boskloof boreholes. 26

Figure 3.20: Water table and temperature fluctuations borehole at Moddervlei and layout of boreholes. 27

Figure 3.21: Water table and temperature variations in boreholes at Uitsig....28

Figure 3.22: Spatial distribution of pH in surface water A) March 2021 B) May 2021, C) July 2021, D) September 2021 29

Figure 3.23: The relationship between pH and distance along the river from from the headwaters in Tussenberge to lowlands at Wiesdrift 30

Figure 3.24: Spatial distribution of EC (mS/cm) in surface water during wet and dry seasons. A) October 2020, B) March 2021, C) July 2021, D) November 2021. 31

Figure 3.25: The relationship between EC and distance along the river from the headwaters in Tussenberge to lowlands at Wiesdrift 31

Figure 3.26: Concentrations of sodium, magnesium, calcium and chlorides in rainwater in the north-western (Tierfontein) and northern (Tussenberge) headwaters, and central lowlands (Modderlei) 32

Figure 3.27: Spatial and temporal variations of selected ions along streams within the Nuwejaars Catchment. Tussenberge 3 = uplands, Jan Swartskraal = midslope, Koue River 2 = midslopes, Pieterseilieskloof 3 = midslope, Nuwejaars 2 = start of lowlands, Elandsdrift = lowlands. 33

Figure 3.28: Spatial distribution of pH in groundwater during wet and dry seasons. a) January 2021, b) February 2021, c) March 2021, d) May 2021, e) July 2021, f) September 2021. 35

Figure 3.29: Spatial distribution of EC (mS/cm) in groundwater during wet and dry seasons. A) January 2021, B) February 2021, C) March 2021, D) May 2021, E) July 2021, F) September 2021. . 36

Figure 3.30: Spatial distribution of selected major ion concentrations in groundwater for September 2021, A) Chloride 2021, B) Sodium, C) Magnesium, D) Sulphate. 37

Figure 3.31: Piper diagram, showing similarities in ionic proportions of groundwater and surface water within the Nuwejaars Catchment. 38

Figure 4.1:Location and distribution of surface water sampling points in the Nuwejaars Catchment (Adapted from Malijani, 2020) 41

Figure 4.2: Distribution of fish along the Nuwejaars Rivers. Red dots represent the sampling sites, whilst the yellow/blue fish symbols represent sites where fish was found. 43

Figure 4.3: Spatial distribution of macroinvertebrates during the (a) wet and (b) dry season in the Nuwejaars River 45

Figure 5.1: Study sites within the Nuwejaars Catchment. 51

Figure 5.2: Sap flow monitoring system 52

Figure 5.3: Soil moisture sensors and the piezometer installed at Moddervlei 52

Figure 5.4: Eddy covariance system (eddy flux tower) installed at a site with Fynbos shrubs. 53

Figure 5.5: Landsat 8 image pre-processing (Shoko, no date) 56

Figure 5.6: SEBS Computation using Landsat 8 Images (Shoko, no date). 56

Figure 5.7: Moddervlei site for tree water use monitoring within the riparian zone of the Nuwejaars River. The green rectangle shows the location of trees monitored, the blue rectangle is where 5 monitoring boreholes are located, the red circle is an automatic weather station (Source: Google Earth Image of 6 February 2021) 57

Figure 5.8: Experimental set-up at Jan Swartskraal. The green rectangle is the sap flow monitoring site adjacent to the stream, while the blue rectangle shows the location of two monitoring boreholes, 7 and 50 m deep (Source: Google Earth Image of 7 May 2019). 58

Figure 5.9: The Spanjaardskloof tree water use monitoring site on a hillslope. Altitude decreases towards the South. 59

Figure 5.10: Tree water use monitoring sites at Sandfontein. The blue rectangle is the location of two monitoring boreholes (Source: Google Earth Image of 6 February 2021)........ 60

Figure 5.11: Experimental set-up at Tussenberg. The green circle is the site of the eddy flux tower, red circle = automatic weather stations, blue rectangle = 3 monitoring boreholes (12, 30, and 50 m deep) (Source: Google Earth Image of 6 February 2021) 61

Figure 5.12: Landcover / landuse from 1973-2021 in the Nuwejaars catchment 62

Figure 5.13: Responses of soil water content in the shallow (0-50 cm depth) and deep (50-100 cm depth) soil layers to rainfall. 63

Figure 5.14: Daily reference evapotranspiration (grey) and transpiration rates (black) at the riparian (Moddervlei and Jan Swartskraal) and non-riparian (Spanjaardskloof and Sandfontein) sites. 65

Figure 5.15:Daily transpiration rates, rainfall, depth to water table (DTW), and soil water content in the shallow (0-50 cm) and deep (50-100 cm) soil layers from February 2019 to August 2021 at the study sites 66

Figure 5.16: Spatial variation of actual evapotranspiration across different land covers on the 25th of December 2018. 67

Figure 5.17: Diurnal variations in transpiration and depth to the water table from the 20th to the 30th of November 2019 at Modderlvei (a & b), Spanjaardskloof (c & d), and Sandfontein (e & f) study sites. Δs is the daily change (evening-morning) in depth to water table (cm). 68

Figure 5.18 :Reference evapotranspiration and actual evapotranspiration at a Fynbos site from August 2019 to November 2020. 69

Figure 5.19: Daily estimated AET and the measured ETo at Moddervlei (a) and Sandfontein (b) from August 2019 to August 2021 using the two-later model. 70

Figure 5.20: Daily actual evapotranspiration of *A. longifolia* and fynbos vegetation from August 2019 to August 2021 71

Figure 5.21: Spatial variation of AET across different land covers in the Nuwejaars Catchment (image source: Landsat 8; 20181225) using SEBS model. The shaded parts on the bottom images show polygons that were extracted from the landcover and AET images on top. 72

Figure 5.22: Spatial variation of evaporation across the catchment for three selected days, 21st July 2019, 10th July 2021 (representing wet season) and 25th December 2018, 1st March 2020 (representing dry season). 73

Figure 6.1: Geology of the Nuwejaars Catchment. White circles with blue crosses indicate locations of monitoring boreholes. Source: 3319 Worcester 1:250,000 Geological Series, Geological Survey of South Africa, Pretoria. 78

Figure 6.2: A 3D conceptual model for the Nuwejaars Catchment (Xaza, 2020) 80

Figure 6.3: Locations of springs in the Nuwejaars Catchment. Blue circle – springs occurring on the 3419C 3419D Gansbaai 3420C Bredasdorp 1963 Geological Map. Purple circles – springs identified by the Project Team. Base map 3319 Worcester 1:250,000 Geological Series, Geological Survey of South Africa, Pretoria 81

Figure 6.4: Influence of geological structures on groundwater flow system and the occurrence of springs 82

Figure 6.5: Baseflow separation using the Nathan and McMahon (1990) (left) and Eckhardt (2005) digital filters 83

Figure 6.6: Comparison of conductivity mass balance hydrograph separation using the EC of rainfall (cs = 144 µS/cm) and EC of peak flows of the Nuwejaars River at Moddervlei EC (cs = 322 µS/cm) to represent surface runoff. 84

Figure 6.7: Schoeller showing river water samples at various locations 85

Figure 6.8: Schoeller showing groundwater samples at various locations 85

Figure 6.9: Relationship between water table and riverbed level at Tussenberg. 86

Figure 6.10: Relationship between water table and riverbed levels at Sandfontein 87

Figure 6.11: Conceptual model for tree water use and surface water-groundwater interactions at the Sandfontein site in the upper part of the Nuwejaars Catchment 87

Figure 6.12: Water table always below the riverbed at Jan Swartskraal site 88

Figure 6.13: Groundwater flow at Jan Swartskraal which is a losing stream. 89

Figure 6.14: Relationship between water tables and riverbed at Boskloof 89

Figure 6.15: Relationship between water table depth and riverbed level at the Moddervlei site within the lowlands 90

Figure 6.16: Radon concentration in boreholes (left) and rivers (right). River sites are plotted generally from upstream to downstream, except for Sandfontein and Koue River 1 which are both located in the uplands close to river sources 94

Figure 7.1: Spatial variation of altitude within the Nuwejaars Catchment (Right), and regions considered to be strategic water source areas for both surface water and groundwater (Left). 97

Figure 7.2: Areas affected by IAPs (Right), and strategic water source areas affected by IAPS (left). 98

Figure 7.3: Farm dams and water licences within the Nuwejaars Catchment. 99

LIST OF TABLES

Table 3.1: Annual rainfall (mm/yr) received during the 2015-2021 period at stations within the Nuwejaars Catchment. For 2021 records end on 31 August 2021. Blank entry reflects a year with some missing data 11

Table 3.2: Annual actual evapotranspiration rates (ETa) estimated using the MOD16A3GF production 14

Table 3.3: Estimated annual flows of the Nuwejaars River at Elandsdrift 17

Table 4.1: Spatial and temporal distribution of taxa collected upstream and downstream in the Nuwejaars River and its tributaries. “Upstream” is above the Moddervlei site; “downstream” is from Moddervlei and downstream. “Wet” is when the river is flowing; “Dry” is when there is no flow. A tick (√) refers to the presence of a taxon. 44

Table 4.2: Prediction of the distribution of macroinvertebrates from the headwaters downstream. IRR = Incidence Rate Ratios; SE = Standard Error; z and P>|z| are the test statistic and p-value, respectively; 46

Table 4.3: Prediction of the distribution of macroinvertebrates from the headwaters downstream. IRR = Incidence Rate Ratios; SE = Standard Error; z and P>|z| are the test statistic and p-value, respectively 46

Table 4.4: Shannon-Wiener and Equitability indices for the Nuwejaars River sites during the dry season 47

Table 4.5: Shannon-Wiener and Equitability indices for the Nuwejaars River sites during the wet/flowing season 47

Table 5.1: Characteristics of the Landsat images used in this study. 55

Table 5.2: Soil textures at various depths in the riparian and non-riparian study sites. 62

Table 5.3: Annual reference evapotranspiration and rainfall measured from December 2018 to August 2021 in the Catchment. 63

Table 5.4: Annual transpiration rates from December 2018 to August 2021 64

Table 5.5: Annual actual and reference evapotranspiration rates measured on invaded and fynbos sites. 71

Table 6.1: Hydro-stratigraphy of the study area (adapted from Mazvimavi, 2017) 79

Table 6.2: Base flow indices obtained for different parameter values of the digital filters 83

Table 6.3: Baseflow index (BFI) estimated using the conductivity mass balance hydrograph separation method 84

Table 7.1: Resource Quality Objectives for the Nuwejaars River in lower part of the catchment. 100

Table 7.2: Groundwater Resource Quality Objectives for the Nuwejaars Catchment 100

ACRONYMS & ABBREVIATIONS

AET	Actual evapotranspiration
BFI	Baseflow Index
CAB	Cation-anion-balance
DO	Dissolved oxygen
EC	Electrical conductivity
GMWL	Global meteoric water line
HDPE	High Density Poly Ethylene
LMWL	Local meteoric water line
MAR	Mean annual runoff
SW-GW	Surface water-groundwater
VSMOW	Vienna standard mean ocean water

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BACKGROUND

1.1 INTRODUCTION

An integrated approach to the management of all elements of the hydrological cycle, which include Surface Water (SW) and Groundwater (GW) is globally accepted as a fundamental basis for sustainable water resources management. This is one of the founding principles of the National Water Act of South Africa. A prerequisite for sustainable water resources management is therefore an understanding of how SW and GW interact and affect the availability of water resources at the catchment scale, from the headwaters to the river mouth. There is however inadequate understanding of the nature of these interactions and how they affect the spatio-temporal dynamics of both quantity and quality of water resources at the catchment scale, since most studies of SW-GW interactions have focused on specific sites or river reaches (Banks et al., 2011). Without adequate knowledge of SW-GW interactions in a specific setting, catchment management plans focus on surface water, the most visible form, without considering the linkages with groundwater.

Previous WRC-funded projects (Parsons, 2004; Hughes et al., 2007; Tanner and Hughes, 2005) have established that the inclusion of SW-GW interactions in models used for water resources assessments is problematic, due to limited information about spatio-temporal variations of these interactions. There is thus a need to improve an understanding of, and the capacity to predict spatial and temporal variations in SW-GW interactions, and their influence on available water resources at the catchment scale. Interannual and seasonal variations of rainfall are known to affect SW-GW interactions. However, there is a low predictive capacity of how these variations influence these interactions. It may be that these interactions reduce adverse effects of inter-annual and seasonal variability. If such a behaviour exists along some parts of a river system, this offers an opportunity to increase the resilience of water users to climate variability by incorporating SW-GW interactions in water resources management plans. However, without knowledge of the existence and the nature of these interactions, it not possible to utilise this opportunity.

Studies in the Nuwejaars catchment showed that riparian vegetation has the potential to influence SW-GW interactions (Mazvimavi, 2018). In particular, alien vegetation associated with riparian zones seems to change water fluxes, reducing connectivity between the headwaters and the lowlands. Alien vegetation also seems to preferentially use fresh and not saline water resources and therefore by increasing evapotranspiration, indirectly increase salinity in the down gradient systems. Currently, we have inadequate knowledge of the differential impact of riparian vegetation on SW-GW interactions along a river from headwaters to lowlands. This information is required for improved riparian zone management, including prioritizing areas that will be most effectively cleared of invasive alien plants.

There is a limited understanding about the influence of SW-GW interactions on aquatic ecosystems, including the abundance and composition of different kinds of organisms (Seaman et al., 2010). What is not clear is how human-induced changes in SW-GW interactions may affect aquatic ecosystems by altering the biophysical qualities of the environment. Furthermore, there is inadequate knowledge of the faunal and floral species that can be used as indicators of locations where a river is either gaining or losing water to groundwater. Such knowledge will assist in rapidly assessing the nature of SW-GW interactions and might be incorporated in the monitoring component of water resources management plans.

A major constraint to understanding SW-GW interactions at the catchment scale is the lack of adequate hydrological and ecological monitoring systems to provide information required for decision-making. The WRC project K5/2324/1 established a monitoring system covering most elements of the water cycle in the Nuwejaars Catchment. This monitoring system consists of 5 automatic weather stations, 10 river water-level stations, 29 monitoring boreholes on hillslopes and across the floodplains of the Nuwejaars Rivers, and 2 tree water use monitoring stations (riparian and hillslope sites). The Nuwejaars catchment provides an opportunity to investigate spatio-temporal variations of SW-GW interactions from the headwaters to the lowlands as part of a living laboratory, with local farmers, land and water resources management agencies being involved using participatory research methods.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To establish the nature of surface water-groundwater interactions from headwaters to lowlands.
2. To determine how surface water-groundwater interactions influence the spatial and temporal variations of available water resources in terms of quantity and quality at the catchment scale.
3. To examine how surface water-groundwater interactions influence ecosystems from headwaters to lowlands.
4. To explore options for managing surface water-groundwater interactions at the catchment scale, and how these options can be integrated in a catchment management plan.

1.3 SCOPE AND LIMITATIONS

The project commenced in May 2018. The main activity undertaken in 2018 was the establishment of monitoring system including drilling 15 monitoring boreholes. During 2019 monitoring of the various elements was initiated. The COVID-19 lockdowns in March 2020 which required students to return to their homes and no travelling brought fieldwork activities to a standstill. The project area is 185 km from the University of the Western Cape, and under normal operating conditions, project team members will put up for some nights in Struis Bay. During 2020 all facilities providing accommodation were closed. Most of the project activities were planned to be undertaken by MSc and PhD students with the assistance of supervisors. Due to the lockdowns this supervision had to be done online. In addition laboratories for analysing water samples at the University of the Western Cape and other commercial operators were closed in 2020, resulting in very limited analysis. The planned setting up of model which could represent surface water and groundwater interactions was therefore not implemented. The project had planned to consult various stakeholders such as Breede-Gouritz Catchment Management Agency and landowners but this was not possible due to limitations on meetings arising from the COVID-19 pandemic.

CHAPTER 2: METHODS

2.1 INTRODUCTION

The study uses hydrological, hydrogeological, and hydrochemical methods to investigate SW-GW interactions within the Nuwejaars Catchment. The hydrological methods include examining temporal variations of river flow patterns to establish periods when rivers could be gaining from or losing water to groundwater, and hydrograph separation to determine the proportion of river flows contributed by subsurface storages. Hydrogeological methods used involved analysis of water tables in monitoring boreholes to determine how hydraulic gradients could affect SW-GW interactions. Hydrochemical characteristics of both river water and groundwater are used to infer occurrences of SW-GW interactions. Stable isotopes of water and radon are also used to infer SW-GW interactions.

2.2 STUDY AREA

The Nuwejaars River which is located in the Cape Agulhas has a catchment area of 760 km^2. Altitude varies from 7 to 654 m above sea level. Lowlands with altitude less than 40 m occupy 35%, mid-slope (41-100 m) 27%, and uplands (>100 m) cover 38% of the catchment (Figure 2.1).

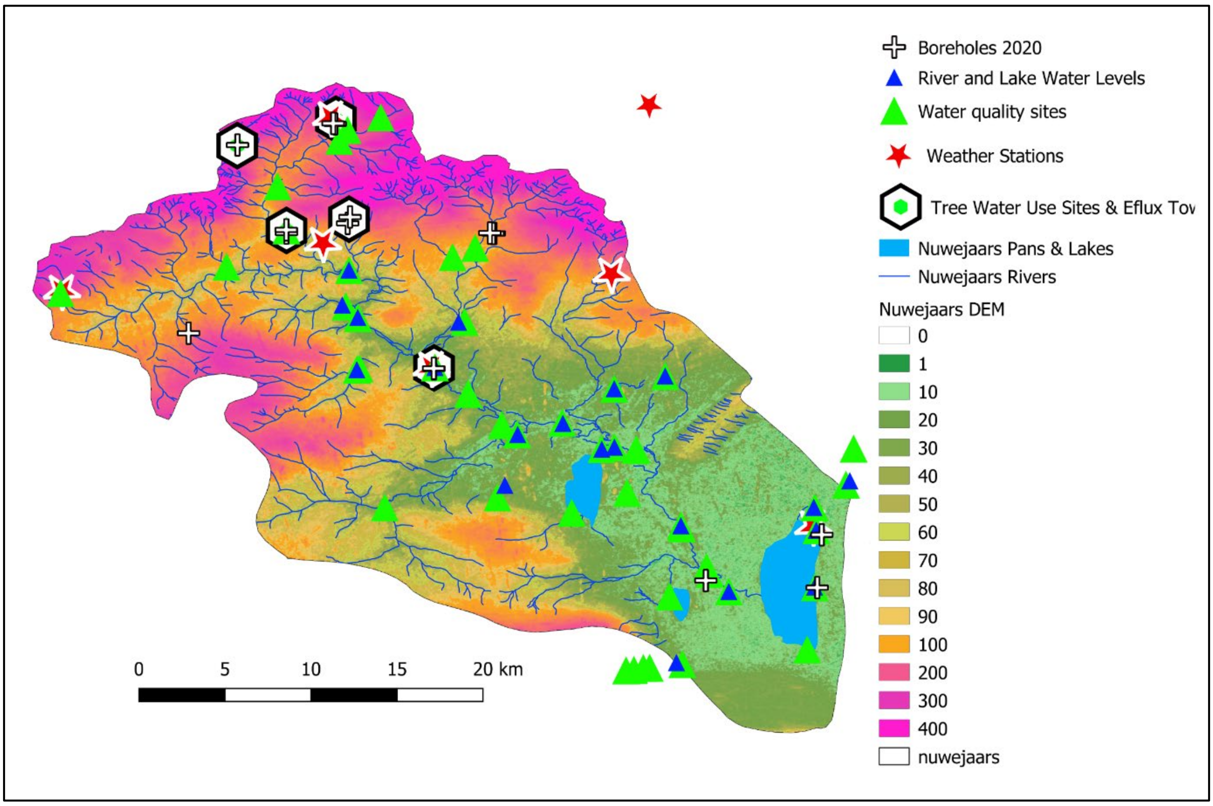

Figure 2.1 Location of the Nuwejaars Catchment in the Cape Agulhas and variation of altitude within the catchment

2.3 COLLECTION OF WEATHER AND RIVER FLOW DATA

Weather data were collected from five automatic weather stations within the catchment (Figure 2.1). Three of these stations (Spanjaardskloof, Tiersfontein, Vissersdrift) were established in December 2015, while Moddervlei was established in June 2016, and Tussenberge in May 2019. The altitude above sea level of these stations are as follows:

- Vissersdrift 7 m
- Moddervlei 25 m
- Spanjaardskloof 85 m
- Tiersfontein 200 m
- Tussenberge 230 m

Four of the weather stations store data at 15-minute interval and while one stations stores hourly data for the following elements; air temperature, relative humidity, atmospheric pressure, solar radiation, wind speed and direction, and rainfall. Weather data were used to estimate catchment rainfall and evapotranspiration rates. The 2015-2020 annual actual evapotranspiration (ETa) estimates based on the *MOD16A3GF* (Running et al., 2019) downloaded from https://lpdaacsvc.cr.usgs.gov/appeears/ were used to provide an indication of the spatial variation of evapotranspiration throughout the Nuwejaars Catchment

River water level data loggers were installed at 11 sites (Figure 2.1). These are equipped with either a HOBO U20L-01 water level logger which measures up to 9 m water depth with a ± 0.1 cm accuracy, or Solinst loggers (Model 3001). River water level measuring stations on the Nuwejaars River at Elandsdrift, and Soetendalsvlei were established in May-June 2015, while for the other stations this was in May 2016. All the stations capture hourly river water level data.

2.4 HYDROGRAPH SEPARATION

Two methods for hydrograph separation which are a) digital filters and b) conductivity mass balance, were used for hydrograph separation. This study used the Nathan and McMahon (1991), Eckhardt (2005) digital filters. The Nathan and McMahon (1991) filter is given by:

$$Q_s(t) = \beta Q_s(t-1) + \frac{(1+\beta)}{2}\{Q(t) - Q(t-1)\} \quad (2.1)$$

$$Q_b(t) = Q(t) - Q_s(t) \quad (2.2)$$

where $Q_s(t)$ = surface runoff at time t, $Q_b(t)$ = baseflow, $Q(t)$= total flow, β = parameter, t = time interval which is daily interval in this study. Smakhtin and Watkins (1997) found that a β of 0.995 gave acceptable results in South Africa.

The Eckhardt (2005) digital filter is given b:

$$Q_b(t) = \frac{(1-BFI_{max})\alpha Q_b(t-1)+(1-\alpha)BFI_{max}}{1-\alpha BFI_{max}} Q(t) \tag{2.3}$$

where BFI_{max} = maximum value of the base flow index, and α is the recession constant.

The conductivity mass balance approach is based on the following steady state mass balance equation:

$$c(t)Q(t) = c_s Q_s(t) + c_b Q_b(t) \tag{2.4}$$

where *c(t)* = is the conductivity of the river flow at time *t,* c_s = conductivity of surface runoff or average conductivity during peak flow period, c_b = conductivity of baseflow (Stewart et al., 2007). Conductivity (EC) values are in microSiemens per centimetre (µS/cm).

Based on Equation (2.4), baseflow is given by:

$$Q_b(t) = Q(t)\frac{(C(t)-c_s)}{(C_b-c_s)} \tag{2.5}$$

The conductivity of surface runoff is assumed to be the measured values of EC during peak flows or EC values of rainwater (Yaing et al., 2020; Stewart et al., 2007). The baseflow c_b, is based on measured values during low flow periods (Saraiva Okello et al., 2018; Yang et al., 2020). The baseflow index (*BFI*) is obtained from Equation (2.6):

$$BFI = \frac{\sum_t^n Q_b(t)}{\sum_t^n Q(t)} \tag{2.6}$$

Large values of the *BFI* (>0.4) indicate catchments with strong subsurface flow contribution to total flow.

2.5 GROUNDWATER DATA

The study required a network of boreholes in the headwaters, mid-slope, and lowlands to establish responses of groundwater to rainfall, water chemistry and stable isotope composition, possible linkages between groundwater and surface water. Geophysical (electrical resistivity, gravimetric) surveys were carried out at 6 sites adjacent to the streams in the study area. Two of the sites (Sandfontein and Tussenberge) were in the headwaters, two sites on hillslopes (Spanjaardskloof, Boskloof), one site in the mid-slope region (Jan Swartskraal), and the Moddervlei site in the lowlands. At each of these sites, 2 to 8 boreholes were drilled to different depths and along a transect leading to or crossing a river. Fifteen boreholes were drilled during October 2018 (Figure 2.2). Another 14 monitoring boreholes had been developed for the previous WRC Project in the study area. Thus, the catchment has 29 monitoring boreholes. Water level data loggers were installed in 15 boreholes. Static water level measurements were made on a monthly interval in all boreholes.

The exact elevations of monitoring boreholes and the river bed adjacent to nest of boreholes were surveyed using a Trimble R7 and R2 Global Navigation Satellite System (GNSS) receivers, and post processing kinematic survey method. A Trimble S3 total station for surveying features near/under vegetation was used since GNSS receivers are limited by these features. The precision of the survey was ± 4 cm for the horizontal position, and ± 8 cm for the vertical position

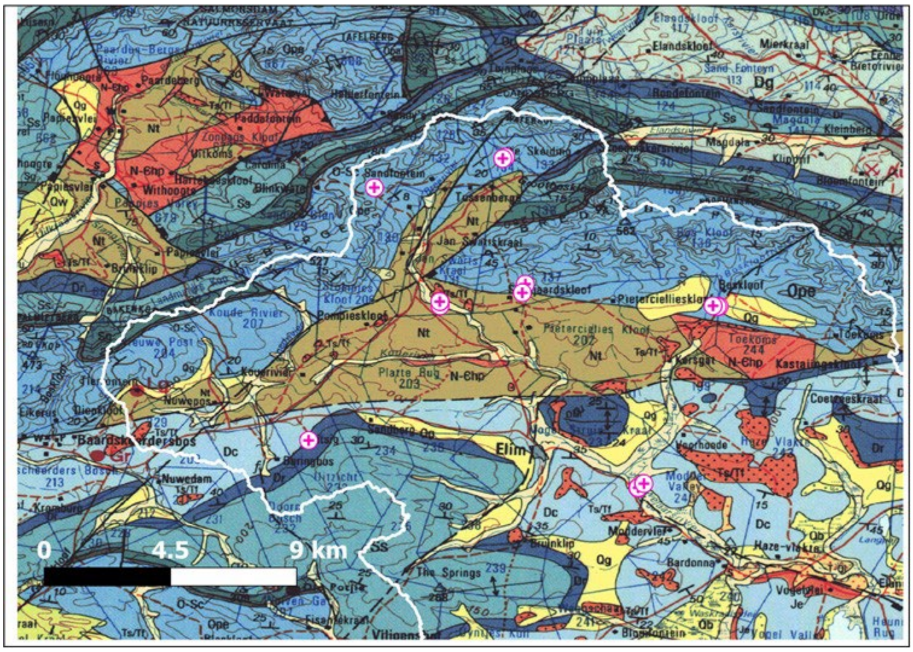

Figure 2.2: Locations of monitoring boreholes used for collecting water samples for isotope analysis. Source: 3319 Worcester 1:250,000 Geological Series, Geological Survey of South Africa, Pretoria.

2.6 SURFACE AND GROUNDWATER CHEMISTRY

Different components of surface water chemistry in the catchment have been investigated since the beginning of 2017. Monthly stream water samples were collected from October 2020 until December 2021 at 24 sites within the catchment (Figure 2.3). Sites were selected to cover all the major streams that stretch from the headwaters to the lowlands of the catchment. Only free flowing water samples were collected at these sites. A Hach HQ40d multi-meter probe was used to measure physico-chemical parameters (temperature, electrical conductivity, pH, and dissolved oxygen in the field. Water samples collected were filtered in-field with 0.45 µm nylon syringe filters and stored in 50 ml high density polyethylene (HDPE) bottles and kept cool under 5°C while in the field and stored later in the fridge prior to laboratory analysis.

Groundwater samples were collected from 26 monitoring boreholes and 3 artesian wells at specific screen depths where applicable using a Proactive® Stainless steel sampling pump (Mega Monsoon XL model). Boreholes were purged for 15-20 minutes before sampling. Static water levels were measured using a Solinst water-level meter prior to sampling. Samples were filtered in-field with 0.45 µm nylon syringe filters and stored in 50 ml HDPE bottles and kept cool under 5°C in the field and later stored in a fridge before being analysed. During instance when the sampling pump was not available either the Solinst specific depth sampler or Hydrasleeves™ was used as passive sampling technique.

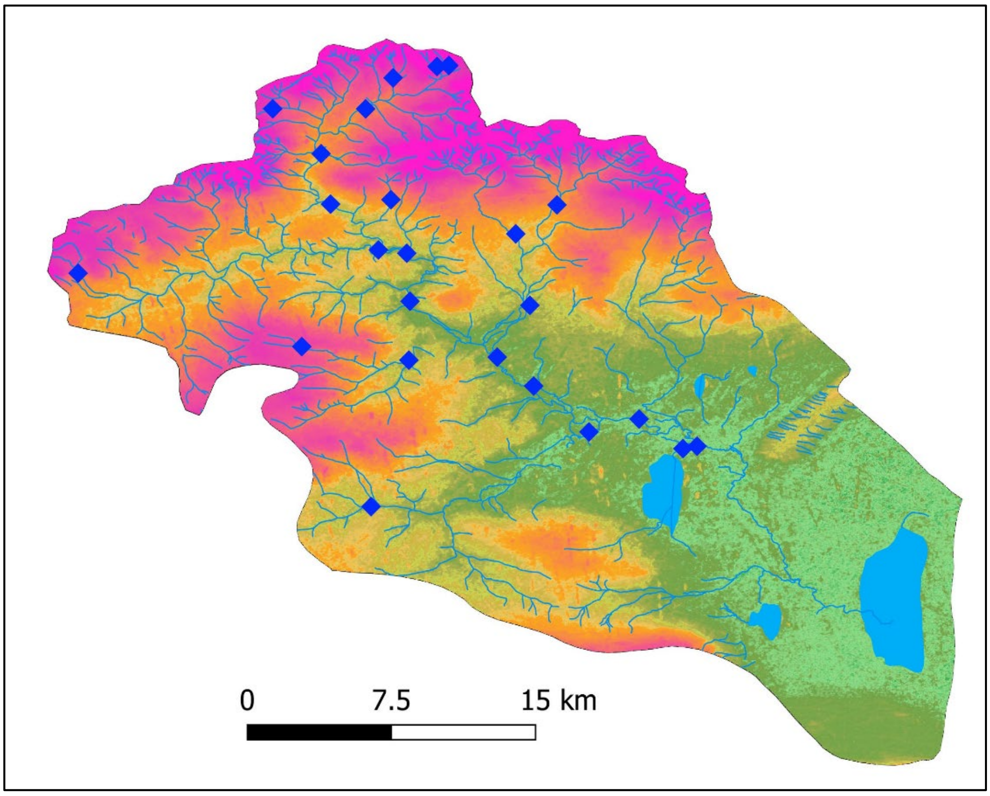

Figure 2.3: Sites in the Nuwejaars Catchment for river water sampling for hydrochemical analysis

2.6.1 Laboratory analysis of water samples

Surface water and groundwater samples collected between the period of July 2017 to December 2019 were analysed using the Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) method, and a high performance iCAP 7600 ICP-OES radial spectrometer or a Thermo ICap 6200 ICP-AES spectrometer**,** manufactured by Thermo Fisher Scientific. The detection limit and sensitivity of the instrument varies from element to element. Minimum detection limits provided for the instrument include calcium 0.02 µg/L, potassium 5.10 µg/L, magnesium 0.04 µg/L and sodium 1.80 µg/L. (Information available on manufacturer's website: http://www.thermofisher.com). Samples collected from October 2020 were analysed at the BIOGRIP Node Unit at the Central Analytical Facility(CAF) Laboratory at Stellenbosch University and Bemlab Laboratories in the Western Cape, South Africa. The BIOGRIP Unit makes use of a Metrohm IC930 Ion Chromatography system which can be used for the quantification of anions (Cl, F, NO2, NO3, PO4, SO4, Br) and cations (Li, Ca, K, Na Mg, NH4,). Surface and groundwater samples with high salinity (> 5000us/cm) were analysed on a Skalar BluvisionTM discrete analyser for the quantification of anions (Cl, SO_4, NO_2, NO_3, PO_4) and total alkalinity. .

The accuracy of the hydrochemical analysis of major ions was validated using the cation-anion balance (CAB). In theory, all portable waters are electrically neutral, hence the sum of cation and the sum of anions in a sample must balance or be equal. This is known as the principle of electroneutrality which governs the reliability of the hydrochemical analysis conducted on major ions (Younger, 2007). Only results from samples that yielded an acceptable CAB of ±15%, as stipulated by Younger (2007), have been used in this report.

Stable isotopes were analysed at the Department of Earth Sciences at the University of the Western Cape. For this analysis, the off-axis integrated cavity output spectroscopy (OA-ICOS) method was used. This was performed on a LGR DLT-100 liquid water isotope (LWIA) analyser (model 908-0008-2010) manufactured by Los Gatos Research Inc. (Mountain View, California, USA). The instrument is connected to a LC PAL liquid auto-sampler (model 908-0008-9001) manufactured by CTC Analytics (Zwingen, Switzerland) for the simultaneous measurement of δ^2H and $\delta^{18}O$ for water samples. The auto-sampler inserted with either a SGE 5 µl (model 5F-C/T-0.47/5C) or a Hamilton 1.2 µl syringe (model 26P/-mm/AS, 7701.2N) by Hamilton Company (Reno, USA) syringe for the injection of water samples into a heated injector block (85°C). The analytical procedure consisted of 12 injections per vial, ignoring the first seven. Data processing procedures to correct for between sample memory, instrumental drift, and normalization to the VSMOW2-SLAP2 scale using the LIMS for Lasers 2015 (version 10.100) was done. A 2-point data normalization using laboratory standards W-31 (high standard) and W-32 (low standard) was utilized and calibrated using VSMOW2 and SLAP2 reference materials from the IAEA. The δ-values for the laboratory standards W-31 and W-32 are -11.9‰ ±0.7 and -3.54‰ ±0.1, -74.1‰ ±0.8 and -9.92‰ ±0.11 for δ^2H and $\delta^{18}O$, respectively. The long-term analytical precision (6 years) for our instrument is ±1.5‰ for δ^2H and ±0.15‰ for $\delta^{18}O$, respectively, which is obtained from a control standard (W-33) of a known isotopic composition for QA/QC purposes.

All the samples were screened with LGR's LWIA Spectral Contamination Identifier™ (version 1.0.0.69) software to identify any samples that may have organic contaminants (alcohol, plant and soil water extracts, etc.) that can cause serious spectral interference, leading to poor isotopic measurement results.

2.6.2 Data Analysis

The isotopic composition of ^{18}O and ^2H, expressed in per mil (‰) deviations from the VSMOW standard of δ^2H and $\delta^{18}O$, were plotted on a $\delta^{18}O$ vs δ^2H plot for interpretation. This relationship was plotted and interpreted in relation to the global meteoric water line (GMWL) and local meteoric water line (LMWL). The Cape Town precipitation data acquired from Harris et al. (2010) were used for the generation of the local meteoric water line (LMWL). In addition, the global meteoric water line (GMWL) defined by Craig (1961) which provides a reference for interpreting the provenance of groundwater, was plotted on the δ^2H vs $\delta^{18}O$ plot based on the following equation:

$$\delta^2H = 8 \times \delta^{18}O + 10 \text{ ‰ VSMOW} \qquad (2.7)$$

Piper diagrams (Piper, 1944) that allow for the identification of water type or hydrochemical facies, ultimately giving an insight on possible interaction between the two water sources, were generated using the Geochemist's Workbench student edition 12.0 software. The water type on these plots is determined by the position of the water sample. Samples that plot within the same region are of the same water type and are therefore likely to originate from the same source.

2.7 AQUATIC FAUNA AND TREE WATER USE

The methods for collecting and analysing data on aquatic fauna and tree water use are described in Chapter 4 and 5 respectively to provide sufficient detail, and facilitate understanding of the results obtained which are described in these chapters.

CHAPTER 3: SPATIOTEMPORAL VARIATIONS OF RIVER FLOWS AND GROUNDWATER

3.1 INTRODUCTION

This chapter presents spatial and temporal variations of river flows, water tables, hydrochemical characteristics of both surface water and groundwater. The information provides a basis for making inferences about surface water-groundwater interactions done in Chapters 4 to 6.

3.2 RAINFALL AND EVAPOTRANSPIRATION

Rainfall data collected during the 2015-2021 period show that the 2020-2021 years received relatively high rainfall, while 2017-2018 had the lowest rainfall (Table 3.1). The WR2012 estimated the mean annual precipitation for the Nuwejaars Catchment to be 492 mm/yr and 2017-2018 received less than this amount. Monthly rainfall rarely exceeded 60 mm/month during years with below average rainfall (Figure 3.1).

Table 3.1: Annual rainfall (mm/yr) received during the 2015-2021 period at stations within the Nuwejaars Catchment. For 2021 records end on 31 August 2021. Blank entry reflects a year with some missing data

Year	Spanjaardskloof	Vissersdrift	Tiersfontein	Moddervlei	Tussenberge	Catchment
2015	629	558	519		706	603
2016	535	366	471		616	497
2017	441	289	399	406	505	408
2018	438	263	544		504	437
2019	445	309	596	446	615	491
2020	674		859	711	922	818
2021*	563	604		668	826	664

The March to August 2021 period has had rainfall exceeding 50 mm/month with the exception of April that received less than 30 mm/month. May 2021 had very high rainfall ranging from 195-273 mm/month in the catchment (Figure 3.1).

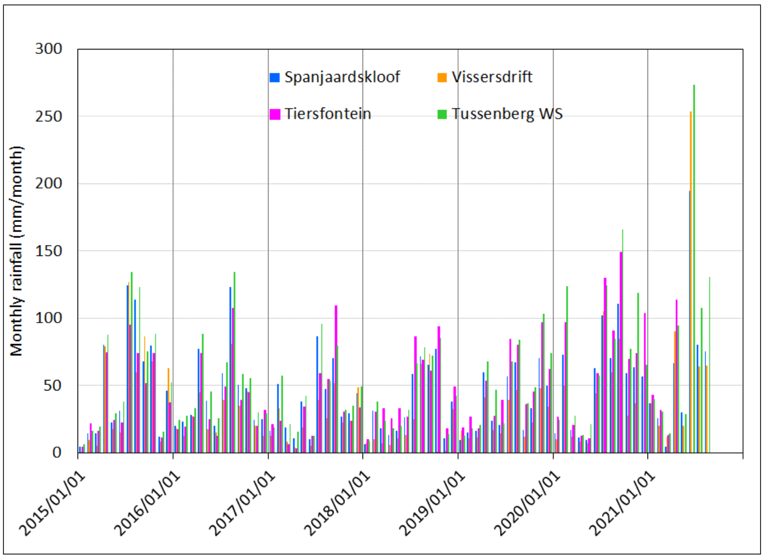

Figure 3.1: Monthly rainfall from 1 January 2015 to 31 August 2021 within the Nuwejaars Catchment.

The reference evapotranspiration (short green grass) varied from 30-0 mm/month during the May-August period to 120-190 mm/month during the November-February period (Figure 3.2). The average annual reference evapotranspiration for the catchment is 1140 mm/year. Reference evapotranspiration rates exceeded rainfall during all the months except from June to August. Based on the 2015-2021 data, the aridity index was 0.45 which shows that the Nuwejaars Catchment is semi-arid.

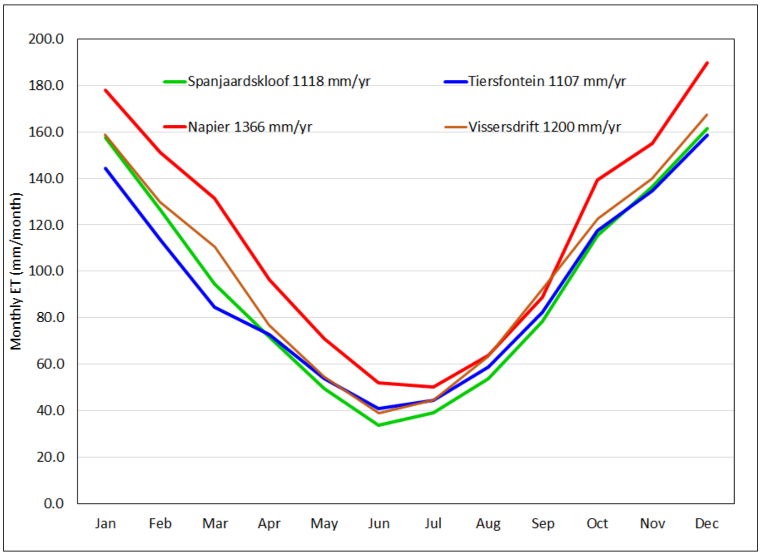

Figure 3.2: Average monthly rates of reference evapotranspiration during the 2015-2021 period.

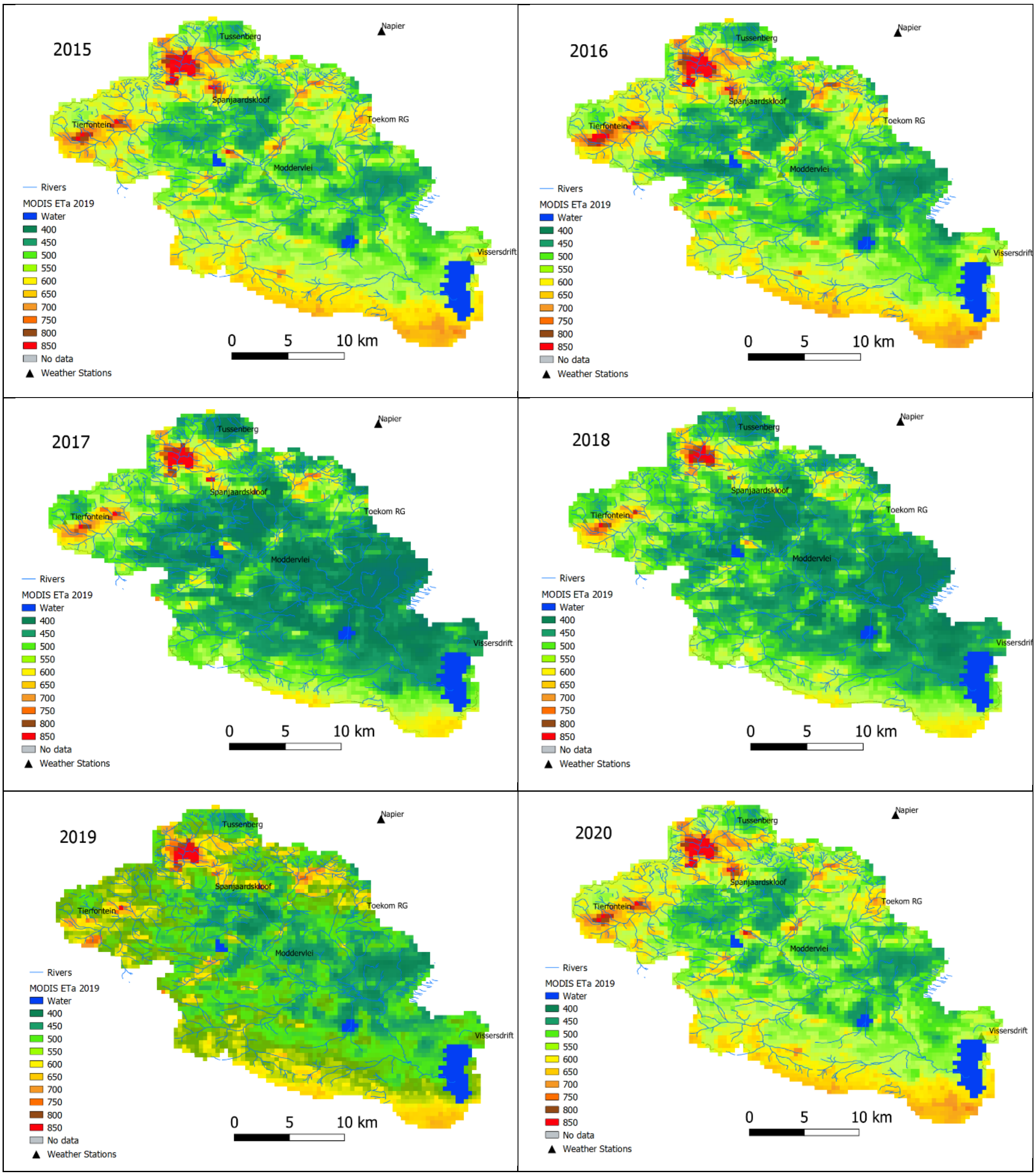

Figure 3.3: Nuwejaars Catchment, annual evapotranspiration rates estimated by the MOD16A3GF product (Running et al., 2019).

The 2015-2020 annual actual evapotranspiration (ETa) estimates based on the *MOD16A3GF* (Running et al., 2019) downloaded from https://lpdaacsvc.cr.usgs.gov/appeears/ were used to provide an indication of the spatial variation of evapotranspiration throughout the Nuwejaars Catchment (Figure 3.3, Table 3.2). ETa estimates based on remote sensing do have some inaccuracies but they provide an indication of the spatial variations of ETa within an area of interest.

Table 3.2: Annual actual evapotranspiration rates (ETa) estimated using the MOD16A3GF production

Year	2015	2016	2017	2018	2019	2020
ETa (mm/yr)	539	528	468	475	517	539

The relatively wet years, 2015 and 2020 had the highest rates of ETa, while the dry years, 2017-2018, had the lowest ETa rates. Cultivated areas occurring mostly on the central part of the catchment have low ETa rates, 400-450 mm/yr. The low ETa rates are due to the fact that most crops are rainfed and after they are harvested, evaporation will gradually decrease due to the drying of soils. Areas with woody invasive plants and natural vegetation especially on areas with high ground have relatively high ETa rates, 600-700 mm/year. The annual ETa rates are about 42% of the reference evapotranspiration rates. Further information on evapotranspiration rates is given in Chapter 5 which deals with tree water use.

3.3 RIVER FLOWS

River water levels were measured using transducers with data loggers at locations shown in Figure 2.1. The most downstream river flow measuring site is on the Nuwejaars River at Elandsdrift which has a catchment area of 510 km^2. Located 8 km upstream of the Elandsdrift site is the Moddervlei flow measuring station with a catchment area of 314 km^2. The Jan Swartskraal site with a catchment area of 163 km^2 is immediately downstream of the confluence of the Koue and Jan Swartskraal Rivers. Except for the site at Nuwejaars River at Elandsdrift, rating curves could not be developed at the other stations because of the nature of channels. The comparison of river water levels at these stations (Figure 3.4) enables an identification of parts of the Nuwejaars River catchment that contribute most of the flows and their spatiotemporal variability. This will also assist in identifying sections of the river that are either gaining from or losing water to groundwater.

River flows at the Jan Swartskraal site have sharp rises reflecting fast runoff from streams draining uplands with high slopes in the Tussenberge region (Figure 3.4). The same is observed on the Pieterseilieskloof River which drains the north-eastern mountains. The Moddervlei site is below the confluence of Pieterseilieskloof and upper Nuwejaars (including Jan Swartskraal), and also has sharp increases of river flows. Immediately upstream of the Moddervlei site is a perennial pool that is about 1 km long and 40-50 m wide. Consequently, the Moddervlei site rarely dries up (Figure 3.4). Elandsdrift, as already stated, is downstream of an 8 km floodplain with in- and off-channel pools. Water storage in these pool and subsequent drainage back into the Nuwejaars River channel dampens daily fluctuations of water levels (Figure 3.4). River flows are reduced to a trickle during the December to April period at Elandsdrift and will dry up during droughts, e.g. 2018. The Voëlvlei Lake with a surface area of about 500 hectares and storage capacity of 7 Mm^3 has a 1.7 km long outlet joining the Nuwejaars River immediately upstream of Elandsdrift. Due to the low gradient, during periods of high flows, water levels on this outlet are almost the same as in the Nuwejaars River at Elandsdrift (Figure 3.4).

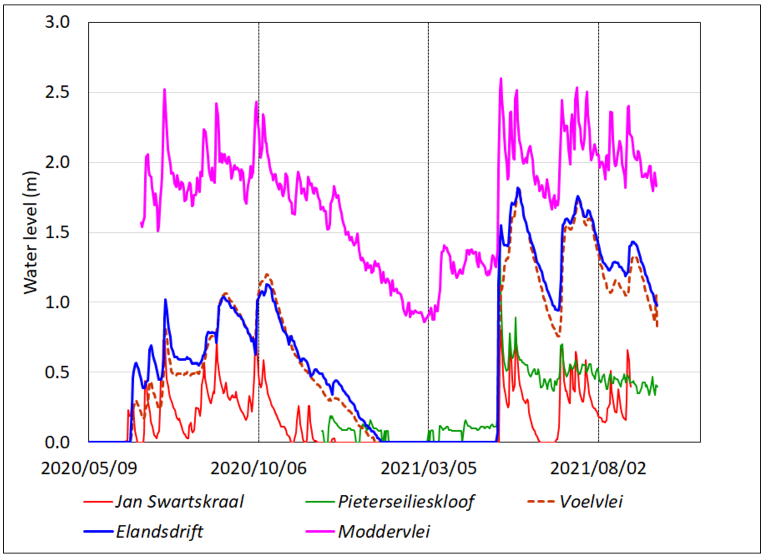

Figure 3.4: Temporal variation of river water levels along Nuwejaars River and the tributaries from June 2020 to September 20201.

The Nuwejaars River at Elandsdrift had low water levels and often dry during the 2017 to 2019 period. The river rarely dries at Moddervlei as the channel consists of a long pool with palmiet (Figure 3.5). However, these pools often become disconnected from the main river during the dry December to April period. The water level data show that when the Nuwejaars River has low water levels, peak flows will take about 5 days to travel from Moddervlei to Elandsdrift, and 1 day during high flow periods. In general, catchment rainfall exceeding 10 mm/day will cause a change in water levels along the Nuwejaars River (Figure 3.6).

Figure 3.5: The Nuwejaars River at Moddervlei showing part of the 8 km long and about 0.5 km wide floodplain with a meandering channel and off-channel pools. X marks the site with boreholes and river water level measurement. Source: Google Earth Image of 1/2014.

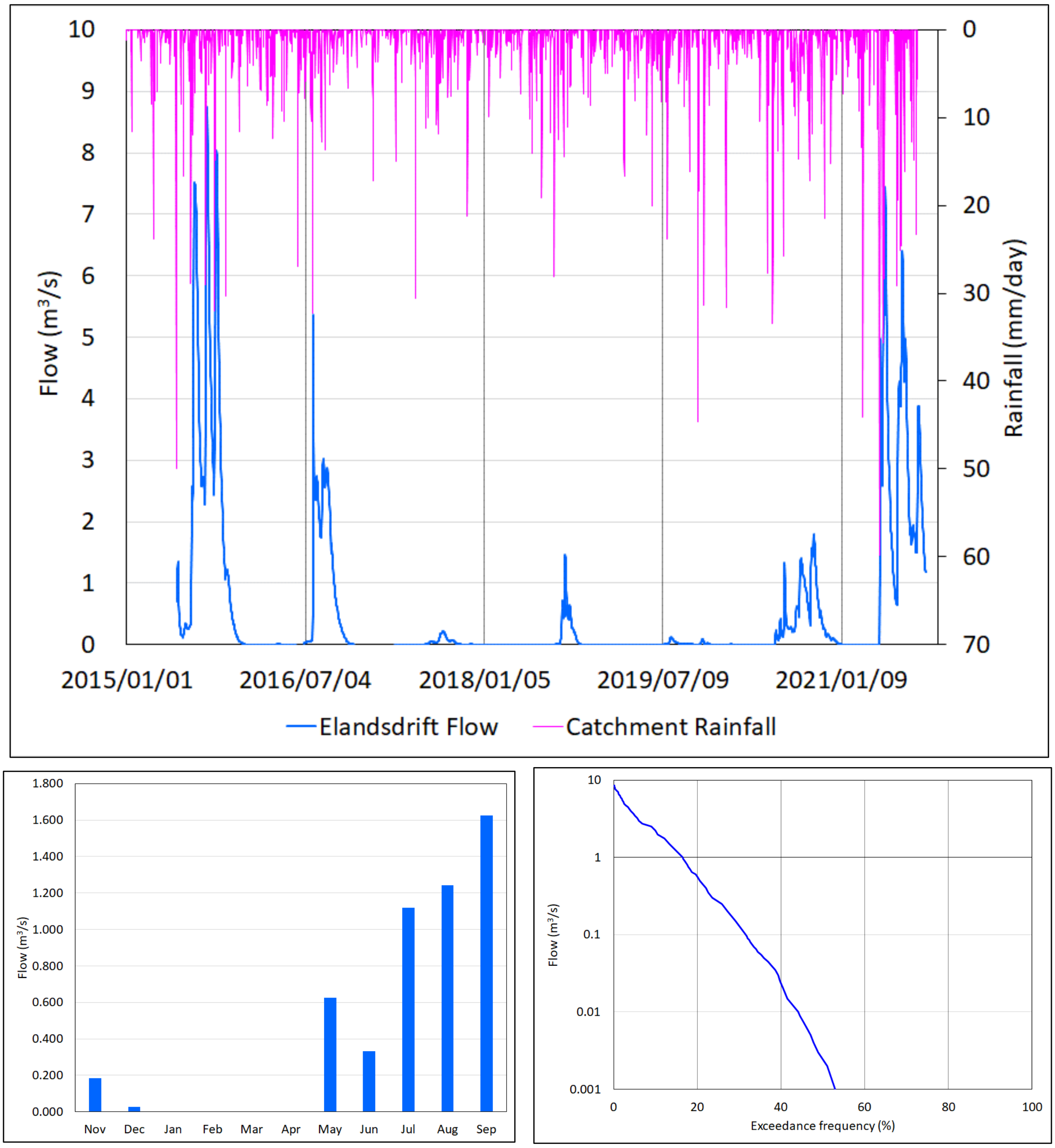

Figure 3.6: Nuwejaars River at Elandsdrift – daily flows (May 2015-Oct 2021) (top), mean monthly flows (bottom right), and flow duration curve

River flow data collected for the Nuwejaars River at Elandsdrift shows that 2015 and 2020 had relatively high flows exceeding 5 m^3/s during the wet season, while 2017 and 2018 had very little flows due to the drought (Figure 3.6). The Nuwejaars River frequently dries up during the January to April period. During the 2015 to 2021 period, the river dried up about 60% of the time. The flow duration curve is steep indicating that this is a non-perennial river (Figure 3.6).

The whole Nuwejaars Catchment is made up of quaternary catchment G50B (339 km^2) and G50C (421 km^2). The WR2012 Water Resources Assessment provides an estimated mean annual runoff (MAR) for G50B as 12.47 Mm^3/year or 37 mm/year, and G50C as 6.31 Mm^3/year or 15 mm/year. On the basis of the WR2012 MAR for G50B and G50C, the MAR for the Nuwejaars Catchment at

Elandsdrift is estimated as 15.92 Mm^3/year or 30 mm/year. The estimated annual flows at Elandsdrift indicate that flows for the 2016-2020 period where less, than the MAR (Table 3.3). The effects of the drought are evident in the low annual flows for the 2017-2019 period.

Table 3.3: Estimated annual flows of the Nuwejaars River at Elandsdrift

Year	Annual Flow (Mm^3/yr)	Annual Flow (mm/yr)
2015	42.778	83.9
2016	14.984	29.4
2017	0.663	1.3
2018	2.039	4.0
2019	0.301	0.6
2020	9.060	17.8
2021 up to Aug	36.592	71.7

3.4 GROUNDWATER RESPONSE TO RAINFALL

3.4.1 Tussenberge

The Tussenberge boreholes were drilled into weathered sandstone. Boreholes BH15 (50 m) and BH17 (12 m) are close to each other (6 m apart) (altitude 202.03 m & 202.42 m respectively), while BH16 (30 m) is 128 m away and upslope (7 m higher, altitude 209.01 m). Water tables at this site declined during November/December-May/June period, and then rose during the wet period July to October (Figure 3.7). The water table declines during the dry season by about 3 m in the 12 m and 30 m boreholes, while in the 50 m this was about 1-2 m. The water table in the 50 m boreholes reaches ground level during the wet season, and becomes artesian, e.g. 17 August-30 November 2020, and 7 July-26 September 2021 (Figure 3.7). It is remarkable that the differences in depths of the water tables among the 3 boreholes remains almost constant throughout the year. The higher water table in the 50 m borehole is indicative of having a recharge zone at a higher elevation resulting in water being under a hydrostatic pressure.

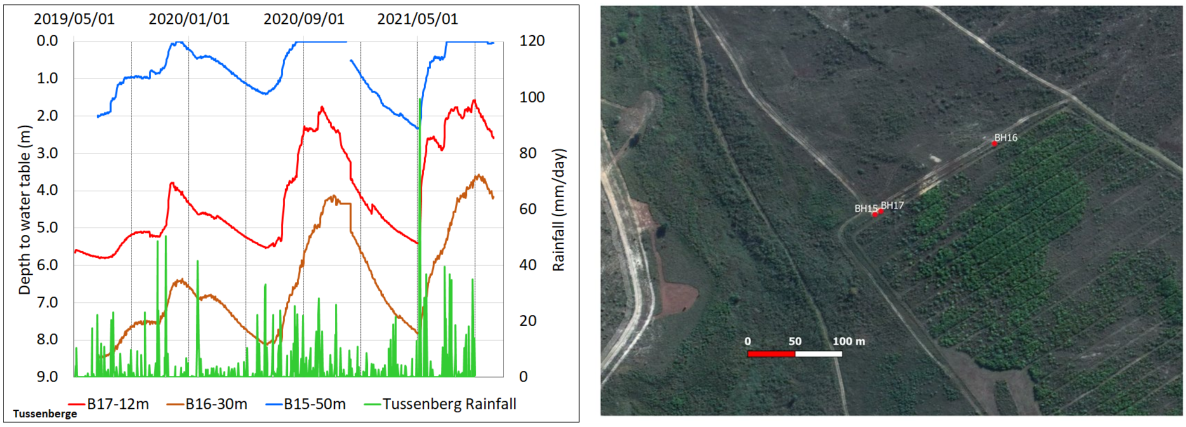

Figure 3.7: Variations of the water table depth below ground level (top right) and above sea level (bottom right) in Tussenberge boreholes, and the layout of boreholes. The nearest stream is at 192 m above sea level and 100 m from BH15 on the south-western part.

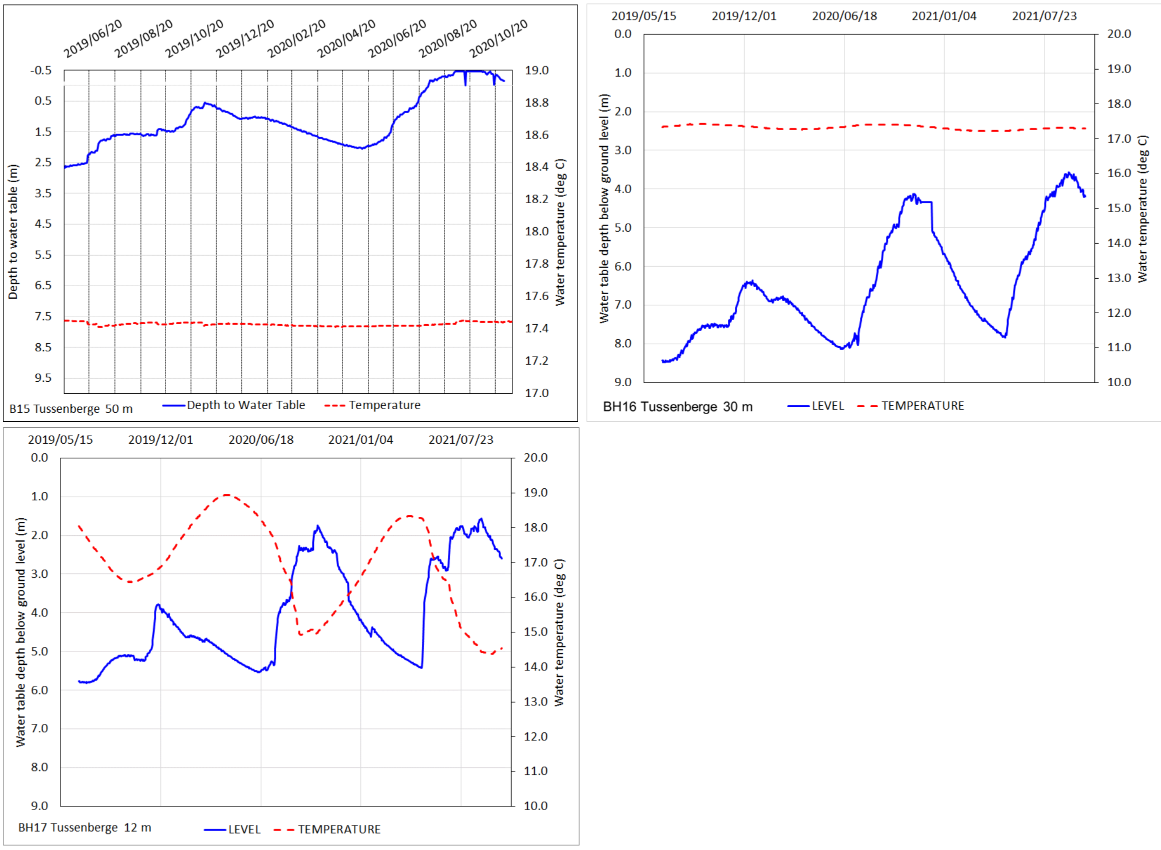

Figure 3.8: Temporal variations of groundwater temperature at Tussenberge

Groundwater in the deep aquifer (BH15 – 50 m) has fairly constant temperature (17.4°C) which is expected for a confined aquifer with a distant recharge area uphill (Figure 3.8). Groundwater temperature in BH16 – 30 m is similar to that in BH15 – 50 m, varying between 17.3° and 17.4°C. Water that was recharging the shallow aquifer, BH17 – 12 m, resulted in the reduction of groundwater temperature between May and September 2020 and then increased when the water table declined. The same pattern occurred in 2021 (Figure 3.8).

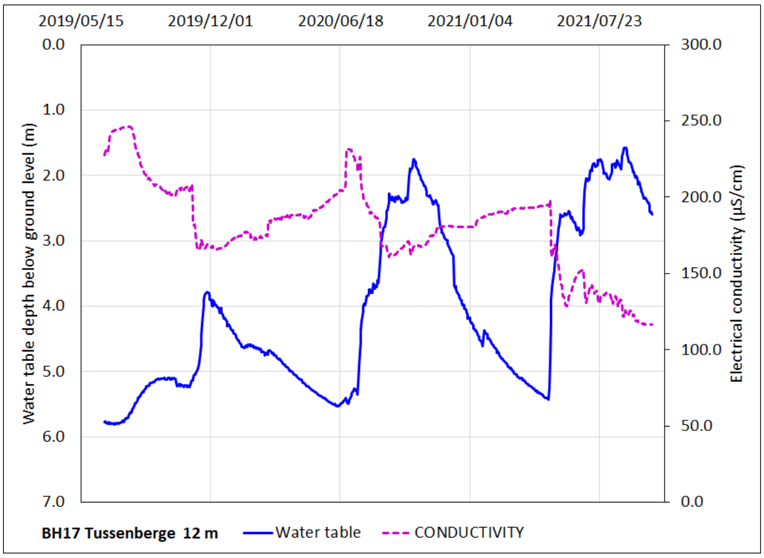

Figure 3.9: Variation of electrical conductivity of groundwater in the 12 m borehole at Tussenberge.

The electrical conductivity of groundwater in the shallow 12 m borehole at Tussenberge (Figure 3.9) increasesas the water table declines, and then decreases when the water table is rising which suggests rainwater recharging the aquifer. The average EC from June 2019 to October 2021 is 181 µmS/cm.

3.4.2 Sandfontein

The Sandfontein site has two boreholes 3 m apart with depths of 50 m and 11 m. The 50 m borehole has the following lithology;

Sandy soil	0-1 m
Weathered sandstone	2-3 m
Fractured sandstone	4-10 m
Sandstone	12-40 m
Shale	41-47 m
Hard sandstone	48-50 m

BH28 – 50 m has a casing up to 40 m depth, while BH29 – 11 m is cased up to 5 m depth.

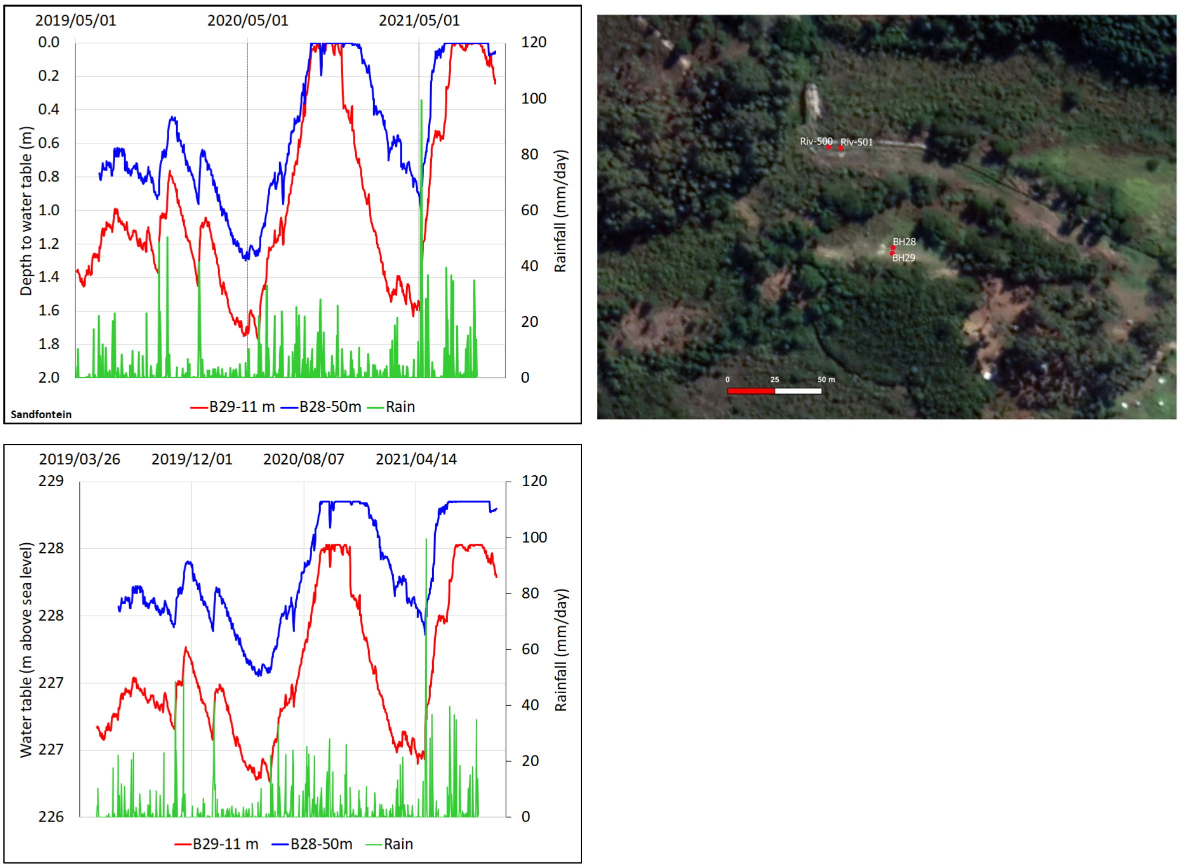

Figure 3.10: Temporal changes in the water table depth in Sandfontein boreholes, and the layout of boreholes with the stream (RIV-500, Riv-501) being at a distance of 55 m on the northern side and altitude of 222.82 m above sea level.

The water table in the Sandfontein boreholes varies from about 0.0 to 1.8 m (Figure 3.10). Pumping test data revealed no connectivity between the deep and shallow aquifer despite the water tables responding in a similar manner. The boreholes are located on the lower part of a hillslope which is a discharge zone, hence the similarity in water table responses. The 50 m borehole has a higher water table due to pressure from water flowing from an upslope recharge area. The water table declines from November/December to April/May. During the observation period, the water table was at the surface from 16 September-9 December 2020, and 25 June to 9 September 2021. The ground surface was observed to be waterlogged during these periods.

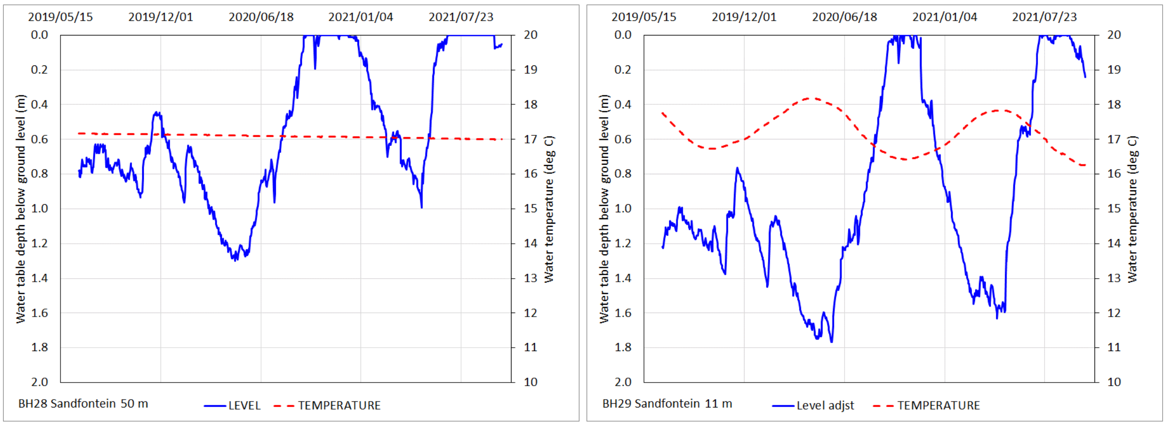

Figure 3.11: Water temperature in the Sandfontein boreholes.

Groundwater temperature at Sandfontein has similar variations to that at Tussenberge (Figure 3.11). Groundwater in the deep aquifer (BH28 – 50 m) has no changes in temperature, while recharge from above the shallow aquifer decreased temperature during the May to September 2020 period. The temperature slightly increased when the water table was declining (Figure 3.11).

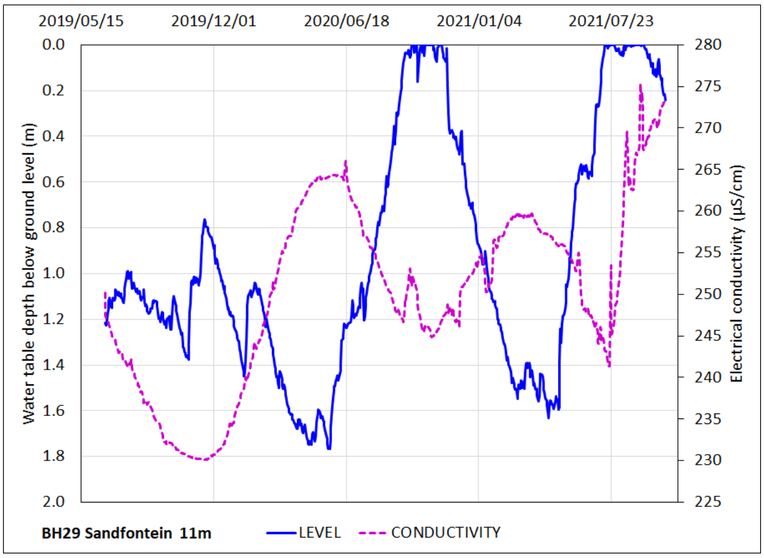

Figure 3.12: Changes of electrical conductivity of groundwater in the 11 m borehole at Sandfontein

Electrical conductivity in the 11 m borehole at Sandfontein (Figure 3.12) follows a similar pattern to the Tussenberge borehole, i.e. increasing as the water table declines and decreases when the water table rises. This again shows freshening of groundwater due to recharge from rainfall. The average electrical conductivity was 250 µmS/cm.

3.4.3 Jan Swartskraal

The Jan Swartskraal site has two boreholes, 5 m apart and drilled to 7 and 50 m depths. This site has coarse grained sandstone for the first 2 m, followed by shale from 2 to 29 m, and medium grained sandstone up to 50 m. The water tables in both boreholes have similar temporal variations. The 7 m borehole dried during the April-June 2020 and March 2021 period (Figure 3.13). The water table did not reach ground level in both boreholes, the highest level being 2.2-2.4 m below ground level and occurs during the July-October period depending on the occurrence of rainfall events sufficient to recharge groundwater (Figure 3.13).

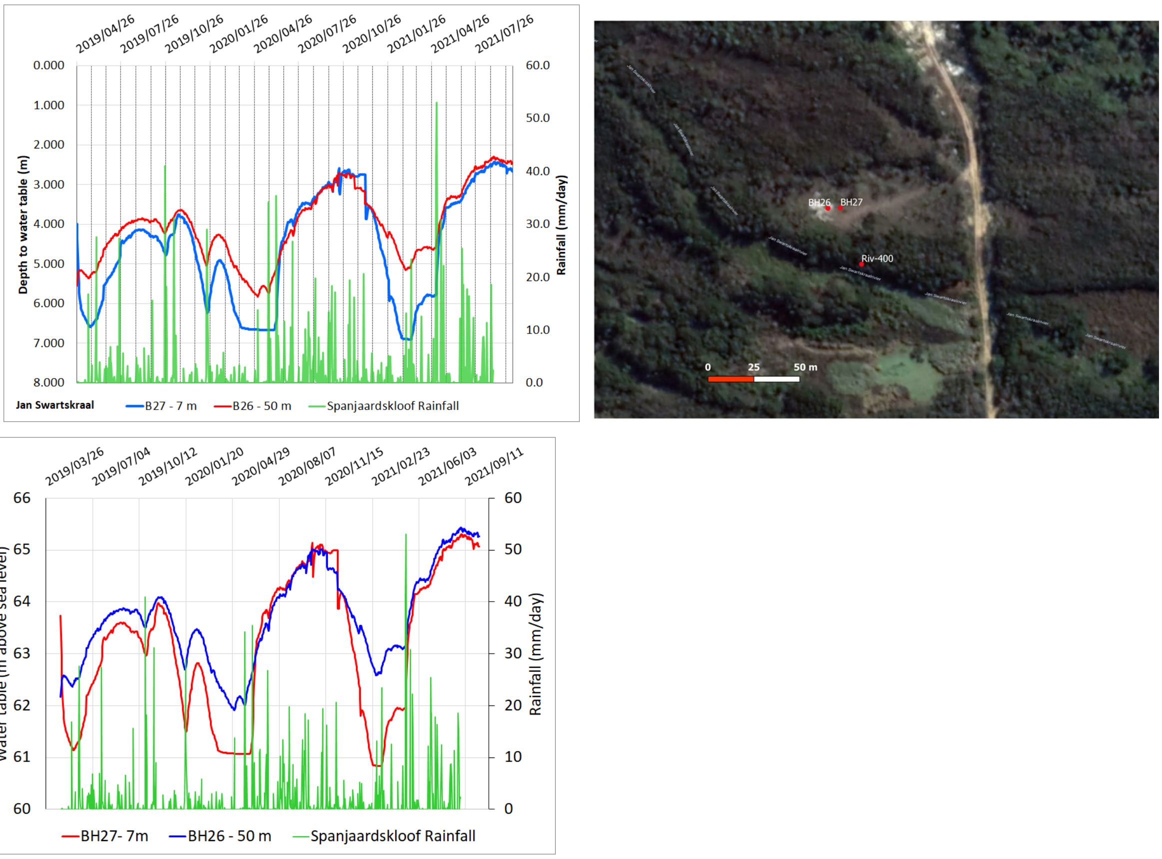

Figure 3.13: Responses of water tables to rainfall for boreholes next to Jan Swartskraal River. Riv-400 is the location of the river

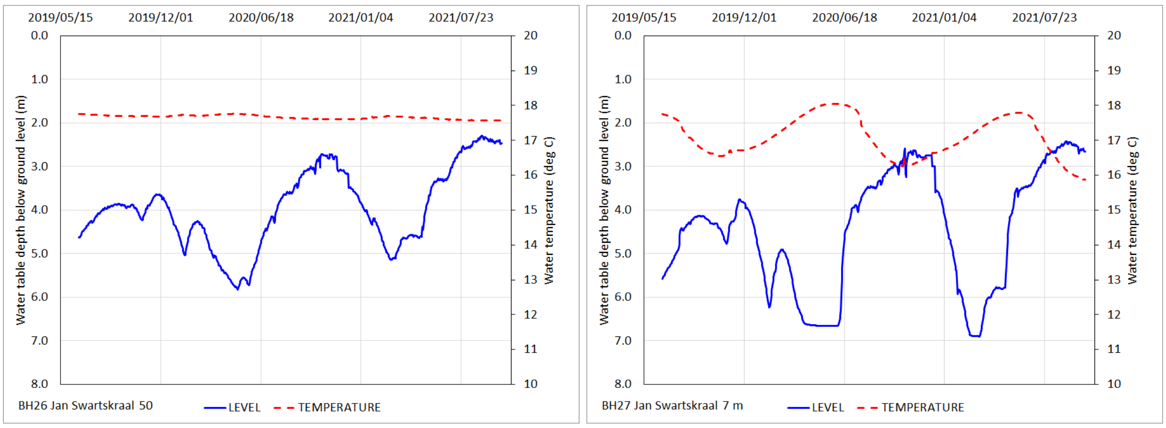

Figure 3.14: Variations of the water table and water temperature in boreholes at Jan Swartskraal, and the layout of boreholes.

Groundwater intercepted by the 50 m borehole (B26) at Jan Swartskraal does not experience temperature changes which is similar to observations at Sandfontein and Tussenberge (Figure 3.14). The drying of the shallow borehole resulted in increase in temperature recorded by the logger. The rapid recharge of the shallow aquifer (BH27 – 11 m) resulted in the reduction of groundwater temperature during the June-September 2020 period.

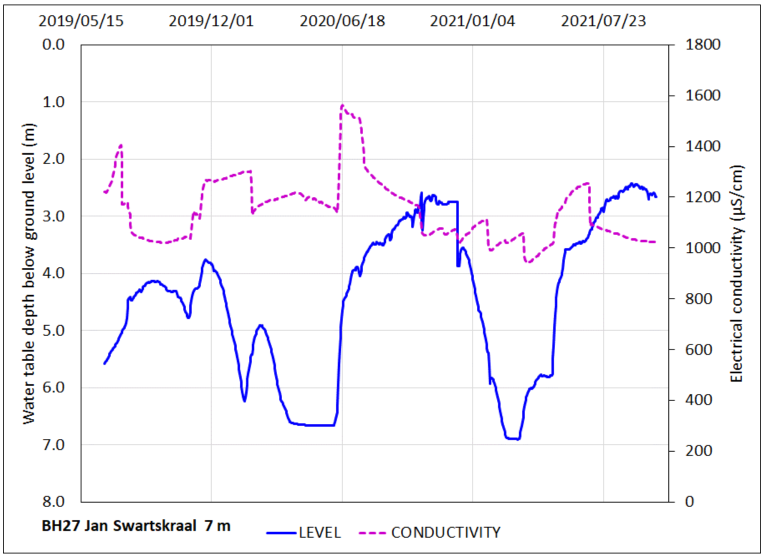

Figure 3.15: EC variations of groundwater in the 7 m borehole next to Jan Swartskraal River.

Electrical conductivity of groundwater in the Jan Swartskraal 7 m borehole shows a tendency to decrease when the water table is rising and increasing with declining water table (Figure 3.15). Groundwater at Jan Swartskraal has an average electrical conductivity of 1147 µmS/cm which is far greater than 181-250 µmS/cm in the headwater boreholes at Tussenberge and Sandfontein.

3.4.4 Spanjaardskloof

The 4 boreholes at Spanjaardskloof are located on a hillslope with elevation varying from 145 to 179 m above sea level. BH9 and BH10 are 4.35 m apart at an altitude of 145.5 m, while BH18 and BH19 at an altitude of 179 m and being 385 m from BH9 and BH10 (Figure 3.16). All the boreholes are in weathered and fractured sandstone. The water table in the 60 m borehole (BH9) responds to cumulative rainfall and not individual rainfall events (Figure 3.18). Thus the response is gradual. In contrast, the water table in BH10 – 20 m rises rapidly as a response to rainfall greater than 20 mm/day which cause rapid downward preferential flow through fractured rock. The water table rises rapidly by about 3-4 m and then declines to the original level within 1-5 days (Figure 3.16).

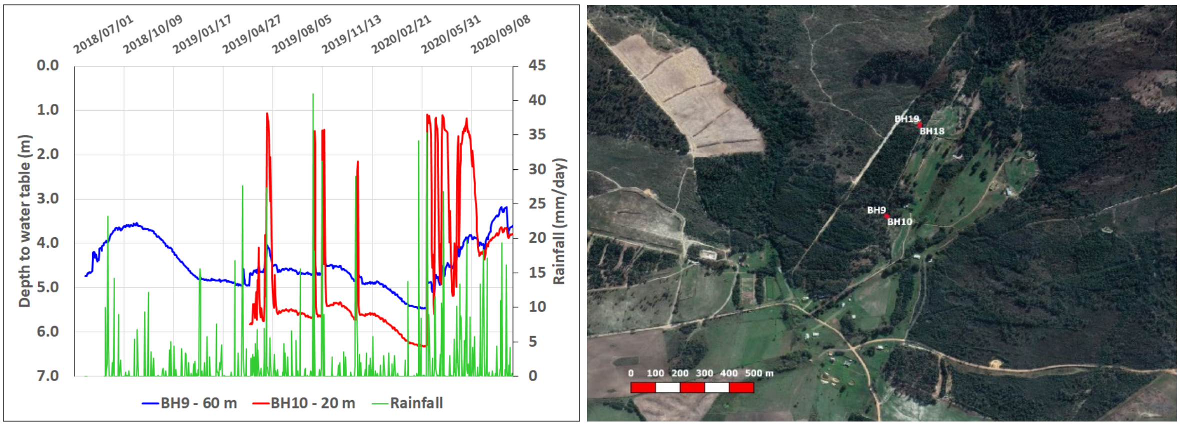

Figure 3.16: Temporal variations of depth to water table at Spanjaardskloof, and layout of boreholes. Boreholes at the southern part are at 145 m while northern boreholes are 179 masl

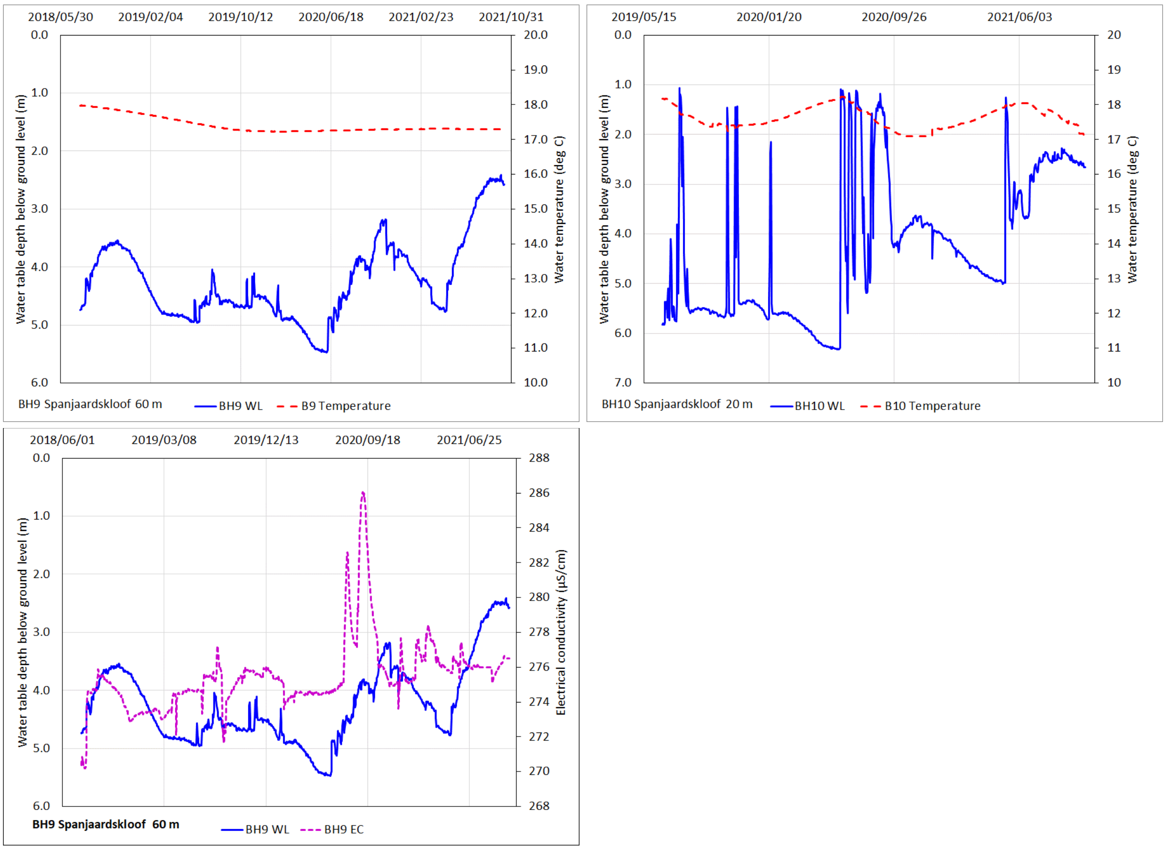

Figure 3.17: Water temperature and electrical conductivity in the Spanjaardskloof boreholes

Water temperature in the Spanjaardskloof boreholes does not have a clear relationship with changes in the depth of the water table (Figure 3.17). The water temperature in the 60 m borehole decreased from 18.0° to 17.2°C between July 2018 and September 2019, after which the temperature remained almost constant despite the rise in the water table. The downward recharge of groundwater due to preferential flow caused slight temperature increases.

3.4.5 Boskloof

The Boskloof site has 6 boreholes along an east-west 220 m transect descending towards the Boskloof Stream (Figure 3.18). Borehole depths range from 6 to 100 m. Sandstone occurs throughout with the exception of the 6 m borehole which has sandy clay, 3-4 m. Water level loggers occur in the 20 m and 60 m boreholes that are 5 m from each other and located at the top end of the transect. There is no difference in the depth to the water table in these two boreholes (Figure 3.18), which suggest that groundwater occurs in a single aquifer. Water tables generally decline from October/November to May/June followed by gradual rising. A similar pattern is observed in the static water levels measured on a monthly basis. Boreholes located on the lower part of the valley, BH21, BH22 and BH23 have water tables that are close to the ground level compared to the upslope BH11 and BH12. This is evident from the near waterlogged conditions occurring where the boreholes on the lower part are located. Following the wet seasons in both 2020 and 2021, the water tables in all the boreholes rose by about 2.0 m.

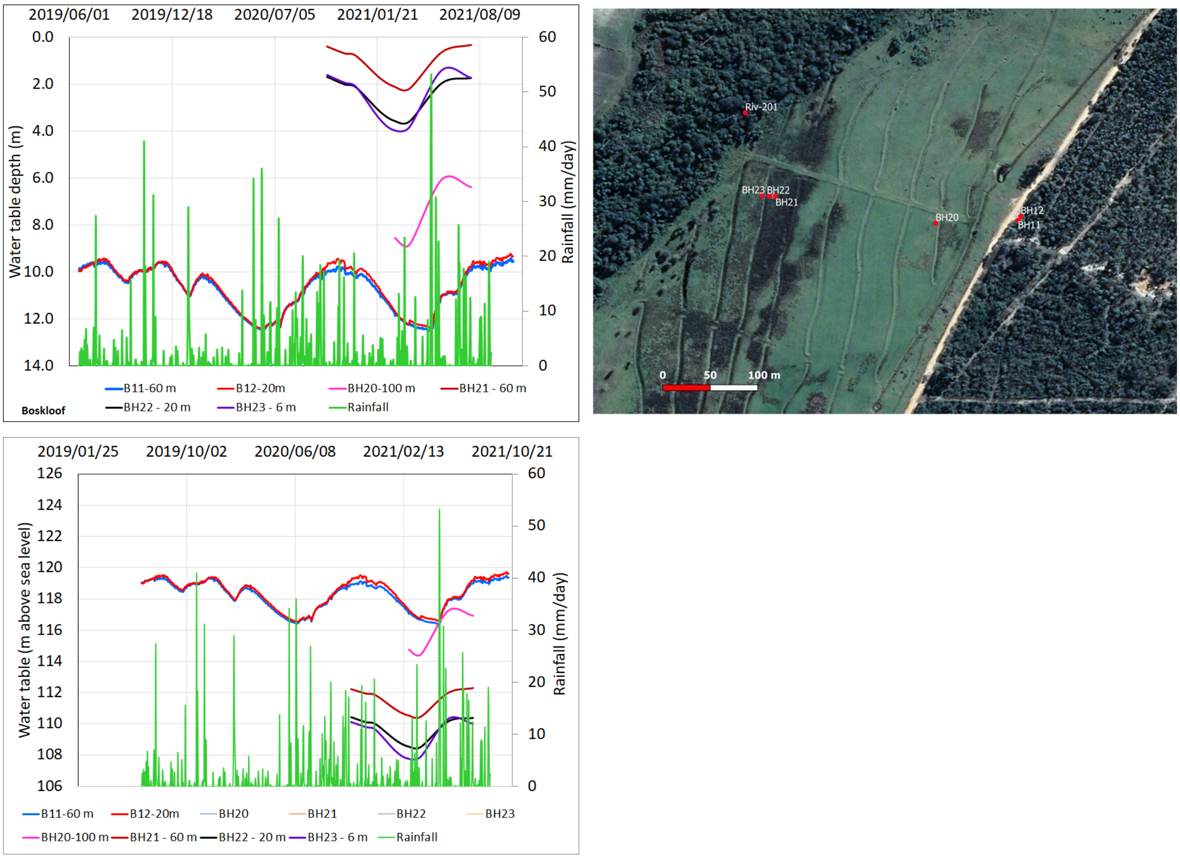

Figure 3.18: Water table fluctuations in the Boskloof boreholes, and the layout of boreholes along the valley slope with Boskloof River (Riv-201) on the western part.

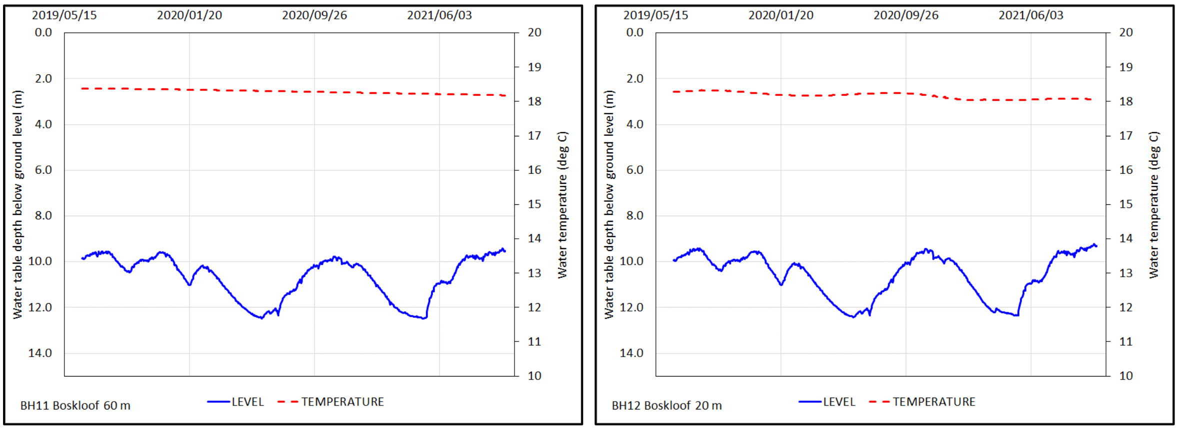

Figure 3.19: Water temperature changes for the Boskloof boreholes.

Groundwater temperature in the deep aquifer, BH11 – 60 m at Boskloof did not change significantly during the monitoring period (Figure 3.19). Very little cooling occurred in the 20 m borehole (BH12) when the water table depth rose.

There is no consistent vertical variation of EC among the Boskloof boreholes (Table 3.4). Boreholes BH11 and BH21 which have the same depth are 212 m apart. BH11 has lower EC values than BH21. The difference could be due to each borehole representing a different profile in the aquifer. The Boskloof boreholes are located in a NE-SW fault which may be influencing recharge processes and the EC. The lower EC at the bottom of the aquifer (BH11 and BH21) could be due to different water flowing from a distant recharge area.

Table 3.4: Electrical conductivity (µS/cm) based on monthly in-situ measurements in borehole depth at Boskloof

Borehole & Depth	Oct 2020	Nov 2020	Dec 2020	Jan 2021
BH23 – 6 m	698	686	827	737
BH12 – 20 m	808	826	927	795
BH22 – 20 m	502	496	560	486
BH11 – 60 m	666	668	759	654
BH21 – 60 m	415	494	498	447

3.4.6 Moddervlei

The Moddervlei site has 7 boreholes (Figure 3.20) with depths ranging from 7 to 50 m. Silt occurs in the top 1 m, followed by 5-10 m clay, and then shale. Water level loggers occur in 2 boreholes. The water table responds quickly to rainfall over 20 mm/day. The 65 mm rainfall received over two days in early June 2020 caused the water table to rise from about 2.0 to 1.0 m. Flooding due to ponding of high rainfall events that occasionally occur enhances recharge at Moddervlei. Groundwater at Moddervlei has very high EC ranging from 10000 to 35000 µS/cm. This could be due the occurrence of sand deposited during previous periods with high sea levels. High salinity occurs in most of the lowland areas. The water temperature was in the 18.0-18.3°C range.

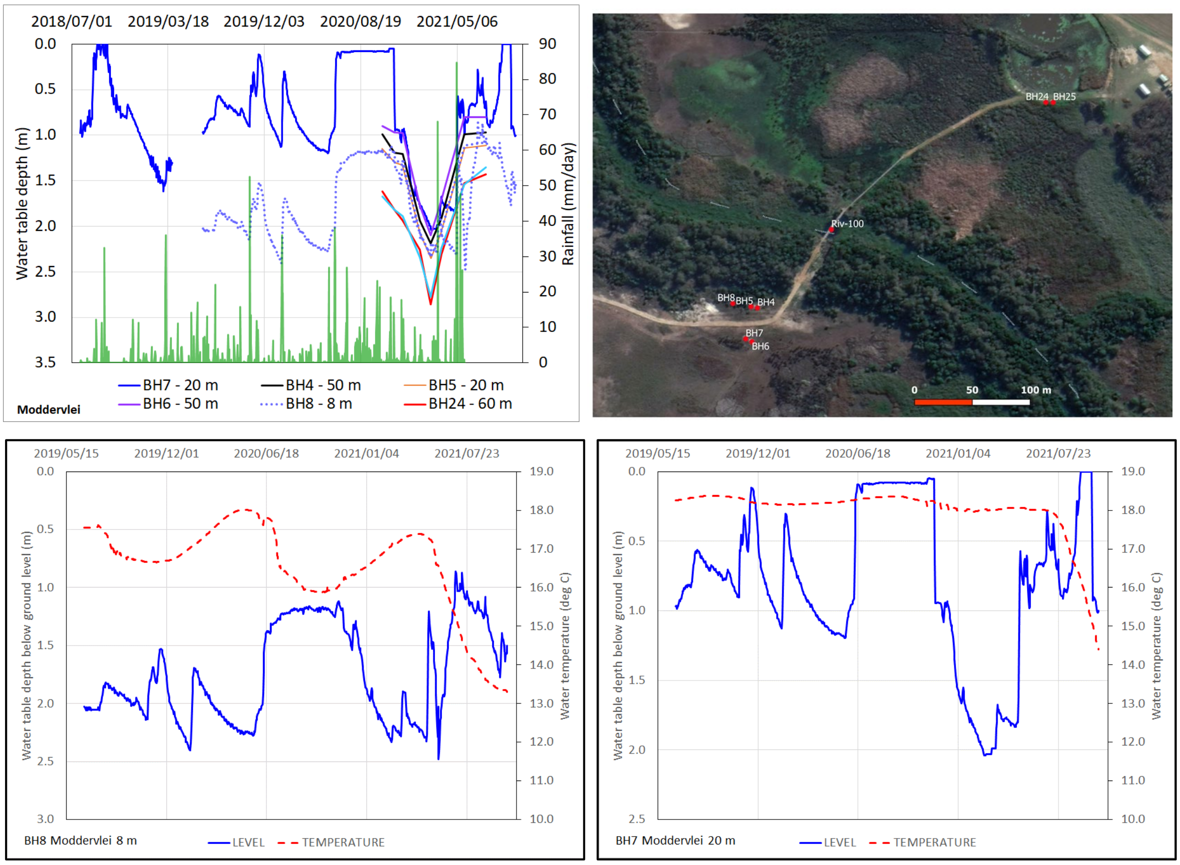

Figure 3.20: Water table and temperature fluctuations borehole at Moddervlei and layout of boreholes.

3.4.7 Uitsig

The Uitsig site has sandstone that varies from being weathered (<25 m) to fractured up to 55 m. The deeper borehole (BH13 – 55 m) has a higher water table than the shallow borehole (BH14 – 20 m). There are 2 nearby artesian wells on this farm which confirms upward movement of groundwater from a deeper aquifer (Figure 3.21). The presence of springs provides evidence that groundwater can make a contribution to surface water.

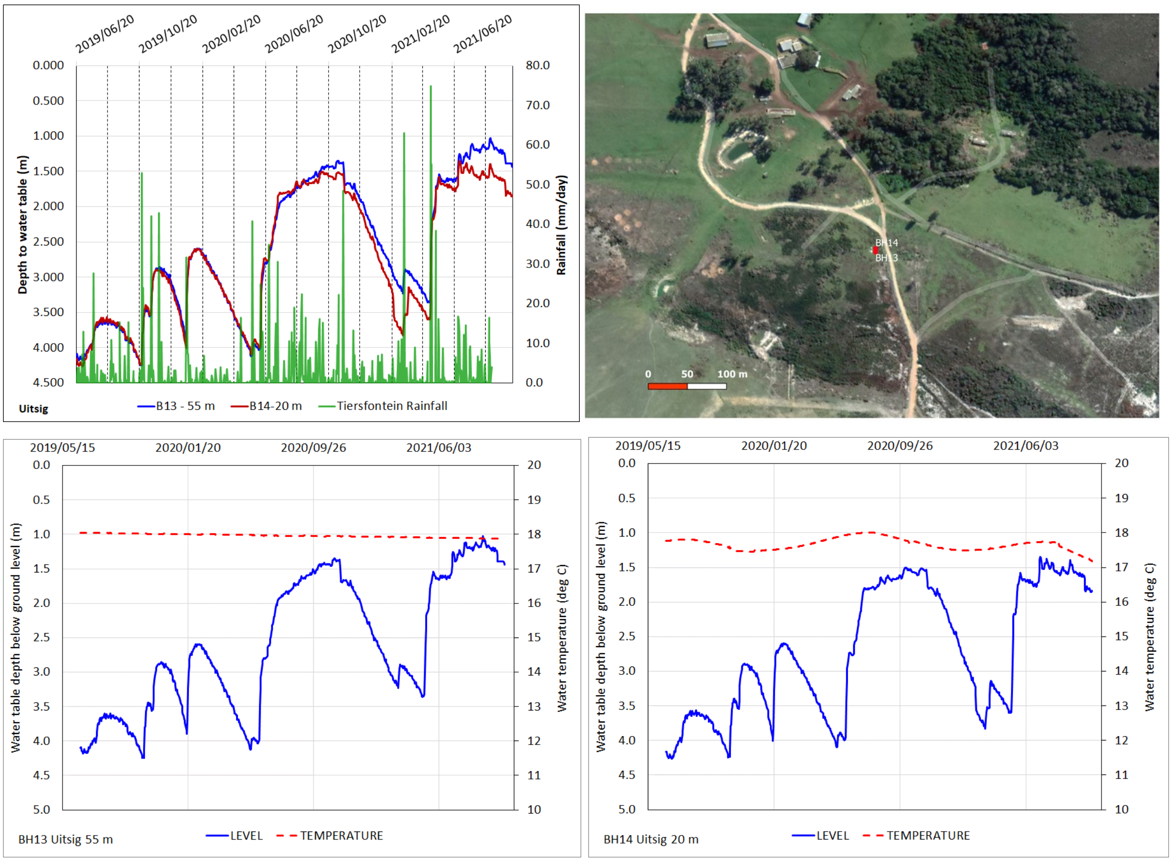

Figure 3.21: Water table and temperature variations in boreholes at Uitsig

3.5 HYDROCHEMISTRY OF SURFACE WATER

This section presents the results of the physico-chemical analysis of rainwater and river water sampled on a monthly basis from October 2020 to October 2021 at 25 sites within the Nuwejaars River catchment. During 2017 and 2018, sampling was done on a seasonal basis.

3.5.1 pH

The pH of river waters varied between 3.7 and 9.2 during the study period (Figure 3.22). The upland areas drained by the rivers Tussenberge, Sandfontein, Koue at Tiersfontein and Boskloof had acidic waters with a pH generally less than 5. River stretches within the midslope region such as Pieterseilieskloof and Jan Swartskraal rivers had pH close to neutral, between 5 and 6. (Figure 3.22).

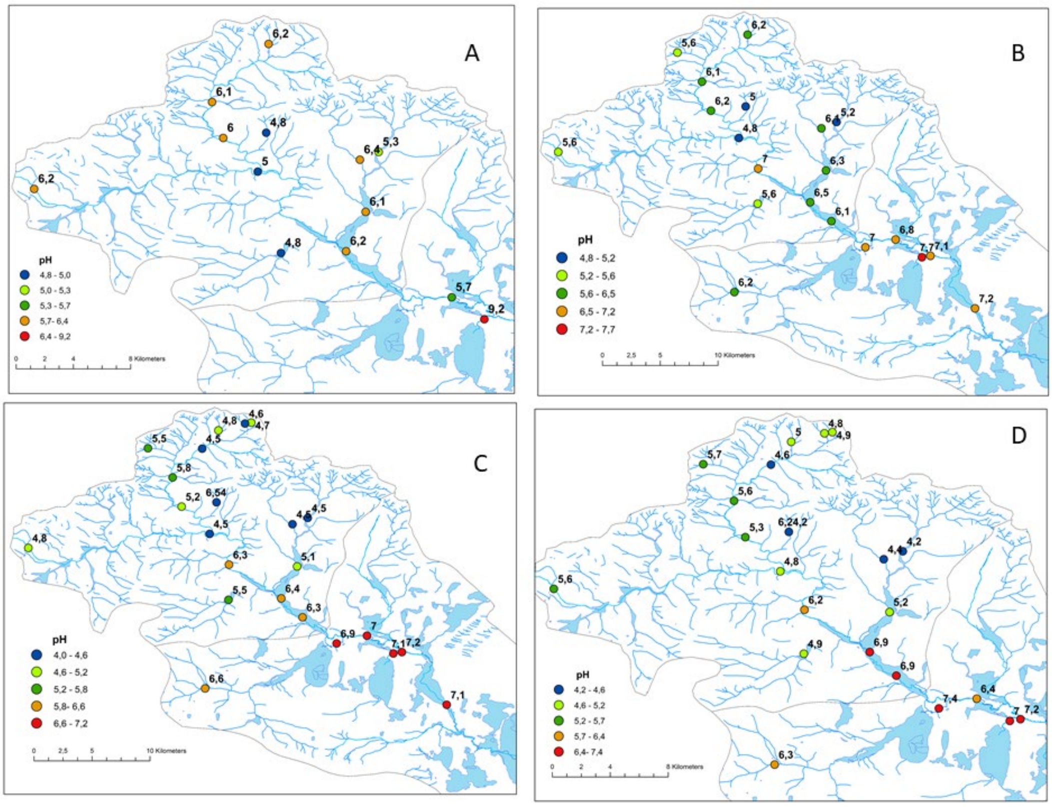

Figure 3.22: Spatial distribution of pH in surface water A) March 2021 B) May 2021, C) July 2021, D) September 2021.

The acidic nature of river waters in the uplands of the catchment is attributed to the presence of fynbos vegetation and the quarzitic formations. In the low-lying parts of the catchment along the Nuwejaars River from Moddervlei to the outlet from Soetendalsvlei, river water had pH from neutral to alkaline (Figures 3.22, 3.23) due to the calcareous soils of the southern Agulhas plain, and photosynthetic activity within the floodplain.

Figure 3.23 shows the change of pH from acidic to alkaline with distance along the rivers from the headwaters to lowlands. The change from acidic to alkaline water occurs at the beginning of the floodplain along the Nuwejaars River at Moddervlei.

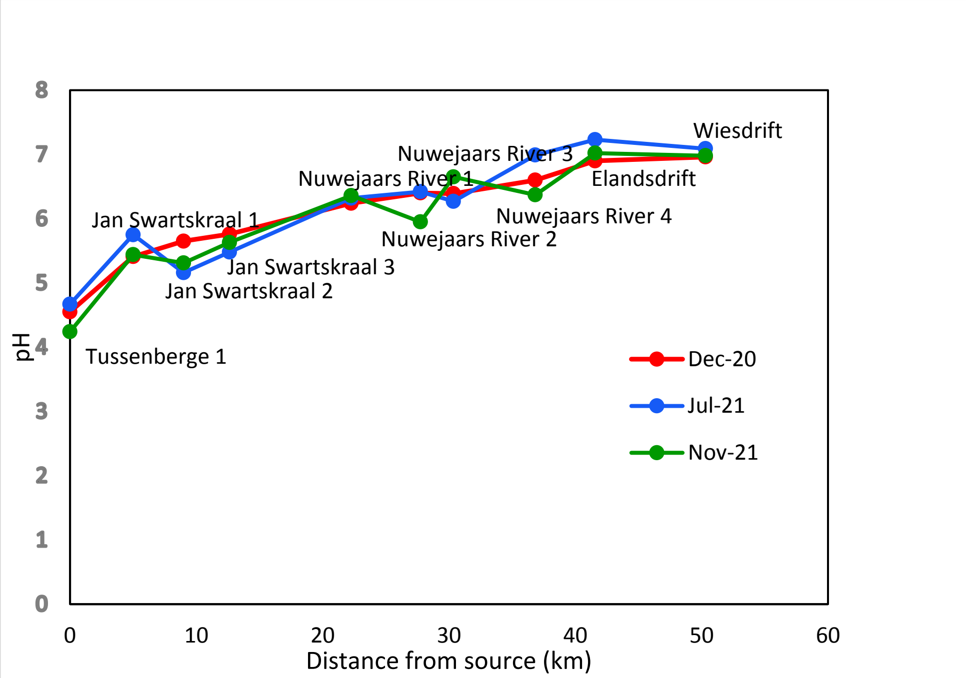

Figure 3.23: The relationship between pH and distance along the river from from the headwaters in Tussenberge to lowlands at Wiesdrift

3.5.2 Electrical Conductivity

EC of river water in the Nuwejaars Catchment is highly variable, ranging between 0.1 and 127.24 mS/cm during the sampling period (Figure 3.24). In the headwaters (Tussenberge, Sandfontein, Koue River) and midslope (Jan Swartskraal, Boskloof, Pieterseilieskloof), river water was generally fresh with EC values < 0.5 mS/cm (Figure 3.24). The EC of river water shows a distinct and significant increase (p value <0.05) from the headwaters to lowlands (Figure 3.24, 3.25). The EC-vs-distance plot shows a gradual increase with distance EC downstream until approximately 36 km from Tussenberge (Figure 3.23). Thereafter, EC increases to over 10 mS/cm until Wiesdrift at the lower end of the Nuwejaars River (Figures 3.24 and 3.25). The lower part of the Nuwejaars River had EC values higher than 20 mS/cm on several occasions, particularly during the drought period, from July 2017 to February 2019. The influence of water draining from lakes and saline pans on EC in the Nuwejaars River is evident from increases in EC at sites downstream of the confluence with the outlet from Voëlvlei and Soetendalsvlei outlet (Figures 3.27). The highest EC for the Nuwejaars River, 127.24 mS/cm, was observed in February 2019 at the SANParks Bosheuwel Educational Centre, which is in the lower part of the catchment. Besides the influence of saline pans that occur along the river, the flat lowlands allow for increased time for solute accumulation and dissolution in river water, coupled with the relatively saline Bokkeveld Group that underlies this region, which all contribute to these high EC values.

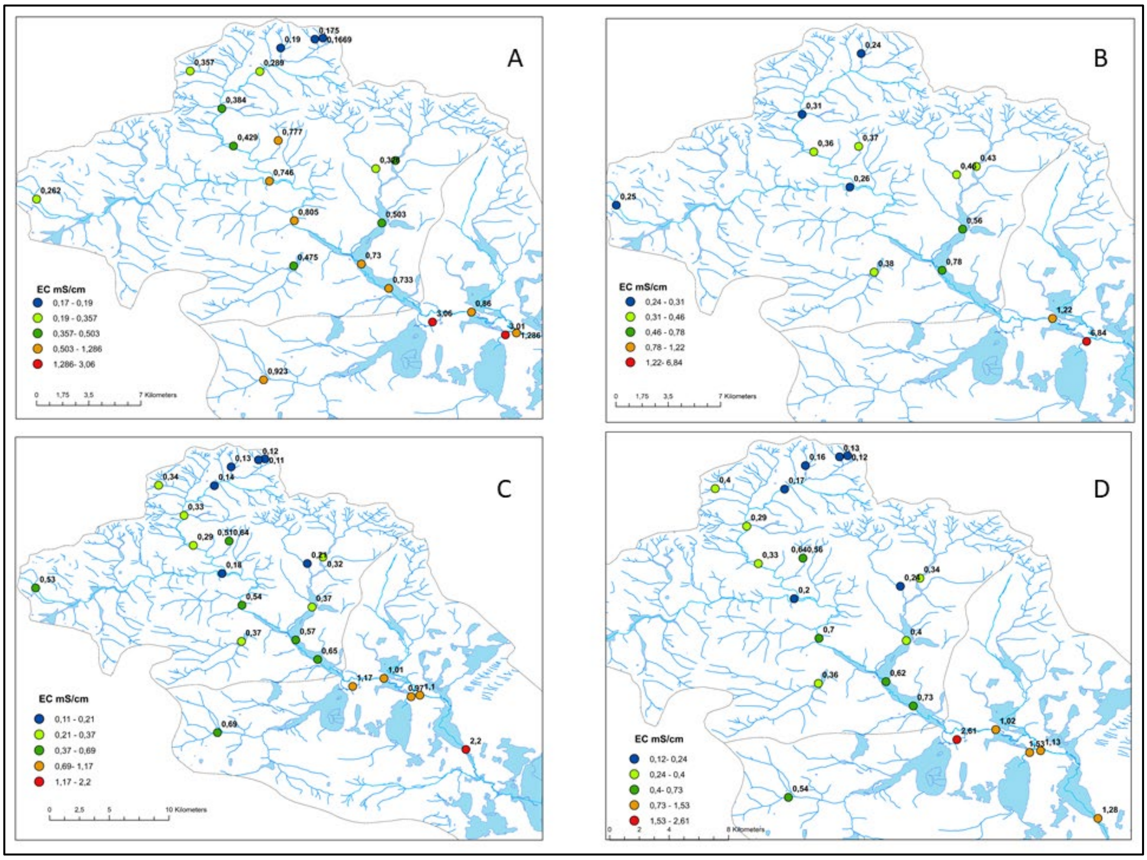

Figure 3.24: Spatial distribution of EC (mS/cm) in surface water during wet and dry seasons. A) October 2020, B) March 2021, C) July 2021, D) November 2021.

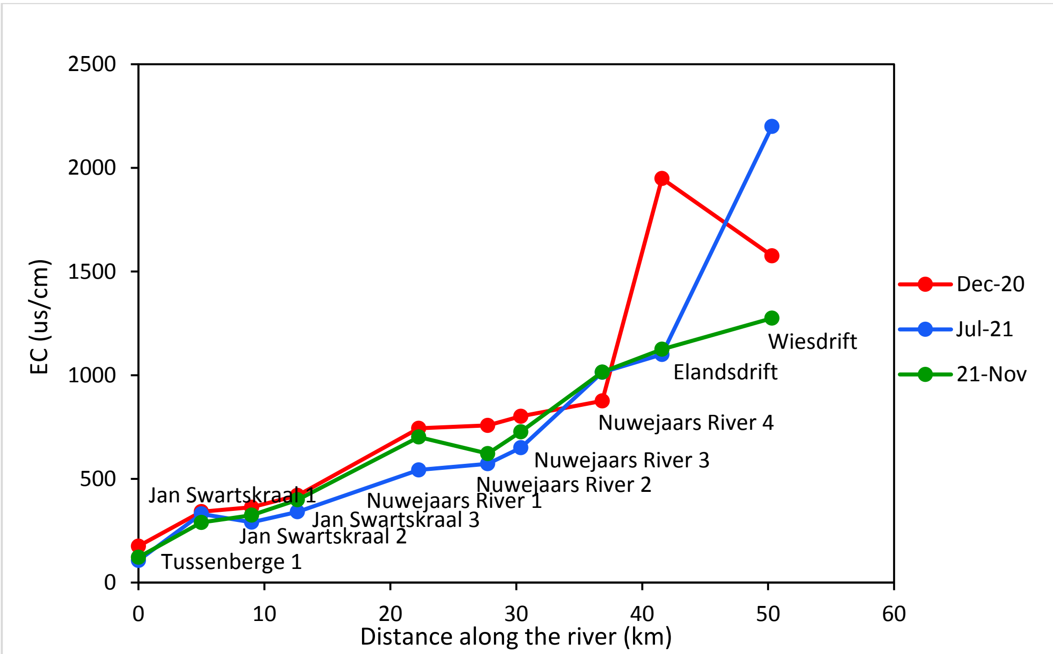

Figure 3.25: The relationship between EC and distance along the river from the headwaters in Tussenberge to lowlands at Wiesdrift

3.5.3 Rainwater

Rainwater samplers were installed at Tiersfontein and Tussenberge representing headwater locations, and Moddervlei in the lowlands. Monthly samples were analysed for major ions. The concentrations of sodium and chloride decreased during the wet period, April to July 2021 (Figure 3.26). Rainwater at Moddervlei in the lowlands has higher concentrations of all the ions compared to the upland locations. Calcium concentrations were higher during the wet season, April to September 2021, compared to the beginning of the year.

Figure 3.26: Concentrations of sodium, magnesium, calcium and chlorides in rainwater in the north-western (Tiersfontein) and northern (Tussenberge) headwaters, and central lowlands (Moddervlei)

The concentrations of major ions (Na, Mg, Cl, SO4) increase from the uplands to the lowlands (Figure 3.27). The concentrations increase during the dry summer period up to April, followed by a decrease during the wet period from June to September 2021. This is due to the dilution of relative large flow rates during the wet period, May-August. For example, peaks in concentrations can be observed at Koue River, particularly in the dry month of April 2021.

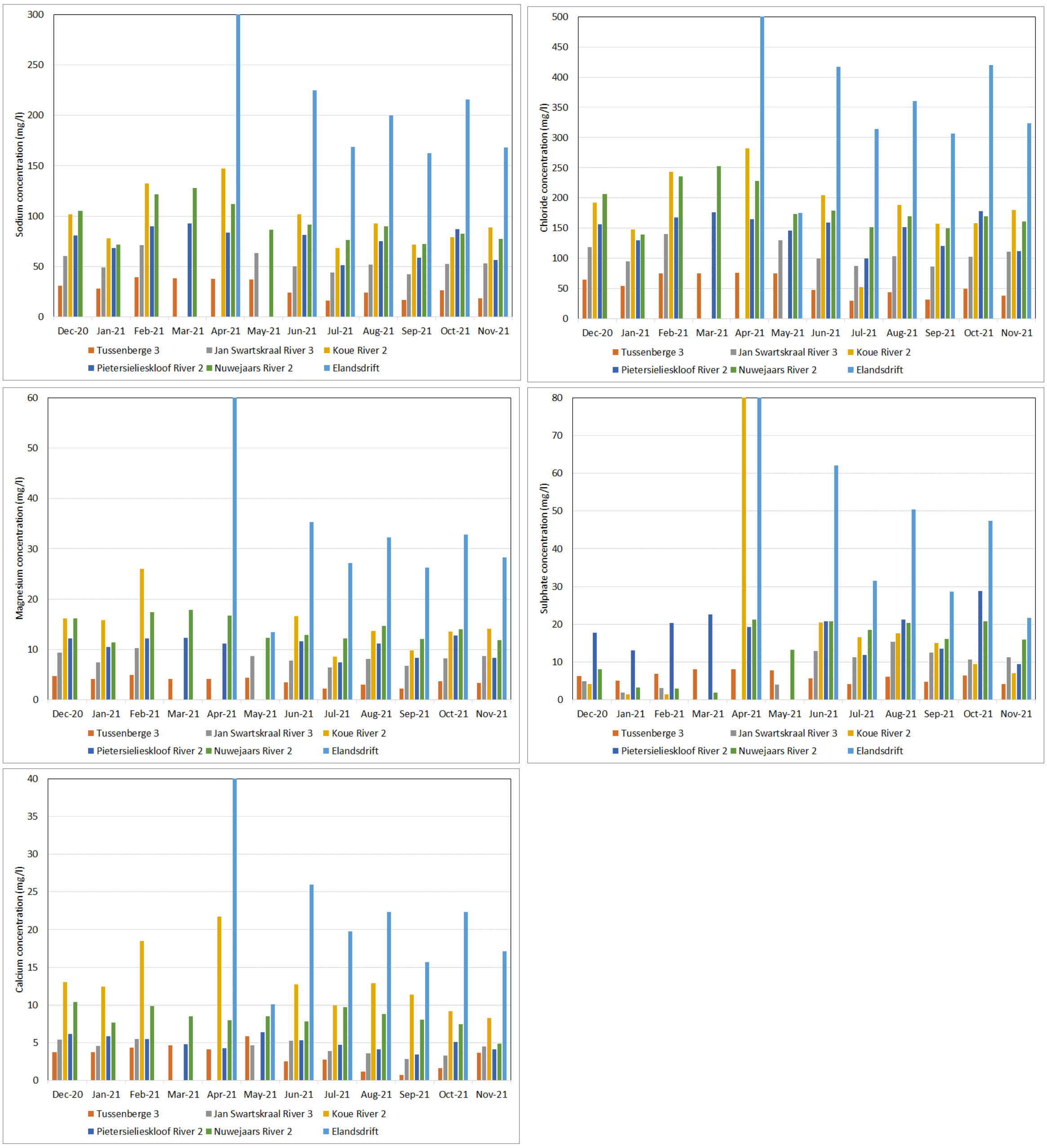

Figure 3.27: Spatial and temporal variations of selected ions along streams within the Nuwejaars Catchment. Tussenberge 3 = uplands, Jan Swartskraal = midslope, Koue River 2 = midslopes, Pieterseilieskloof 3 = midslope, Nuwejaars 2 = start of lowlands, Elandsdrift = lowlands.

3.6 CHARACTERIZATION OF GROUNDWATER CHEMISTRY

This section presents the results of the physico-chemical analysis of groundwater in the Nuwejaars catchment during the 2017-2021 period. Minimum and maximum pH and EC values of groundwater are given in Table 3.5.

Table 3.5: Summary of pH and EC of groundwater during the July 2017-November 2021 period.

Sampling period	pH		EC (mS/cm)	
	Min	Max	Min	Max
Jul-17	5.3	8.2	0.32	13.98
Oct-17	4.9	7.4	0.01	13.29
Mar-18	5.0	8.9	0.34	29.9
Jul-18	4.4	7.5	0.21	20.84
Feb-19	5.2	10.6	0.32	18.56
Jul-19	6.5	11.9	0.25	18.27
Aug-19	4.8	11.9	0.24	36.6
Oct-20	5.0	11.9	0.23	56.4
Nov-20	4.8	11.9	0.25	57.5
Dec-20	5.1	11.6	0.24	64.5
Jan-21	4.3	10.6	0.25	49.6
Feb-21	4.5	11.5	0.23	47.3
Mar-21	4.0	7.3	0.26	48.5
May-21	4.9	7.3	0.19	1.33
Jul-21	5.1	11.9	0.17	71.9
Sep-21	4.8	11.9	0.17	36.28

3.6.1 pH

The pH for groundwater ranged from 4.0 to 11.9 (Table 3.5, Figure 3.28). The pH of groundwater reflects the influence of the underlying rock formations. The acidic groundwater in the uplands is due to the Table Mountain Group (TMG) rocks. The presence of carbonate bearing formations such as limestone in the lower sections of the catchment, allows for rapid reaction rates of carbonate minerals, resulting in acid neutralisation and therefore alkaline groundwater.

The highest pH of 11.9 were recorded in July 2019 and September 2021 in borehole BH19 with a 20 m depth drilled in sandstone at Spanjaardskloof. Interestingly BH9 (60 m) and BH10 (20 m) drilled into sandstone and fractured sandstone, located 388 m downslope of BH19, had acidic water with a pH of about 5.3. The lowest pH reading (4.0) was recorded in March 2021 in BH16 (30 m) drilled in sandstone at Tussenberge in the uplands. The differences in pH between the upper and lower regions of the catchment were found to be statistically significant (p value <0.05).

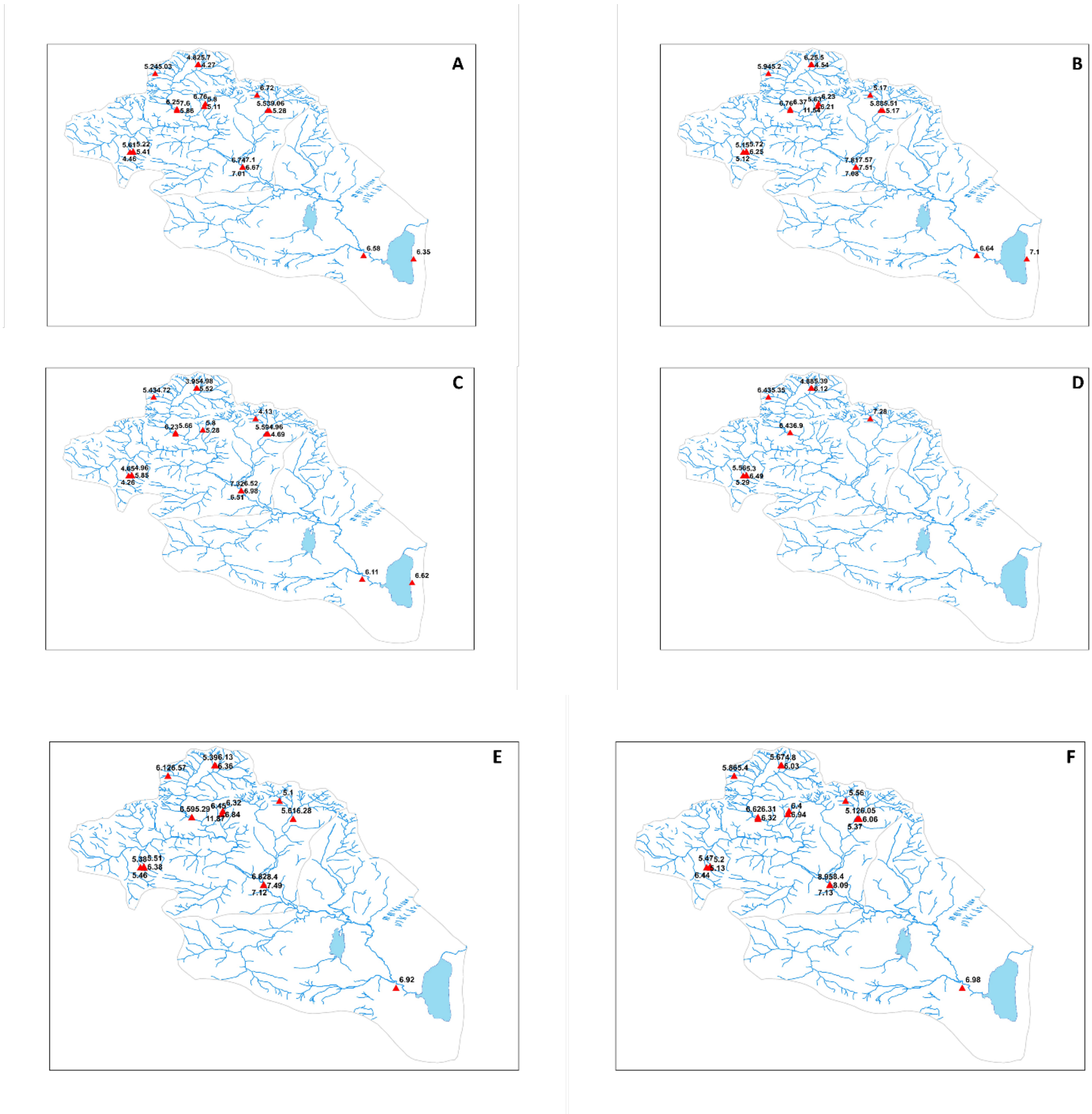

Figure 3.28: Spatial distribution of pH in groundwater during wet and dry seasons. a) January 2021, b) February 2021, c) March 2021, d) May 2021, e) July 2021, f) September 2021.

3.6.2 Electrical conductivity (EC)

EC ranged from 0.01 to 71.90 mS/cm during the sampling period and generally increased significantly from upstream to downstream (p value <0.05) (Figure 3.29). EC values as low as 0.01 mS/cm during October 2017 were confined to the upper catchment, which is underlain by geological formations of the Table Mountain Group. Rocks of this formation are heavily weathered and therefore inert and do not contribute significantly to salinity. The uplands are recharge areas of the catchment, hence more groundwater dilution occurs in this region. Meanwhile, groundwater in the lowlands from Moddervlei towards the sea, are underlain by shale formations and were characterized by high EC values.

Spatial differences in groundwater EC may also be attributed to topography. In the upper part of the catchment groundwater flows fast reducing contact time with aquifer material. On the contrary, due to low elevations and gradient in the lowlands, a small hydraulic gradient exists limiting groundwater flow resulting in a long residence time that allows for long contact periods between groundwater and the aquifer material. This may explain the higher EC concentrations measured in the lower sections of the catchment.

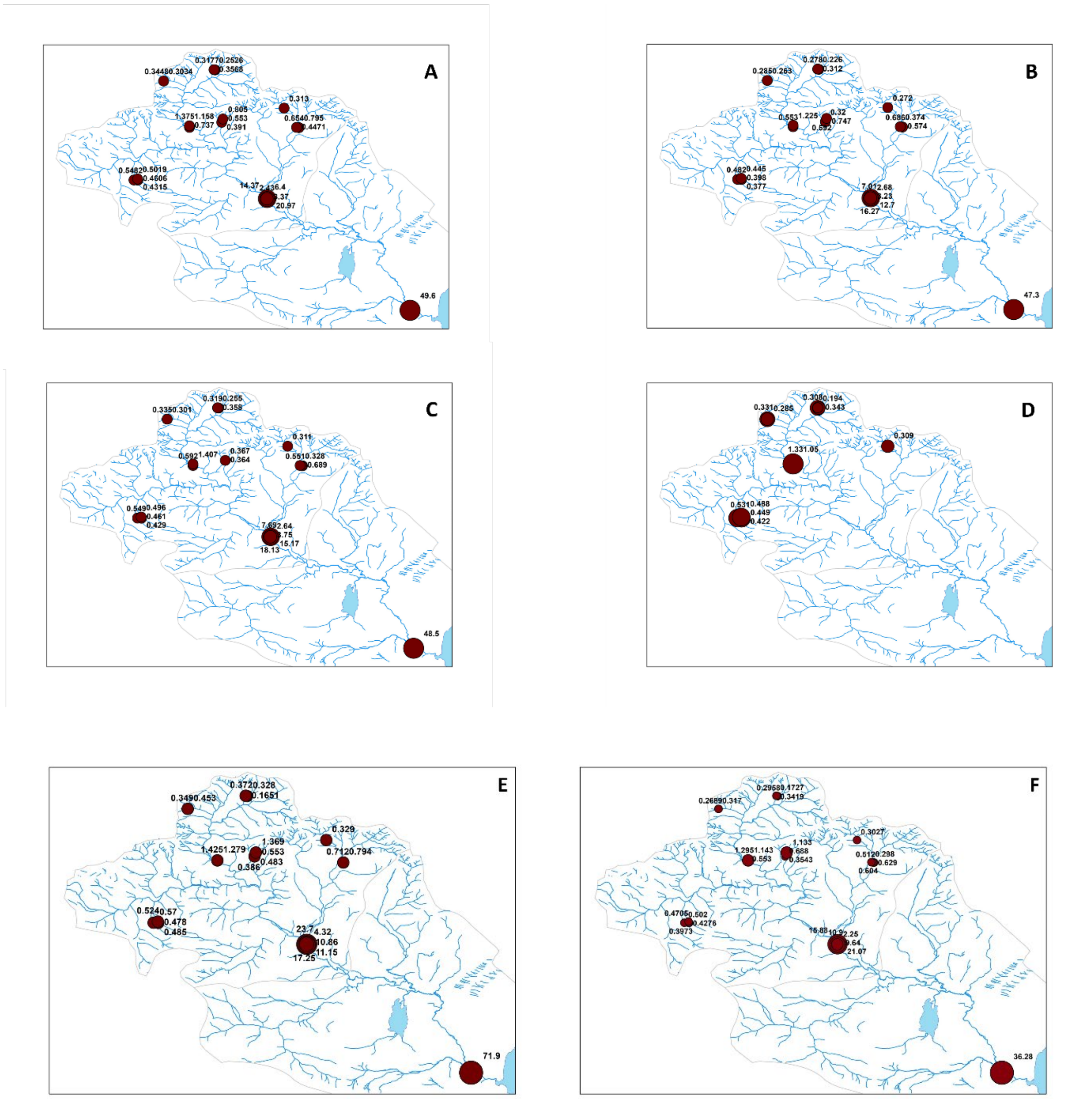

Figure 3.29: Spatial distribution of EC (mS/cm) in groundwater during wet and dry seasons. A) January 2021, B) February 2021, C) March 2021, D) May 2021, E) July 2021, F) September 2021.

3.6.3 Major ion distribution

The concentrations of sodium and chloride follow a similar trend increasing from the uplands to the lowlands (Figure 3.30). Tussenberge in the uplands had the lowest concentrations for the selected ions while the highest concentrations occur in the lowlands at Moddervlei. Chloride concentrations in deep groundwater in the sandstone region of the upper catchment were low, in the range 43-100 mg/l range, while the sections further downstream, underlain by shale and limestone, yielded higher concentrations, 2000-14455 mg/l. The variations in chloride concentrations in groundwater can be attributed to the nature of the underlying lithology and groundwater residence time. Groundwater flow downstream is limited, hence the increased concentrations of salts in this region, due to longer residence times. The results show that concentrations of magnesium and sulphate do not necessarily follow the same trend as sodium and chloride (Figure 3.30). Sandfontein in the uplands had raised sulphate whereas Moddervlei in the lowlands had low concentrations of sulphate.

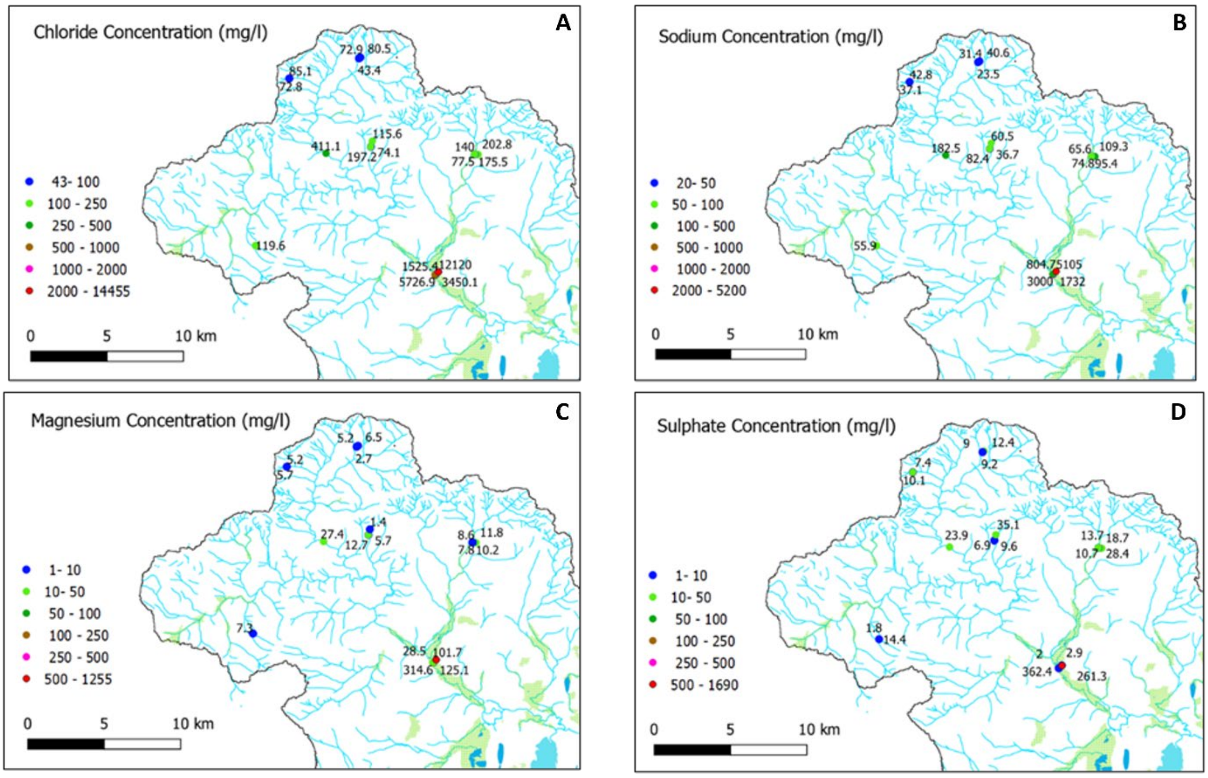

Figure 3.30: Spatial distribution of selected major ion concentrations in groundwater for September 2021, A) Chloride 2021, B) Sodium, C) Magnesium, D) Sulphate.

3.6.4 Water types

Groundwater and surface water in the Nuwejaars Catchment generally contain high proportions of major ions, particularly sodium and chloride. The data further indicate that the increase of a particular ion in groundwater also leads to an increase of that particular ion in surface water. Such similar changes in major ion concentrations between the two water sources suggests that groundwater and surface water may be interacting. This may suggest that the chemical qualities of surface water in certain sections of the catchment are often impacted by the quality of groundwater.

Major ions in groundwater and surface water had the following order of abundance: chloride > sodium > magnesium > sulphate > calcium > bicarbonate > potassium. Based on the proportions of cations and anions in groundwater and surface water, Piper diagrams were generated (Figure 3.31).

Groundwater and surface water in the study area predominantly belong to the sodium-chloride water type (Na-Cl water type), apart from BH 19, and rainwater (Tussenberge, Tiersfontein, Tussenberge 1 and 2) that deviated from the cluster and plotted in the Ca-Mg-Cl type water region. Similarities in water type between groundwater and river waters as illustrated in Figure 3.31, indicate that these waters originate from a similar source. This suggests the occurrences of surface water-groundwater interactions within the study area. Although Piper diagrams give insight into the possibility of connectivity between the rivers and aquifers within the study area, these diagrams do not show differences in ionic concentrations between samples which would be necessary to establish the location of groundwater discharge zones. Concentrated and dilute samples may fall in the same position on the piper diagram despite the samples having vast differences in ionic concentrations. This is a limitation of using piper diagrams to infer surface water-groundwater interactions.

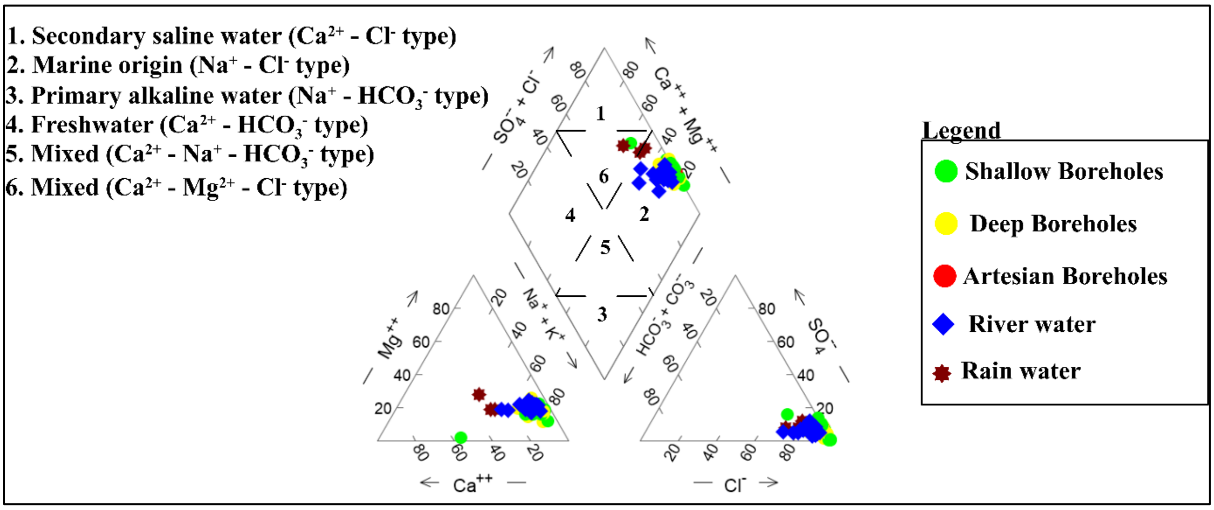

Figure 3.31: Piper diagram, showing similarities in ionic proportions of groundwater and surface water within the Nuwejaars Catchment.

The rainfall samples also plot in the Ca-Mg-Cl region on the diagram, the presence of high proportions of chloride in rainwater can be owed to sea-spray along the coast. The surface water and groundwater samples have different proportions of ions compared to the rainfall in the area. Shallow and deep groundwater also display similar proportions of ionic compounds. While certain river water samples show similar proportions to the groundwater, others tend toward the rainwater compositions, similarly for the groundwater, one shallow borehole seems to be reflecting similar ionic proportions to the rainwater of the region (Figure 3.31).

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CHAPTER 4: AQUATIC FAUNA ALONG THE NUWEJAARS RIVER

4.1 INTRODUCTION

The aim of the biotic component of the current project was *to examine how surface water-groundwater interactions influence ecosystems from headwaters to lowlands.* The objectives specifically of the faunal component were 1) to identify instream faunal assemblages in the Nuwejaars River in order to 2) find diversity patterns matching identified sections of the stream where ground and surface waters interact.

Like many other rivers in semi-arid and arid Mediterranean regions (e.g. de Moor & Day, 2013), the Nuwejaars River experiences frequent hydrological disturbances such as flash floods, droughts, and human impacts such as water abstraction, which affect the responses of plant and animal assemblages. The 18-month super-drought (2016 into 2018) that the Nuwejaars catchment experienced prior to the commencement of data collection for this project shrank the availability of water and thus habitats for aquatic organisms in the area. The drought made it practically impossible to sample and monitor aquatic organisms such as fish and invertebrates for part of the duration of the project. Often, the surface water in the Nuwejaars River disappeared or was reduced to isolated pools during the drought, although until then it had been considered to be a perennial stream. It can now be considered to be a non-perennial river (N-PR). These disconnected pools serve as transitional habitats of major ecological relevance in intermittent rivers (Bonada et al., 2020). They may serve as refugia that support aquatic ecosystems, thus maintaining local and regional biodiversity. Knowledge of patterns of species diversity and distribution is paramount in biomonitoring programmes, more so in highly dynamic and threatened freshwater systems (Altermatt et al., 2014).

Invertebrates are some of the first inhabitants of freshwater ecosystems when the system has water in it. Usually, when the water disappears, many of these ‘tiny animals’, the aquatic invertebrates, disappear with it. They either die or diapause into persisting propagules such as a resting egg, a young encysted larva or even as a desiccated larva or adult during these drought disturbances. Other species of invertebrates find refuge in disconnected pools that become established along the dry riverbed. Invertebrate diversity of these temporary systems is largely affected by migratory insects that fly in from permanent water bodies in the area (Day et al., 2010), and fly away when the water begins to dry up.

Invertebrates play critical roles in ecosystem functioning, such as leaf litter processing, although their activities are sometimes restrained by flow intermittence. Also, fish, reptiles, birds, and mammals prey on macroinvertebrates, especially during the dry period when they are trapped and exposed in the drying channels (Leigh et al., 2013; Stubbington et al., 2017). Thus, any changes in macroinvertebrate numbers, diversity, etc. may have a direct negative and spiralling effect on other species in the food web.

Although rivers like the Nuwejaars shift between lotic (flowing), lentic (ponding) and dry habitat phases, most research efforts seem to target the lotic phase, with very little research attention given to the lentic and dry phases. Dynamics of flooding and drying that lead to fragmentation of lotic ecosystems are a common occurrence especially in N-PRs, the Nuwejaars River included. Nonetheless, their ecological significance has not been extensively researched and rarely are the resident communities that occupy these systems during ponded phases represented in monitoring and management programmes.

The reasons for the distribution of species assemblages of invertebrates are diverse. The most common assertion is that 'delicate' species – i.e. those intolerant of wide fluctuations in water chemistry and temperature, and with narrow food requirements – are most likely to occur in the headwaters, while species with wider tolerance ranges are able to occur further downstream, where temperatures are higher and chemical conditions more variable. The usefulness of biomonitoring methods such as SASS, e.g. Dallas, 2021, depends on these differences in tolerance of aquatic invertebrates. Pollutants entering the stream will also affect species assemblages. It is also possible that assemblages will be affected by subsurface inflow of groundwater, particularly if the water chemistry of the surface and groundwater are detectably different to members of the assemblage (salinity, for instance). Knowing that, in the Nuwejaars catchment, groundwater has strong influences on surface flows, and that the salinity of the groundwater varies significantly from headwaters to lowlands (Malijani, 2020), we hypothesised that we would be able to find significant differences in invertebrate species assemblages down the length of the river, and that these could be associated with inputs of less or more saline groundwater. That is what we investigate in this chapter. Our attempts to answer this question were somewhat stymied by the drought: because samples could not be taken from sites that became dry, resulting in small numbers of samples.

Besides giving details of the spatio-temporal structure of macroinvertebrate communities collected during this temporary riverscape, this report also gives a snapshot of the fish that were coincidentally collected during this sampling period. Thus, the research provides a provisional checklist at a local scale of a gradient of faunal assemblages in an N-PR setup during both the wet and ponded phases. Findings from this work can inform the enhancement of biomonitoring programmes designed to characterize intermittent rivers ecosystems and ultimately to raise awareness of and support for conservation.

4.2 METHODS

4.2.1 Nuwejaars River and Catchment Characteristics

The Nuwejaars River has several tributaries in its upper catchment, although only the Koue, Jan Swartskraal and Boskloof were sampled for fauna during this research work. The lower Nuwejaars reaches are flat and low-lying, promoting the developments of pans and vleis, including Waskraal, Voëlvlei and Soutpan, that may drain into the river on occasion. Further downstream, the Nuwejaars flows into the Soetendalsvlei, the overflow from which has a confluence with the Kars River (Bickerton, 1984).

4.2.2 Description and location of the sampling sites

The number of sampling sites was not constant throughout the sampling period. On occasion some of the sampling points dried up completely, so no aquatic fauna occurred during those periods. Overall, we had twelve sampling points along the Nuwejaars River. Figure 4.1 presents their locations.

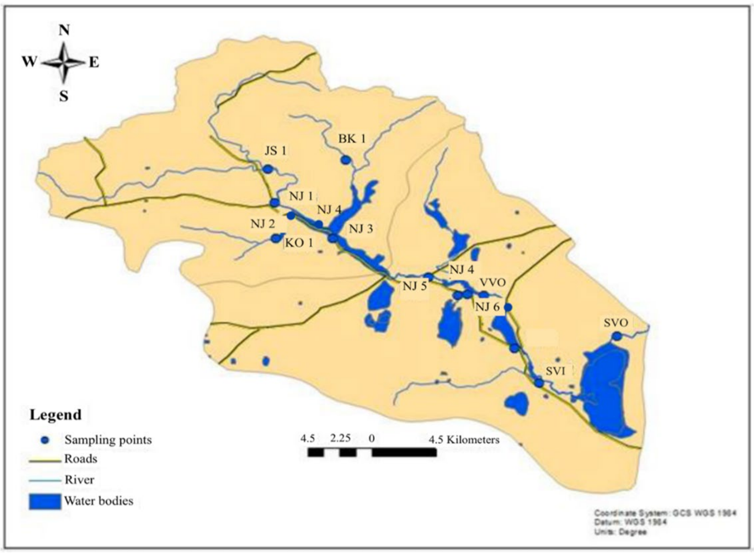


Figure 4.1: Location and distribution of surface water sampling points in the Nuwejaars Catchment (Adapted from Malijani, 2020)

4.2.3 Data collection

Macroinvertebrates were sampled semi-quantitatively using hand-nets with an opening of 400 x 200 m with 80 µm mesh. This exercise was carried out between July 2018 and August 2020. To ensure the representation of each taxon present, efforts were made to sample all available micro-habitats. Thus, besides sampling through the water column at the surface and above the sediment surface, sampling also involved sweeps through overhanging roots and vegetation patches. Fish were incidentally caught in the process. Furthermore, the hand-net sampling technique was supplemented by visual and hand searches under boulders, logs, etc.

To capture data for both dry and wet seasons, the study assessed diversity patterns within the different sampling months. In situ identification was performed, together with further identification to the best possible operational taxonomic resolution in the laboratory with the assistance of specialists. Collected samples were preserved in the field in 70% ethanol. For fish, taking too many specimens of the rare species was avoided by taking pictures of the individual specimens before releasing the fish back into the water.

4.2.4 Data Analysis

The total number of taxa (TNT), Shannon-Wiener diversity index (H′, $\log_{10}$) and Equitability were calculated at each site. Alpha (α) (differences in taxon richness and abundance within communities) and beta (β) (differences in taxon composition among communities) diversity patterns among and within rivers were compared to examine the macroinvertebrate diversity patterns. A two-tailed z-test $P(Z<=z)$ of difference between means with unequal variances was performed and Poisson distributions were assessed to predict the chances of occurrence of macroinvertebrates at different sampling points along the rivers. All the data were $\log_{10}(x+1)$ transformed before analysis to achieve the condition of normality and homoscedasticity of the data.

4.3 RESULTS

4.3.1 Fish

Usually, fish cannot exist out of water for any length of time, so they are rarely found in N-PRs. Whenever fishes are found in these temporary riverscapes, they must have come from a perennial upstream tributary or a reservoir. Exceptions are a few fishes like the lungfishes, which burrow into the sediment, and the killifishes, which bury their eggs in the sediment as the water dries up; neither occurs in South Africa. In the Nuwejaars River, juvenile fishes were encountered when using hand-nets to collect invertebrates in the river. The presence or absence of fish may be a useful aspect of biomonitoring of non-perennial rivers, especially when there is little data on the perenniality or otherwise of a river. In Agulhas, fish were collected only at four sites, all of which are in the headwaters. These sites are Tussenberge, Nuwejaars bridge, Boskloof and Moddervlei (Figure 4.2). Fish species were not found downstream of Moddervlei.

All three of the species that have been recorded from the river are still present: *Galaxias zebratus*, the Cape galaxias; *Sandelia capensis*, the Cape kurper; and a newly-recognised species of redfin minnow, *Pseudobarbus* sp. nov. “heuningnes”. Most of the specimens found in the river are aliens, however – mostly tilapias. At the Elim Flow Diversion, *S. capensis* occurred only once, in 2019 when the river was flowing. Thus, the fish might have been brought downstream by the current. This site was always dry, with no pools, when the riverbed was dry. It was only at Tussenberge and Boskloof sites that fish were reported during both the flowing and the dry seasons.

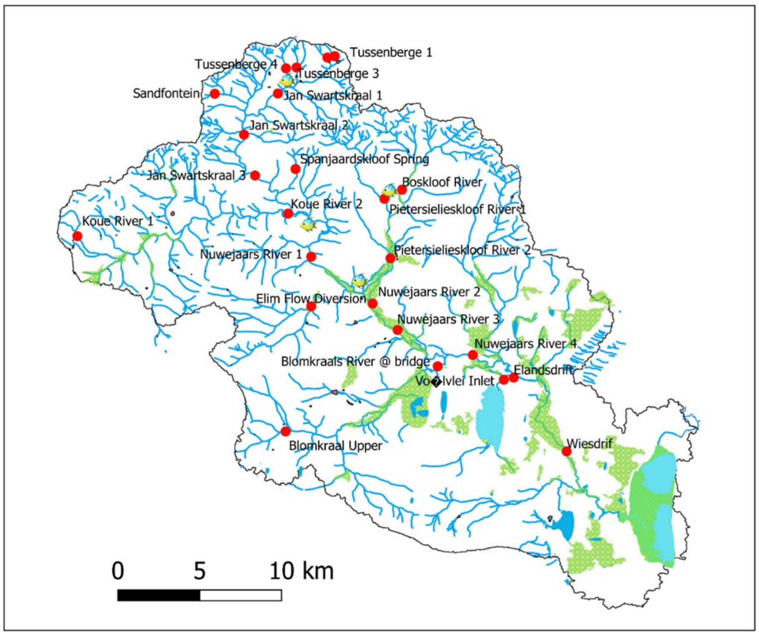


Figure 4.2: ***Distribution of fish along the Nuwejaars Rivers. Red dots represent the sampling sites, whilst the yellow/blue fish symbols represent sites where fish was found.***

In all macroinvertebrate cases, the research study attempted to test the following statistical hypotheses:
H_0: The mean number of individuals for each taxon is equal from

i. Case 1: headwaters to downstream,

ii. Case 2: from wet to dry

iii. Alternative Hypothesis/H_1: The mean number of individuals for each taxon is not equal.

Since the sample sizes are greater than 30, a two-tailed Z-test was done to test if there is a significant difference between means with unequal variances. Results showed that there are no significant differences ($Z < z$, 0.05) between headwaters and downstream macroinvertebrates. Thus, the data is essentially the same across all the sites, at the 5% level of significance.

Forty-four macroinvertebrate taxa (see Table 4.1) were reported from the 12 Nuwejaars River sampling sites. A tick was used to indicate that the taxon was reported from that site during the visits. The catch contained a greater percentage of instars of aquatic insects and a few adult insects, making identification very difficult. Owing to sampling bias, and behavioural and physiological adaptation by some of the taxa, the actual number of genera collected might not be a true representation of the actual diversity present in the area (Mlambo et al., 2009b).

4.3.2 Spatial and temporal distribution and trends of macroinvertebrates in the Nuwejaars River

Of the 52 macroinvertebrate families (Table 4.2) found in the Nuwejaars catchment, 19 were found only during the dry season, in lentic conditions. On the other hand, five of the species were not found during this dry period.

Table 4.1: Spatial and temporal distribution of taxa collected upstream and downstream in the Nuwejaars River and its tributaries. "Upstream" is above the Moddervlei site; "downstream" is from Moddervlei and downstream. "Wet" is when the river is flowing; "Dry" is when there is no flow. A tick (√) refers to the presence of a taxon.

Taxon	Upstream	Downstream	Wet	Dry
Crustacea				
Anostraca	√	√	X	√
Conchostraca	√	√	√	√
Cladocera	√	√	√	√
Copepoda	√	√	√	√
Ostracoda	X	√	X	√
Amphipoda	√	√	√	√
Arachnida				
Hydracarina	√	√	√	√
Insecta				
Isotomidae	√	√	√	√
Plecoptera				
Notonemouridae	√	X	X	√
Ephemeroptera				
Baetidae	√	√	√	√
Caenidae	√	√	√	√
Leptophlebiidae	√	X	X	√
Teloganodidae	√	X	X	√
Odonata				
Aeshnidae	√	√	√	√
Coenagrionidae	√	√	√	√
Gomphidae	√	X	X	√
Libellulidae	√	√	√	√
Chlorolestidae	√	√	X	√
Hemiptera				
Corixidae	√	√	√	√
Notonectidae	√	√	√	√
Naucoridae				
Gerridae	√	X	X	√
Veliidae	√	√	√	√
Trichoptera				
Ecnomidae	√	X	X	√
Hydroptilidae	√	√	√	√
Coleoptera				
Dryopidae	X	√	√	X
Dytiscidae	√	√	√	√
Elmidae	√	√	√	√
Hydrophilidae	√	√	√	√

Taxon	Upstream	Downstream	Wet	Dry
Scirtidae	√	X	X	√
Hydraenidae	√	√	√	√
Gyrinidae	√	X	X	√
Diptera				
Simuliidae	√	√	√	√
Tipuliidae	√	√	√	√
Ephydridae	√	√	√	√
Culicidae	√	√	√	√
Chironomidae	√	√	√	√
Tabanidae	√	√	√	√
Lepidoptera				
Crambidae	√	√	√	√
Mollusca				
Planorbidae	X	√	√	√
Physidae	X	√	X	√
Annelida				
Oligochaetae	√	√	√	√

No patterns in spatial distribution of macroinvertebrates are evident in the data during both the wet and dry seasons (see Figure 3 a. and b.).

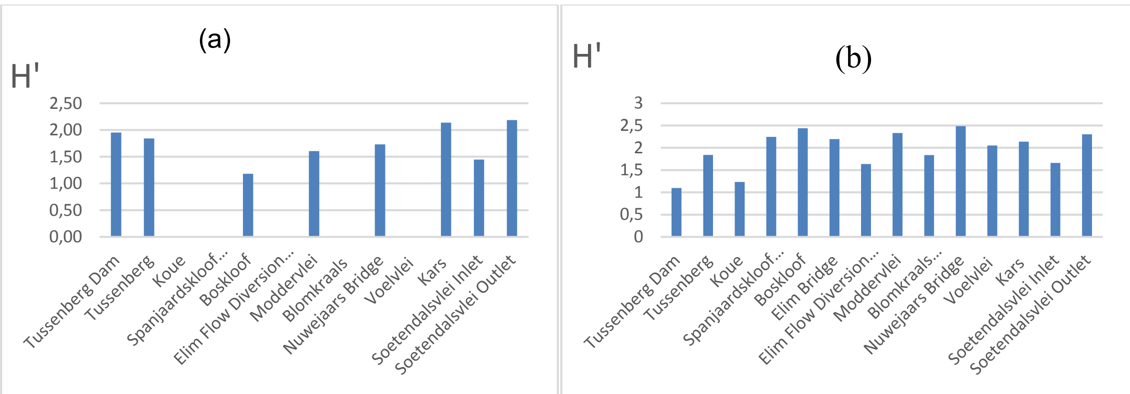


Figure 4.3*: Spatial distribution of macroinvertebrates during the (a) wet and (b) dry season in the Nuwejaars River*

The assemblages at the different sites appeared to behave independently. Furthermore, there is no evidence overall of significant differences in the number of macroinvertebrates over time (z test, p=0.968).

The Poisson distributions (Table 4.2) did show, however, that there is a greater chance of larger numbers of macroinvertebrates as one moves downstream from the headwaters. With the upstream reference site being Tussenberge, sites like the Koue are therefore expected to have few macroinvertebrates, while Boskloof is twice as likely to have more inverts than Tussenberge. The Soetendalsvlei outlet, which happens to be the downstream-most site for this project, was predicted to be 0.5 times less likely to have macroinvertebrates compared to Tussenberge, which is in the headwaters.

Table 4.2: Prediction of the distribution of macroinvertebrates from the headwaters downstream. IRR = Incidence Rate Ratios; SE = Standard Error; z and P>|z| are the test statistic and p-value, respectively;

Site name	IRR	SE	Z	p>|z|	[95% Conf. Interval
Koue tributary	0.75	.4050463	-0.53	0.954	0.2602 2.1615
Jan Swartskraal tributary	1.5	.6846532	0.89	0.374	0.6132 3.6695
Boskloof	2	.8660254	1.60	0.109	0.8559 4.6731
Elim Bridge	0.875	.4528555	-0.26	0.796	0.3173 2.4129
Elim Flow Diversion Point	1.25	.5929271	0.47	0.638	0.4933 3.1672
Moddervlei	1.125	.5466517	0.24	0.808	0.4341 2.9158
Blomkraals (Waskraal)	0.75	.4050463	-0.53	0.594	0.2602 2.1615
Nuwejaars Bridge	1.875	.8208703	1.44	0.151	0.7950 4.4224
Voëlvlei Outlet	1	.5	0.00	1.000	0.3753 2.6644
Soetendalsvlei Outlet	1.5	.6846532	0.89	0.374	0.6132 3.6695
Soetendalsvlei Inlet	1	.5	0.00	1.000	0.3753 2.6644
_cons	8	2.828427	5.88	0.000	4.0008 15.9969

Though not statistically significant (p=0.839), the Poisson distribution output (Table 4.3) which is a general comparison of the upstream and the downstream sites, revealed that the numbers of invertebrates at downstream sites are slightly (1.03 times) likely to be greater than at upstream sites.

Table 4.3: Prediction of the distribution of macroinvertebrates from the headwaters downstream. IRR = Incidence Rate Ratios; SE = Standard Error; z and P>|z| are the test statistic and p-value, respectively

Site name	IRR	SE	Z	p>|z|	[95% Conf. Interval
Downstream	.9992404	.0194773	-0.04	0.969	.9618 1.0382
_cons	9.457266	1.673757	12.70	0.000	6.6853 13.3787

4.3.3 Biodiversity indices for the Nuwejaars River sites during the dry season

We characterized community composition, alpha diversity and beta diversity across a seasonal and spatial gradient of drying. The study monitored the compositional changes and changes in benthic alpha diversity over seasons. Some of the macroinvertebrate taxa frequented both the flowing and non-flowing river sites. Significant variation ($z < 0.05$) was noted with regards to temporal variations of species composition across sites. For both the wet and the dry seasons, the headwater sites had very high diversity. This is supported by the high Shannon-Wiener and Equitability indices in Tables 4.4 and 4.5. The measure of Equitability ranges from 0 to 1. A site is considered diverse when its Equitability status is close to 1 and less diverse if closer to 0. In this particular case, most of the sites which are in the middle section of the catchment (e.g. Blomkraals and Elim Diversion) had low Shannon-Wiener diversity and Equitability. Some of the sites indicated a zero diversity index because they were dry during that season. The sites that were sampled during this period were the disconnected pools that persisted during the dry period. Headwater sites like Tussenberge, Spanjaardskloof and Boskloof consistently had high diversity across seasons.

The flowing/wet season provided the habitat for the aquatic fauna, and hence the increase in the diversity index. Although the difference is not statistically significant, the flowing season was defined by the increase in diversity across all the sites. As fairly predicted by the Poisson distribution, the diversity increased as one from headwaters to downstream.

It is noteworthy that some of the invertebrate taxa were exclusively found at upstream or downstream sites, and vice versa. This scenario was also observed in fish as they were exclusively found upstream of Moddervlei. Description of biodiversity patterns and the underlying drivers is of uttermost importance in the monitoring and management of freshwater ecosystems, especially in the scarcely studied N-PRs.

Table 4.4: Shannon-Wiener and Equitability indices for the Nuwejaars River sites during the dry season

	Tussenberge Dam	Tussenberge Bridge	Koue	Spanjaardskloof	Boskloof	Elim Flow Diversion	Moddervlei
H'	1,95	1,84	0,00	2.24	1,18	0,00	1,60
Equitability	0,52	0,49	0,00	0.59	0,31	0,00	0,42
	Blomkraals	Nuwejaars Bridge	Voëlvlei	Kars	Soetendalsvlei Inlet	Soetendalsvlei Outlet	
H'	0,00	1,73	0,00	2,14	1,45	2,19	
Equitability	0,00	0,46	0,00	0,56	0,38	0,58	

Table 4.5: Shannon-Wiener and Equitability indices for the Nuwejaars River sites during the wet/flowing season

	Tussenberge Dam	Tussenberge Bridge	Koue	Spanjaardskloof	Boskloof	Elim Flow Diversion	Moddervlei
H'	1.10	1.84	1.23	2.24	2.44	1.63	2.33
Equitability	0.29	0.49	0.33	0.59	0.64	0.43	0.62
	Blomkraals	Nuwejaars Bridge	Voëlvlei	Kars	Soetendalsvlei Inlet	Soetendalsvlei Outlet	
H'	1.84	2.49	2.05	2.14	1.66	2.30	
Equitability	0.49	0.66	0.54	0.56	0.44	0.61	

Although literature (e.g. Herbst & Mienis, 1985) indicates that the lower reaches of coastal flowing rivers are characterized by a gradual transition (zonation) from freshwater to marine fauna, the Nuwejaars does not in any pattern show this gradual change.

4.4 DISCUSSION

As indicated at the beginning of this chapter, the aim of the biotic component of the current project was *to examine how surface water-groundwater interactions influence ecosystems from headwaters to lowlands.* The objectives specifically of the faunal component were 1) to identify instream faunal assemblages in the Nuwejaars River in order to 2) find diversity patterns matching identified sections of the stream where ground and surface waters interact.

It is unfortunate that the proposed sampling campaign could not be carried out in its entirety because several of our sites dried up during the course of the project. We had hoped to be able to untangle the effects on the aquatic fauna of natural changes down the length of the river and its tributaries, and the hypothesised effects of inflow of groundwater at one or more intervals down the river. The results are inconclusive, although the following observations can be made.

All the streams/tributaries of the Nuwejaars River in the uplands are perennial due to groundwater discharge even during the dry season. Groundwater discharge to these streams occurs in the form of diffuse discharge along the channel and flows from some springs. The Jan Swartskraal River in the midslope zone is not perennial despite receiving flows from tributaries in the uplands. The water table is always below the river bed at the site we are monitoring. Furthermore, the dense stands of invasive alien trees and native palmiet reeds within the riparian zone obstruct the flow of water. At the same time evapotranspiration by these plants depletes flow so that the river does not flow during the dry season. Data on the water table in the floodplain shows that during the wet season, ponding of rainfall during the wet season recharges groundwater, resulting in relatively shallow water tables that even daylight during wet periods. At these times the channel also has high water levels, so there may not be any significant groundwater discharge into the river channel, however. During the dry season, on the other hand, the water table declines and drops slightly below the channel bed, which would restrict groundwater flow to the channel. In addition, the hyporheic zone has clay plus peat with low transmissibility of groundwater. Thus groundwater discharge into the channel may not be significant. Furthermore, the low land gradient/slope means there is not much of a hydraulic gradient to cause significant groundwater discharge. The conditions may be spatially variable along the channel in the lowlands. There will be sections with very sandy beds where groundwater discharge may be occurring, hence the presence of some perennial pools in the floodplain. Thus, the species of invertebrates occurring at lowland sites are mainly influenced by a) water chemistry and b) the presence/absence of surface water in the channel and pools. Fishes are clearly restricted to the upper reaches and probably for the same reasons.

In short, our data provide hints as to the ways in which surface/groundwater interactions may affect the aquatic fauna if this river continues to be used as a laboratory for understanding such interactions, then it may be possible to continue using invertebrate assemblages to address this question. It will be necessary, though, to use the abiotic data generated during the course of this project to identify sites where such interactions clearly occur, and to concentrate on those sites, perhaps using hyporheic rather than benthic assemblages.

4.5 CONCLUSIONS

- This project has demonstrated the considerable biodiversity of a river and its tributaries in an area experiencing increasing aridity as a result of climate change.
- A relatively short cessation of flow, as seen in the Nuwejaars River, had little demonstrable effect on the invertebrate community.
- Numerous species of aquatic invertebrates and fish can survive in pools even in non-perennial systems.
- Certain taxa can be useful indicators of ecosystem conditions.
- Sampling of the hyporheos might prove useful for investigating groundwater-surface water interactions in a system like the Nuwejaars.

CHAPTER 5: TREE WATER USE

5.1 INTRODUCTION

This part of the report presents an assessment of the impacts of invasive alien plants (IAPs) groundwater-surface water interactions in lowlands, mid-slope regions, and headwaters. The Nuwejaars Catchment has 48% of the area under fynbos, 35% cultivated, and 11% occupied by IAPs. The dominant IAPs are *Eucalyptus*, *Pinus* and *Acacia* (*Acacia longifolia, A. cyclops* and *A. saligna*) (Nowell and Esler, 2011). *Acacia longifolia* which is commonly known as long-leaved wattle is evergreen growing to 2-8 metres and is a dominant species occurring on both riparian and non-riparian locations (Morais and Freitas, 2012, 2015; Mkunyana *et al.*, 2019). The species is highly problematic in most of the wetter parts of the Western Cape, Eastern Cape, Kwa-Zulu Natal and scattered parts of Mpumalanga Province (Henderson, 2007). In a previous study, Mkunyana et al. (2019) found differences in water use rates of *Acacia longifolia* occurring at riparian and hillslope sites. What is uncertain is how water use rates of this plant occurring on different parts of the study catchment affect surface water-groundwater interactions.

5.2 METHODS

The following five study sites representative of the different conditions in which IAPs occur within the Nuwejaars Catchment were selected for investigation (Figure 5. 1)):

I. A riparian lowland (altitude 22 m) *Acacia longifolia* stand within a 50 m wide zone adjacent to the Nuwejaars River at Moddervlei
II. A riparian midslope (altitude 67 m) *Acacia longifolia* stand within a 30 m wide zone adjacent to the Jan Swartskraal River
III. A hillslope (altitude 145 m) *Acacia longifolia* stand with no nearby stream at Spanjaardskloof
IV. A hillslope (altitude 228 m) *Acacia longifolia* stand located 60 m from a stream at Sandfontein
V. A hillslope (altitude 230 m) fynbos area with a stream that is 360 m away at Tussenberge

The fynbos site was selected to establish the differences in water use between the indigenous fynbos and IAPs.

The study used sap flow measurements using the heat pulse velocity of the heat ratio method (Figure 5.2) to estimate water use rates of selected *Acacia longifolia* trees at each of the four sites (Moddervlei, Spanjaardskloof, Jan Swartskraal, Sandfontein). Soil water content up to a depth of 1.0 m was monitored using Decagon 5TE soil water sensors, while piezometers were installed to monitor changes in shallow water tables (Figure 5.3). Soil texture analysis was done from pits in which the soil water sensors were installed. In addition, each site had at least 2 monitoring boreholes drilled up to 20 and

60 m. Water table changes in these boreholes were monitored by transducers with data loggers. Data on water table changes in the boreholes were used to establish the extent to which transpiration rates are affected by or affect groundwater levels. The water use rates of the indigenous fynbos at Tussenberge were monitored using an eddy covariance system (Figure 5.4).

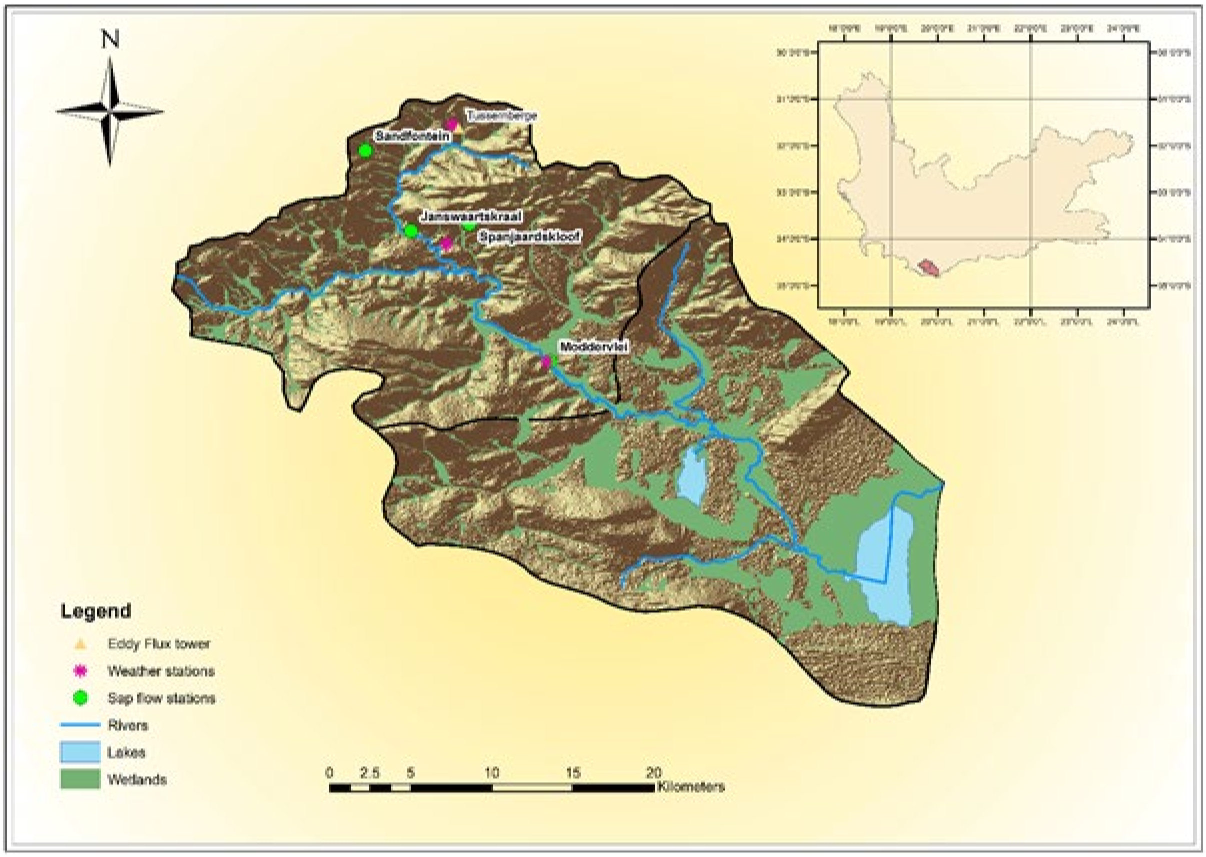


Figure 5.1: Study sites within the Nuwejaars Catchment.

Figure 5.2: Sap flow monitoring system

Figure 5.3: Soil moisture sensors and the piezometer installed at Moddervlei

An eddy covariance system (IRGASON integrated CO2/H2O Open-Path Gas Analyzer and 3D Sonic Anemometer) was installed at a site dominated by indigenous fynbos shrubs (Figure 5.4) to estimate actual evapotranspiration. The infrared gas analyser, sonic anemometer and pyranometer were installed at 8 m above ground. This system included soil heat flux plates and soil water content sensors.

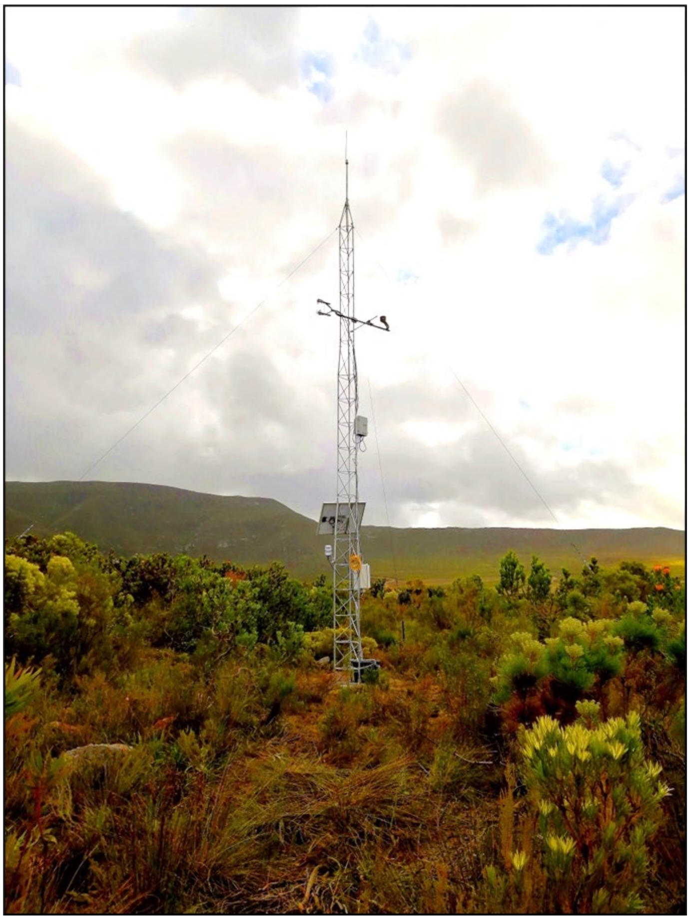


Figure 5.4: Eddy covariance system (eddy flux tower) installed at a site with Fynbos shrubs.

Since the HPV systems in the invaded sites quantified transpiration rates by *Acacia longifolia*, a two-layer model was developed to scale up daily AET to annual actual evapotranspiration rates using the in-situ transpiration rates and microclimate from the invaded sites. The model was developed and successfully used by Dzikiti et al. (2013) to simulate actual evapotranspiration by riparian and non-riparian pines in the Western Cape. The model partitioned the *Acacia longifolia* stands into two layers namely, the upper transpiring layer comprising the tree canopies, and the below canopy layer in which soil evaporation (E_s) is assumed (Dzikiti et al., 2013). Transpiration (**Tc**) from the canopies was modelled using the following equation which is based on the Penman-Monteith equation (Zhang et al., 1997):

$$T_c = LAI \frac{\lambda[Rn_c \; x \; S + 0.93 \; x \rho c_p \; x \; (e_s - e_a) x \; r_b]}{(S + \gamma \; x \; 0.93 \; x \; (2 + \frac{r_b}{r_s})} \qquad (5.1)$$

where LAI is the leaf area index of the canopy, λ is the latent heat of vaporisation of water (J kg^{-1}), Rn_c is net radiation intercepted by the tree canopies (W. m-2), S is the slope of the saturation vapour pressure against temperature curve (Pa °C^{-1}), $\boldsymbol{\rho}$ is the density of air (kg m^{-3}), $\mathbf{c_p}$ is the specific heat of air at constant pressure (J kg^{-1} °C^{-1}), $\mathbf{e_s} - \mathbf{e_a}$ is the vapour pressure deficit (VPD) of the air (Pa), $\boldsymbol{\gamma}$ is the psychrometric constant (Pa °C^{-1}), $\mathbf{r_b}$ and $\mathbf{r_s}$ are the aerodynamic and canopy conductance (m s^{-1}), respectively. The aerodynamic conductance (r_b) was calculated using the equation for the leaf boundary layer resistance as explained by Dzikiti et al. (2013) and the canopy stomatal conductance (r_s) was estimated according to Zhang et al. (1997) equation. According to Shuttleworth and Wallace (1985), soil evaporation ($\mathbf{E_s}$) can be simulated using:

$$E_s = \frac{\rho c_p \, x \, (es_o - ea_s)}{\gamma \lambda \, x \, rs_o} \tag{5.2}$$

where $\boldsymbol{\rho}$ is the density of air (kg m^{-3}), $\mathbf{c_p}$ is the specific heat of air at constant pressure (J kg^{-1} °C^{-1}), $\boldsymbol{\gamma}$ is the psychrometric constant (Pa °C^{-1}), λ is the latent heat of vaporisation of water (J kg^{-1}), rs_o is the soil/substrate surface resistance to water vapour transport. Actual evaporation (ea_s) and saturation vapour pressure (es_o) at soil surface were simulated as:

$$ea_s = es_o x \, \frac{RH}{100} \tag{5.3}$$

where RH is the relative humidity.

$$es_o = 610.8 \, exp \frac{(17.27 \, x \, T_s)}{(273.3 \, x \, T_s)} \tag{5.4}$$

Where T_s is surface or soil temperature (°C)
Actual evapotranspiration (AET) by *Acacia longifolia* stands was estimated from:

$$AET = T_C + E_S \tag{5.5}$$

5.2.1 Assessment of the spatial extent of different land cover and land use types

Landsat images from the period 1973-2021 were used to establish how the four major land cover types, namely water, IAPs, cultivated land, and fynbos changed in spatial extent. To assure the best comparability, images that were used in this study had a cloud cover of less than 10% (Table 5.1). Ground truthing points were collected using a handheld Geographical Positioning System (GPS) in August 2018, which coincided with the flowering period of vegetation in the catchment. These points were used during classification and overall accuracy assessment.

Table 5.1: Characteristics of the Landsat images used in this study.

Description	*Date*	*Number of bands*	*Resolution*
Landsat 01	1973/09/09	4	80 m
Landsat 05	1996/11/10	7	30 m
Landsat 05	2006/11/14	7	30 m
Landsat 08	2015/12/17	11	30 m
Landsat 08	2020/11/12	11	30 m
Landsat 08	2021/07/10	11	30 m

Ground verification was conducted using simple random sampling but ensuring that all classes were represented, and the samples were well distributed within the area of study. The verification was done using an error/confusion matrix which contains information about actual and predicted classes done by a classification process. This means that the pixels that had been categorized from the satellite image were compared to the same site in the field. Change detection analysis was also performed to determine the spatial extent of different land cover types between the years.

5.2.2 Estimation of spatial variations of actual evapotranspiration at catchment scale

Water use measurements made using the sap flow and eddy covariance systems are representative of the specific sites. To estimate the relative effects of evapotranspiration on surface water-groundwater interactions at the catchment scale, there was a need to determine the spatial variations of actual evapotranspiration rates using satellite-derived data. The surface energy balance systems (SEBS) model was used for this purpose (Su, 2002). The SEBS model which uses Landsat 8 data has been applied extensively for the estimation of regional fluxes and actual ET (Yang *et al.*, 2009; Zhou *et al.*, 2013).

The SEBS model estimates daily actual ET from remotely sensed and meteorological data by calculating the energy required for water to change phase from liquid to gas. Actual ET estimates from this model were validated using data from the eddy covariance system installed in the catchment. Landsat images were pre-processed using the ENVI software (Figure 5.5), thereafter, the acquired reflectance bands were used to compute actual evapotranspiration (AET) (Figure 5.6).

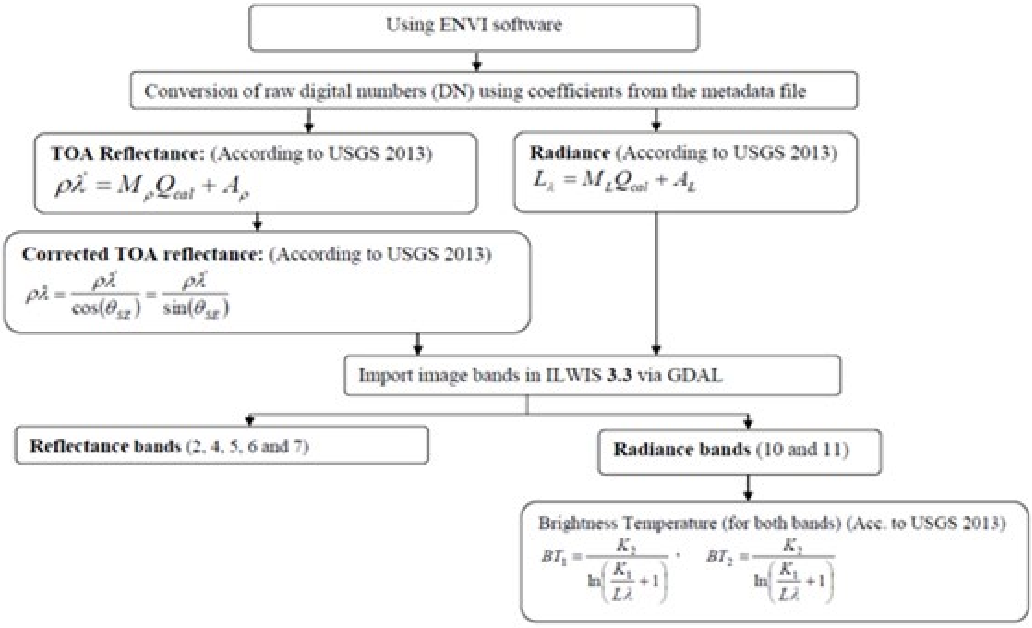


Figure 5.5: Landsat 8 image pre-processing (Shoko, no date).

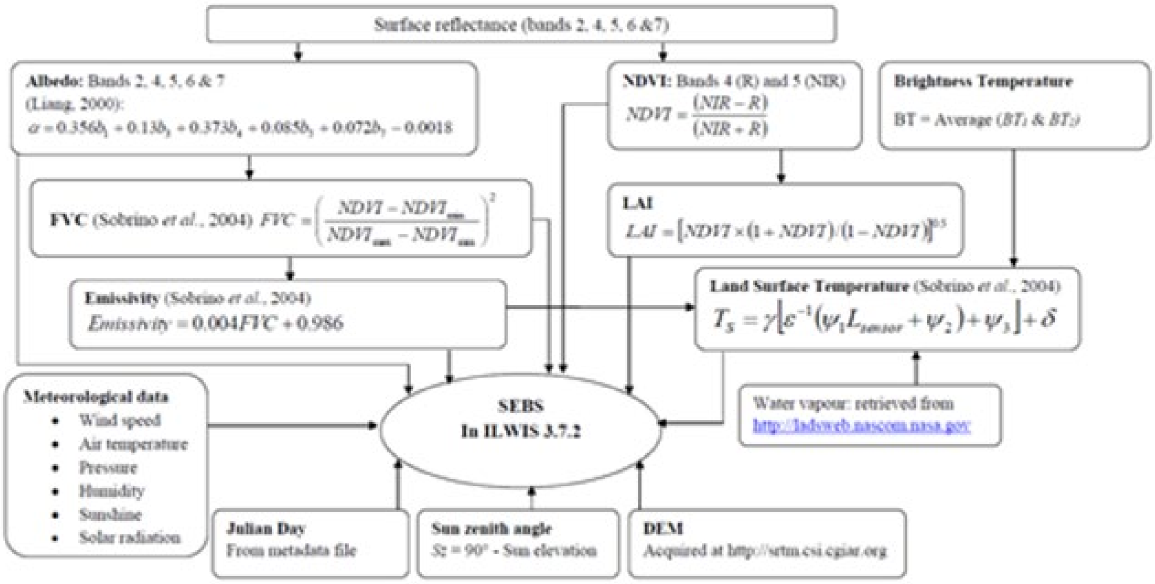


Figure 5.6: SEBS Computation using Landsat 8 Images (Shoko, no date).

5.2.3 Site descriptions

5.2.3.1 *Moddervlei*

This is a riparian site located 20 m from the Nuwejaars River and with an altitude of 22 m above sea level (Figure 5.7). Four trees were selected for sap flow measurement. The circumferences of the trees ranged from 34 to 68 cm. Soil water sensors were installed at 10 cm intervals from 10 to 100 cm depth below the surface. Three piezometers with a depth of 3 meters were installed at distances of 3, 18, and

30 m from the river channel. A nest of 5 monitoring boreholes with depths ranging from 8, 20 and 50 m exists about 50 m from instrumented trees. An automatic weather station was established 100 m outside the *Acacia longifolia* stand (Figure 5.7).

Figure 5.7: Moddervlei site for tree water use monitoring within the riparian zone of the Nuwejaars River. The green rectangle shows the location of trees monitored, the blue rectangle is where 5 monitoring boreholes are located, the red circle is an automatic weather station (Source: Google Earth Image of 6 February 2021)

5.2.3.2 *Jan Swartskraal*

This is a second riparian site located at ~10 m from the Jan Swartskraal River (Figure 5.8). The elevation of the site is approximately 67 m above sea level. Three *Acacia longifolia* trees were selected to monitor sap flows. The circumferences of the trees ranged from 33 to 57 cm. Soil water sensors were also installed from 10 to 90 cm depth below the surface. Water table fluctuations were monitored by a piezometer ~2 m from the river channel. An automatic weather station located about 2 km away was used to monitor relevant weather parameters.

Figure 5.8: Experimental set-up at Jan Swartskraal. The green rectangle is the sap flow monitoring site adjacent to the stream, while the blue rectangle shows the location of two monitoring boreholes, 7 and 50 m deep (Source: Google Earth Image of 7 May 2019).

5.2.3.3 *Spanjaardskloof*

This is a non-riparian midslope site located on the southern slopes of the Bredasdorp Hills (Figure 5.9). The elevation of the site is 145 m above sea level. Sap flows were monitored on three selected trees with circumferences ranging from 23 to 47 cm. Soil water variations were also monitored from 10-90 cm below the surface. Weather conditions were monitored from an automatic weather station located 1.6 km from the site. There are two monitoring boreholes with a depth of 20 and 60 m.

Figure 5.9: The Spanjaardskloof tree water use monitoring site on a hillslope. Altitude decreases towards the South.

5.2.3.4 *Sandfontein*

This site is at an altitude of 228 m above sea level and is 58 m from a stream (Figure 5.10). The tree stand selection is outside the riparian zone on sloping ground with a gradient of 0.10. Based on the assessment done during site selection, this site represents the highest elevation at which *A. longifolia* trees occur within the Nuwejaars catchment. Sap flows were monitored on four selected trees with circumferences ranging from 24 to 61 cm. Variations in soil water content were monitored from 10-40 cm below the surface. An unconsolidated material was observed below 40 to 100 cm depth, where a solid bedrock was observed. A soil water sensor was installed at a depth of 100 cm. Two monitoring boreholes, 11 m and 50 m deep were drilled 20 m from the trees instrumented for sap flow measurements. The Tussenberge automatic weather station which is 4.8 km away and at an altitude of 230 m was used to determine the weather conditions at this site.

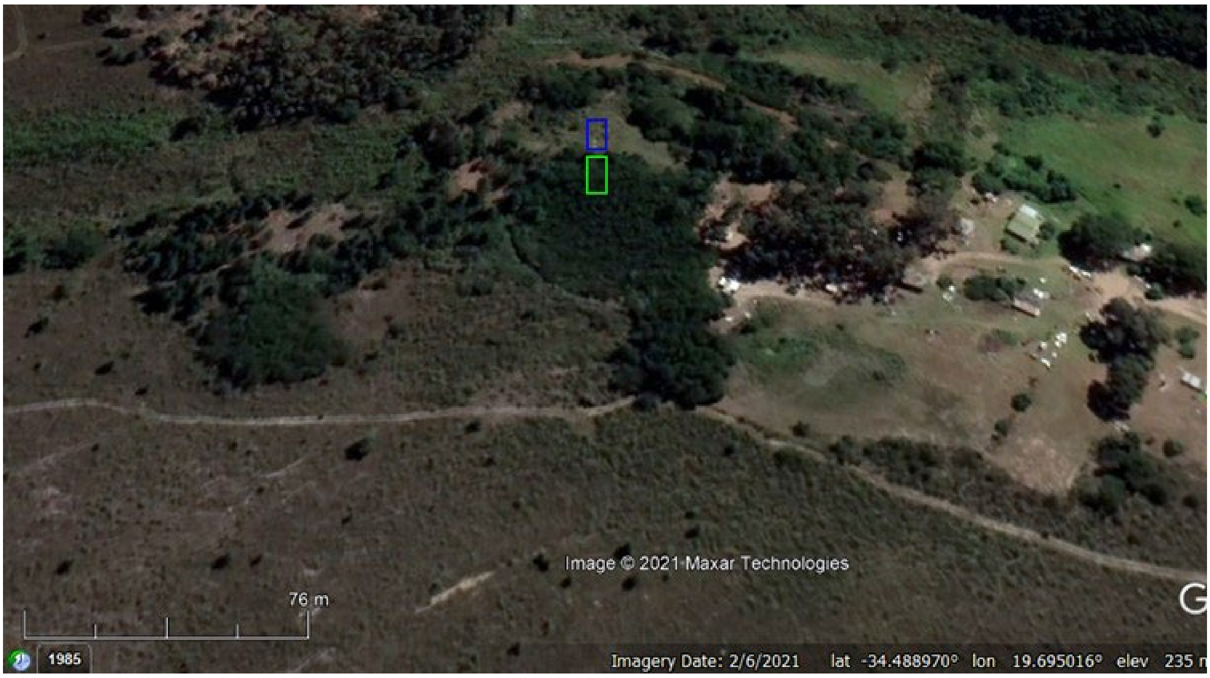


Figure 5.10: Tree water use monitoring sites at Sandfontein. The blue rectangle is the location of two monitoring boreholes (Source: Google Earth Image of 6 February 2021).

5.2.3.5 *Tussenberge*

This site is mostly dominated by indigenous fynbos shrubs (dominated by Proteas, Erica). The elevation of the site is 230 m above sea level, and the gradient is about 0.10. An eddy covariance system was installed to monitor actual evapotranspiration rates. An automatic weather station was also installed 300 m away from the flux tower to monitor weather conditions. Three monitoring boreholes were drilled and have depths of 12, 30 and 50 m (Figure 5.11).

Figure 5.11: Experimental set-up at Tussenberge. The green circle is the site of the eddy flux tower, red circle = automatic weather stations, blue rectangle = 3 monitoring boreholes (12, 30, and 50 m deep) (Source: Google Earth Image of 6 February 2021)

5.3 RESULTS

5.3.1 Spatial extent of land use and land cover types

The dominant land cover type in the Nuwejaars Catchment was fynbos in 1973. IAPS then covered most of the northern headwaters. Since 1973, cultivation has become the most dominant land use (Figure 5.12). The spatial extent of areas covered by fynbos shrubs has decreased from 40 597 ha (53%) in 1973 to 36 483 ha (48%) in 2021. Cultivated areas have increased from 13 906 ha (18%) observed in 1973 to 26 727 ha (35%) in 2020. The spatial extent of IAPs has decreased from 18 883 ha (25%) to 8 348 ha (11%) between 1973 and 2021 due to clearing by the landowner who formed the Nuwejaars Wetlands Special Management Area forum which has an objective of clearing of invasive alien plants from their lands.

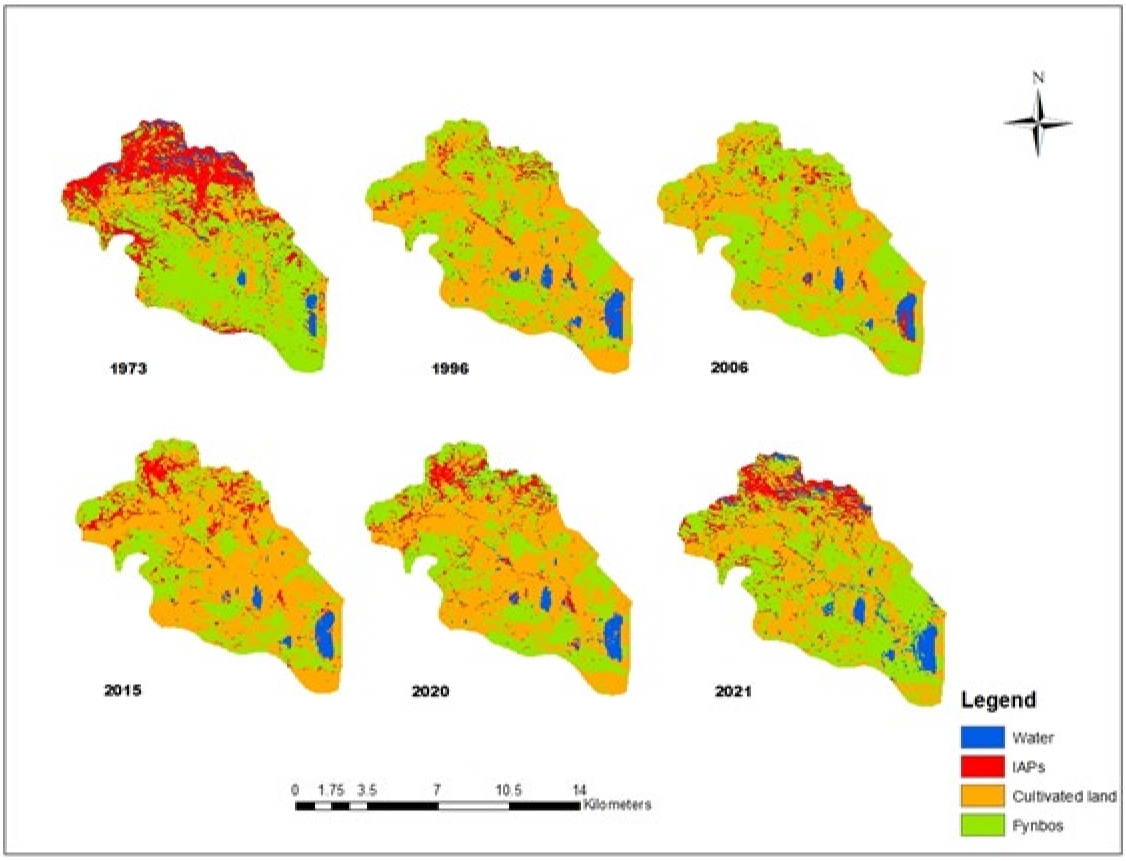


Figure 5.12: Landover / land use from 1973-2021 in the Nuwejaars catchment

5.3.2 Water use rates by IAPs along a topographic gradient: *A. longifolia* case study

(i) The response of shallow and deep soils to rainfall at riparian and non-riparian sites

Moddervlei (riparian) and Spanjaardskloof (hillslope) sites had similar soil characteristics (Table 5.2), with sandy clay loam occurring from 0 to 30 cm depth and loamy fine sand between 61 and 90 cm depths.

Table 5.2: Soil textures at various depths in the riparian and non-riparian study sites.

Depth (cm)	Moddervlei	Spanjaardskloof
0-30	Sandy clay loam	Sandy clay loam
31-60	Sandy clay loam	Sandy loam
61-90	Loamy fine sand	Loamy fine sand

Following the rainfall events from June 2019, the riparian sites, Moddervlei and Jan Swartskraal had increased soil water contents in the deep soil layers (50-100 cm depths) compared to the shallow layers

(Figure 5.13). In contrast, at the non-riparian sites, Spanjaardskloof and Sandfontein, the soil water content in the deep soil layers increased after significant rainfall events. The Spanjaardskloof soils had the least soil water content compared to other sites throughout the study period. Notably, a significant increase of soil water in both shallow and deep soil layers was observed between June and December 2020 at all the study sites (Figure 5.13).

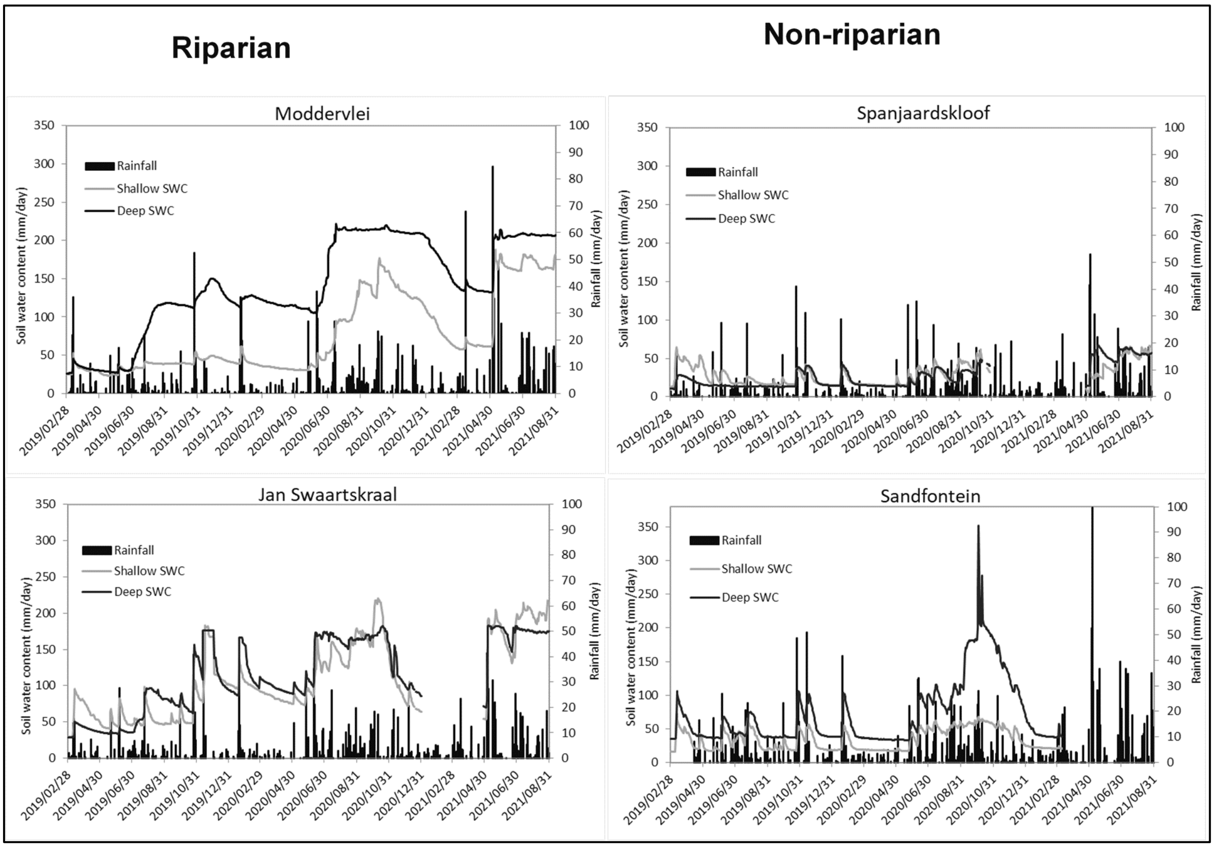


Figure 5.13: Responses of soil water content in the shallow (0-50 cm depth) and deep (50-100 cm depth) soil layers to rainfall.

(ii) Drivers of water use: reference evapotranspiration and rainfall patterns

Table 5.3: Annual reference evapotranspiration and rainfall measured from December 2018 to August 2021 in the Catchment.

	2018/2019		2019/2020		2020/2021	
	mm/year		mm/year		mm/year	
	ETo	Rainfall	ETo	Rainfall	ETo	Rainfall
Moddervlei	1 199	443	1 124	669	779	721
Spanjaardskloof	1 139	440	1 096	652	763	600
Tussenberge	1 104	528	1 067	906	881	865

*Shaded 2020/2021 indicates an incomplete year from December 2020 to August 2021

December 2018 to December 2019 recorded the highest evapotranspiration rates and the least rainfall across the sites (Table 5.3). The Moddervlei weather station had the highest ETo rates from 2018 to 2020 (1 199 and 1 124 mm/year) with the lowest rainfall of 443 and 669 mm/year for the respective years compared to other weather stations. ETo rates in the midslope of the catchment (Spanjaardskloof) was 1 139 and 1 096 mm/year during the 2018 to 2020 period, with an annual rainfall of 440 and 652 mm. The ETo rates were higher than 1 104 and 1 067 mm/year observed on the headwater. As expected, rainfall on the headwaters was higher compared to other parts of the catchment. During the drier 2019/2019, rainfall was 47% of the ETo in the uplands, and 38% in the lowlands. In a relatively wetter year, 2019/2020, these were 85% and 60%, respectively.

(iii) Transpiration dynamics by riparian and non-riparian A. longifolia stands along the topographic gradient

The monitored tree stands on the headwaters which received higher rainfall than the lowlands I had higher rates of transpiration. However, the lowland riparian sites had high rates of water use compared to the non-riparian upland site (Figure 5.14). The stand transpiration rates by *Acacia longifolia* trees from the lowlands to headwaters between December 2018 to August 2021 were 1 537 mm at Moddervlei, 1 054 mm at Jan Swartskraal, 914 mm at Spanjaardskloof, and 1 641 at Sandfontein. Peak transpiration rates across sites occurred during the October-December (dry season) period, while low rates (0.16-0.3 mm/day) as expected were between the cool April and August (wet season) (Figure 5.14). As a result of high ETo rates during the 2018/2019 period, transpiration rates across all the sites were high with 646, 584, 403, and 737 mm/year observed at Moddervlei, Jan Swartskraal, Spanjaardskloof, and Sandfontein, respectively. The high rainfall on the headwaters resulted in high transpiration rates at Sandfontein compared to other sites in the catchment. Even though Spanjaardskloof had higher ETo rates, but the site received the least rainfall compared to other sites. Thus, resulting in less water available for the plant to transpire (Figure 5.14, Table 5.4).

Table 5.4: Annual transpiration rates from December 2018 to August 2021

	Transpiration (mm/year)		
	2018/2019	2019/2020	2020/2021
Moddervlei	646	551	340
Jan Swartskraal	584	470	
Spanjaardskloof	403	296	215
Sandfontein	737	546	365

*Shaded 2020/2021 indicates an incomplete year from December 2020 to August 2021

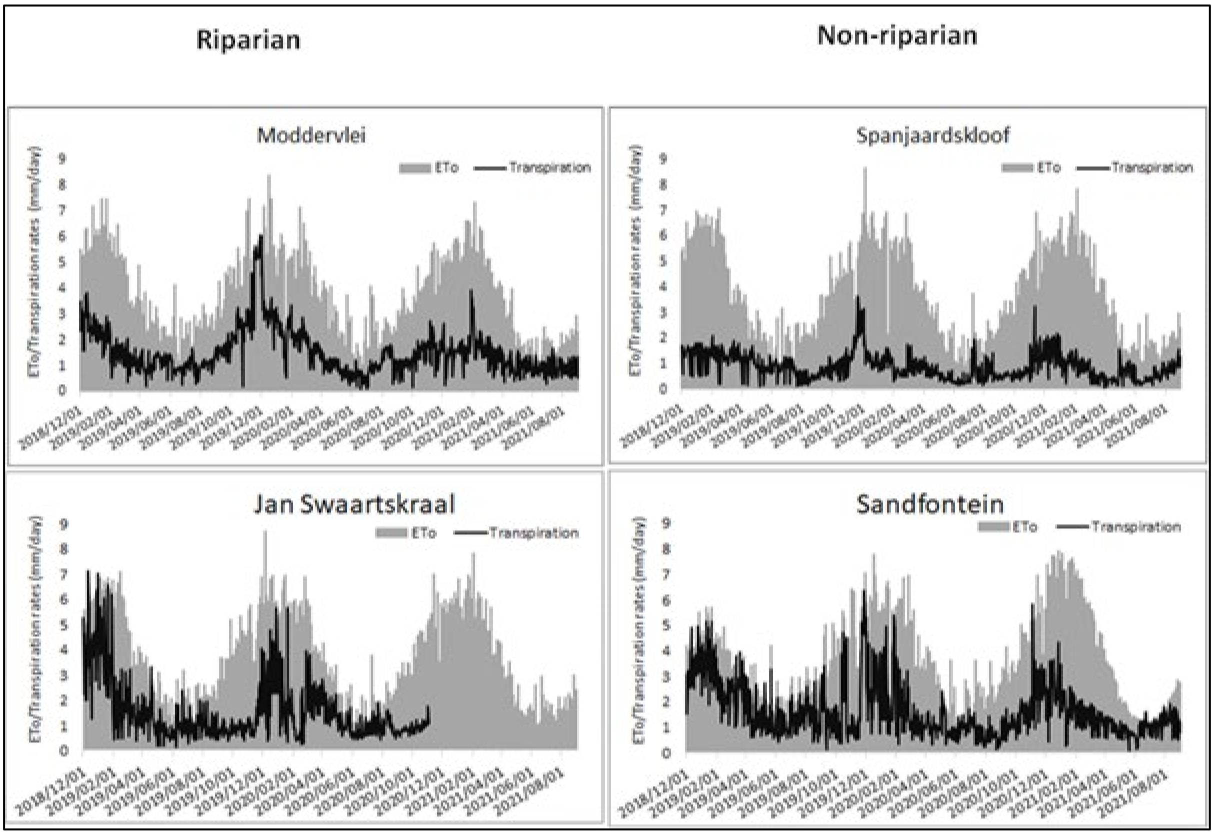


Figure 5.14: Daily reference evapotranspiration (grey) and transpiration rates (black) at the riparian (Moddervlei and Jan Swartskraal) and non-riparian (Spanjaardskloof and Sandfontein) sites.

5.3.3 Water sources used by riparian and non-riparian *Acacia longifolia* trees

Even though the evaporative demand (shown by reference ET) was the major driver of water use. However, water availability also plays a significant role in water use patterns by trees. This was observed in Spanjaardskloof, where water availability was the prevailing factor for tree water use at the site. The two riparian sites, Moddervlei and Jan Swartskraal had shallow water tables which ranged between 2.2 m in January 2020 and 0.35 m in May 2021 at Moddervlei. At Jan Swartskraal, the water table was between 1-1.6 m during the same period. A peak transpiration rate of 6.1 mm/day was observed on the 30th of November 2019 at Moddervlei. On this day, the water table was 1.6 m below the surface (Figure 5.15). Thus, high transpiration rates during this period were a result of the rise in the water table. At Jan Swartskraal, a peak transpiration rate of 5.6 mm/day was observed between the 29th of December 2019 and the 21st of January 2020. During this time, the water table ranged between 1.1 m and 1.4 m. Thus, also suggesting the rise in the water table resulted in to increase in the rate of water use by these trees (Figure 5.15)). The impact of waterlogging at riparian sites was also observed at Moddervlei and Jan Swartskraal, where it was also notable that the transpiration rates during 2021 were lower than transpiration rates in 2020 as a result of increased rainfall events and flooding for most of the period during 2021. On the other hand, the non-riparian sites had increased transpiration rates during the summer period in 2020. This was attributed to increased moisture in the soils.

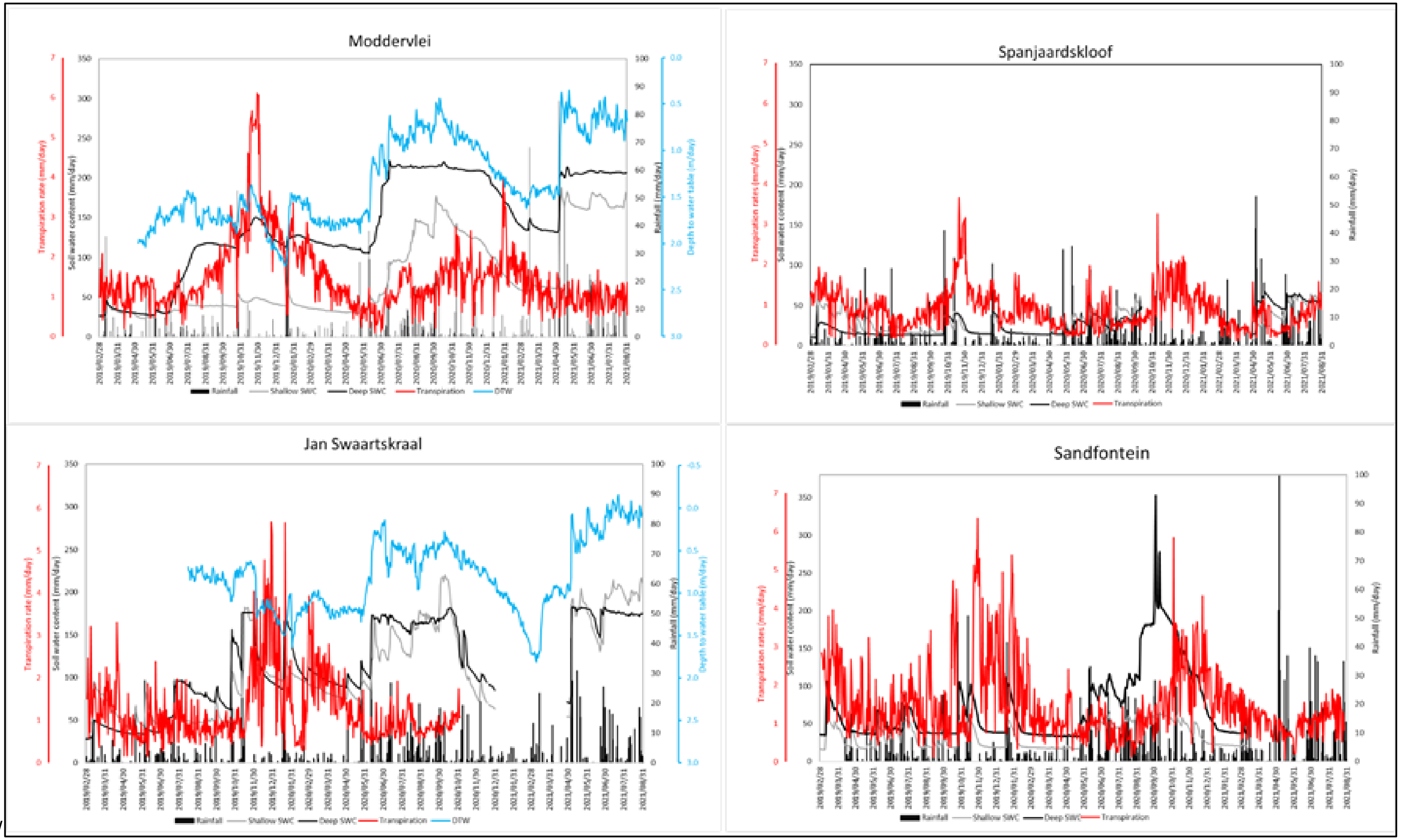


Figure 5.15: Daily transpiration rates, rainfall, depth to water table (DTW), and soil water content in the shallow (0-50 cm) and deep (50-100 cm) soil layers from February 2019 to August 2021 at the study sites

Actual evapotranspiration rates estimated for all parts of the catchment using SEBS were used to compare AET rates in areas with and without *Acacia longifolia* stands (Figure 5.16) on 25 December 2018 when suitable satellite images were available. Water bodies as well as the IAPs had high rates of water use between 6.2 to 7.3 mm/day. Areas dominated by fynbos, especially on the lower parts of the catchment, had AET rates between 5.8-6.1 mm/day. The high AET observed on the mountainous parts and along the riparian zones, which are associated with the infestation by IAPs (Figure 5.16), may suggest groundwater use by *A. longifolia* trees since December 2018 was a very dry year during the study period.

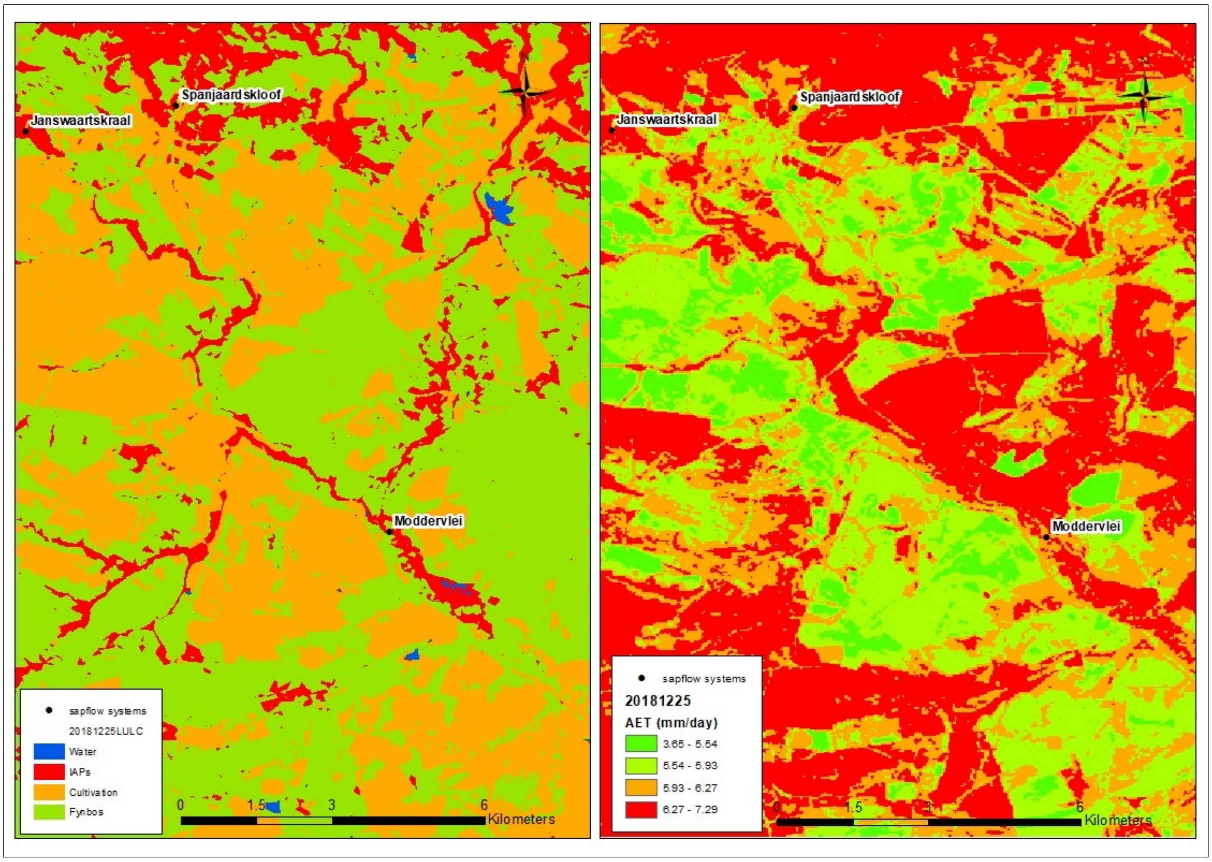


Figure 5.16: Spatial variation of actual evapotranspiration across different land covers on the 25th of December 2018.

Seasonal rates of transpiration along the topographic gradient showed high transpiration rates in November 2019, across all the study sites (Figure 5.16). The dates 20-30 November 2019 was selected to investigate the impacts of tree water use on the water table fluctuations (Figure 5.17). The water table in the boreholes showed diurnal changes, with the water table declining during the day and rising overnight. During the selected period, the depth to the water table at Moddervlei was between 1.34 and 1.42 m in the 8 m borehole and 0.94-0.96 in the 50 m borehole. The water table changes were 20 mm in the shallow (8 m) borehole, which was more than the 10 mm change observed in the 20 m borehole. Also, a declining trend in the water table was observed in the 8 m borehole. At Spanjaardskloof, the 60 m borehole had 40 mm changes which was more than the 10 mm change observed in the 20 m borehole. The water table at Sandfontein was close to the surface, the depth to water table ranged between 0.9 to 0.78 m in the 11 m borehole, and 0.51 to 0.42 m in the 50 m borehole. The change in the water table was 40 mm in both the shallow (11 m) and deep (50 m) boreholes (Figure 5.17). Consequently, transpiration rates at this site were higher compared to the other sites.

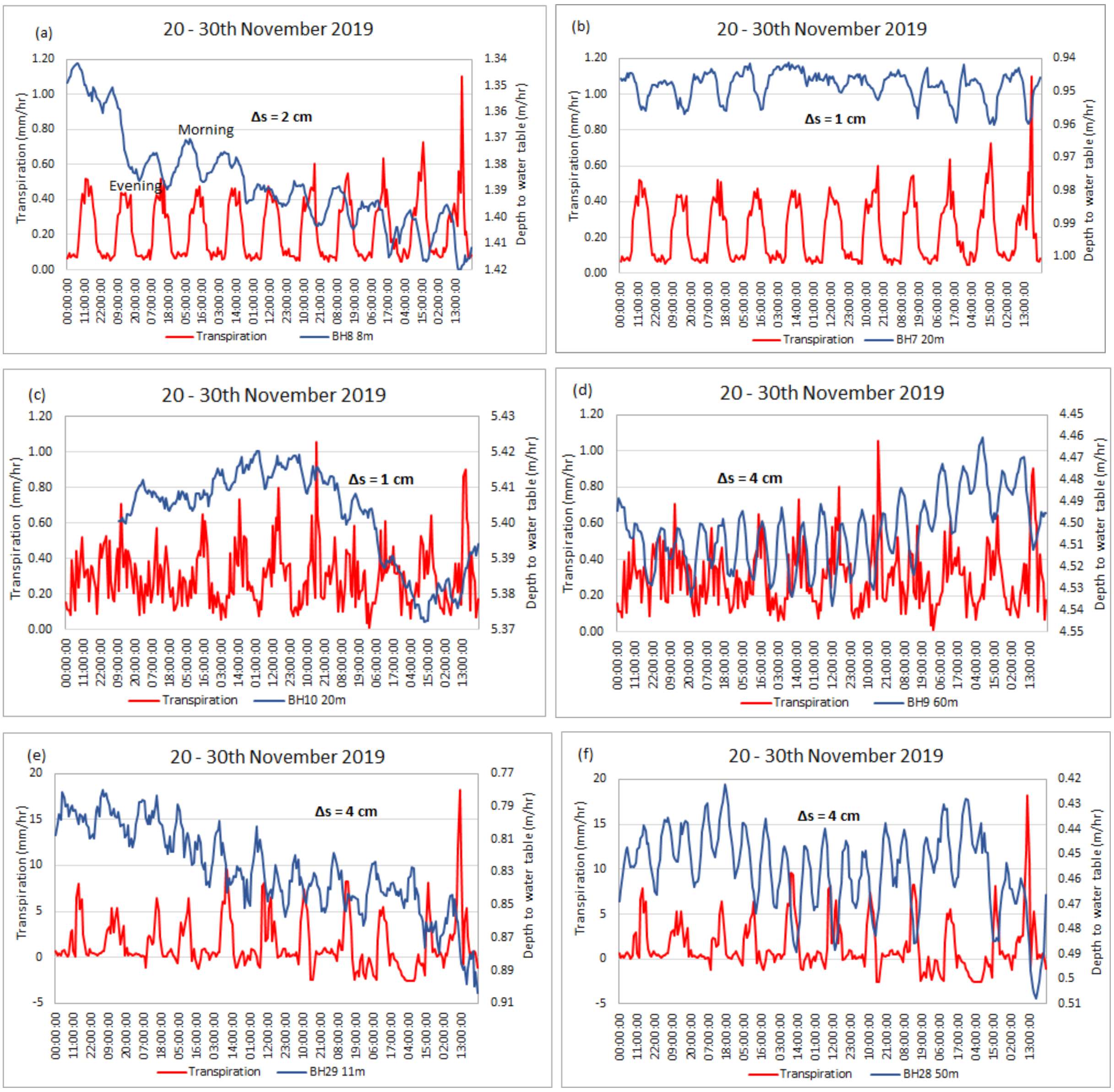


Figure 5.17: Diurnal variations in transpiration and depth to the water table from the 20th to the 30th of November 2019 at Moddervlei (a & b), Spanjaardskloof (c & d), and Sandfontein (e & f) study sites. Δs is the daily change (evening-morning) in depth to water table (cm).

The diurnal changes in the water table depth indicate that transpiration by the *Acacia longifolia* predominating at each site had significant effects on groundwater. The decline during the day implies that the rate of water abstraction by the plants will be greater than groundwater flow to the site. If the groundwater flow rate was greater than the rate of abstraction by trees, water abstracted will be replenished at a faster rate, hence no decline in the water table. However, during the night without significant transpiration, the water table recovers from groundwater flow.

5.3.4 Actual evapotranspiration rates of fynbos

Rates of actual evapotranspiration from the fynbos site have a slight seasonal variation. During the October to March summer period, actual evapotranspiration generally varied from 1.0 to 4.1 mm/day, while reference evapotranspiration was in the 2.2 to 7.7 mm/day range (Figure 5.18). Soil water content had no significant relationship with actual evapotranspiration rates at a fynbos site. The lower rate of fynbos evapotranspiration without a significant relationship with soil water content suggests that this type of vegetation has adapted to using water conservatively even when climatic conditions enable high rates of evapotranspiration as shown by the relatively higher reference evapotranspiration rates. During winter, actual evapotranspiration rates at the fynbos sites were in the 0.5-1.7 mm/day range, which almost approximate reference evapotranspiration rates. Thus, in winter, climatological conditions (especially available radiation, vapour pressure deficit) constrain evapotranspiration rates as expected. Actual evapotranspiration rates were 696 mm/year from August 2019 to September 2020, and 509 mm/year from September 2020 to August 2021. The respective values for reference ETo were 1 165 and 1 173 mm/year. Thus, actual evapotranspiration for the fynbos was 52% of the reference ET.

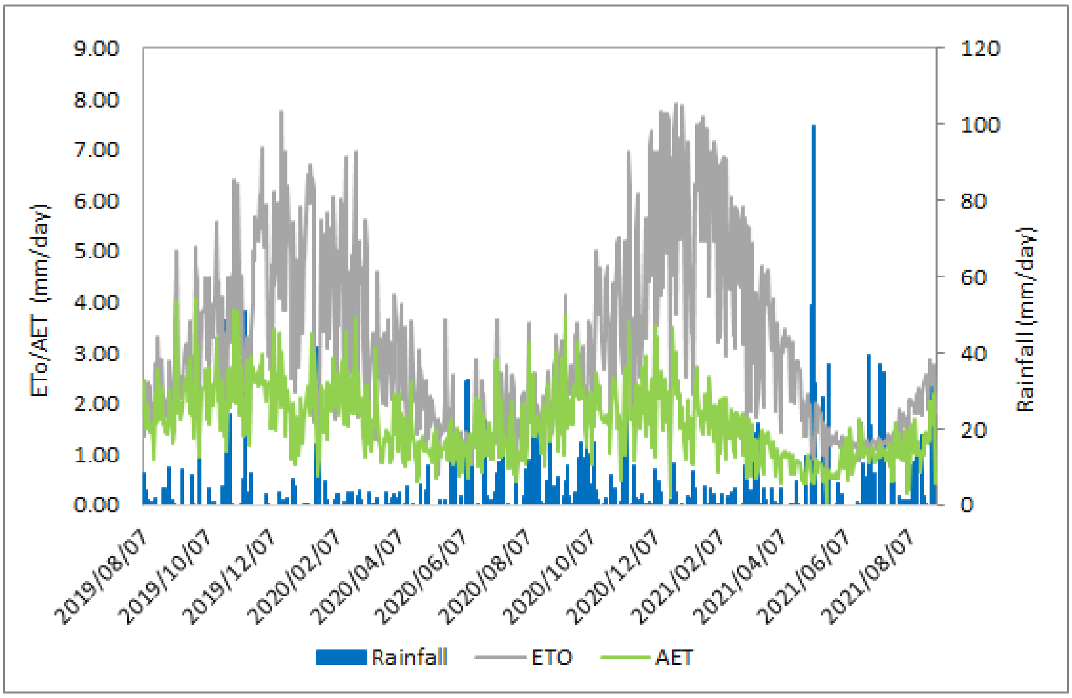


Figure 5.18: Reference evapotranspiration and actual evapotranspiration at a Fynbos site from August 2019 to November 2020.

5.3.5 Actual evapotranspiration of riparian and non-riparian *Acacia longifolia* stands.

The estimated actual evapotranspiration using the two-layer model from August 2019 to August 2021 on the invaded sites illustrated high rates of water use by invasive *A. longifolia* trees compared to the water use by fynbos shrubs that were measured with the eddy covariance system (Figure 5.19). In the invaded sites, the actual evapotranspiration rates by riparian *A. longifolia* stand were 1 060 mm/year from August 2019-September 2019, and 879 mm/year from September 2020-August 2021. The respective values from the non-riparian *A. longifolia* stand were 746 mm/year and 629 mm/year. Thus, suggested high water use rates by riparian *A. longifolia* stand compared to the non-riparian stand. (Figure 5.19, Table 5.5).

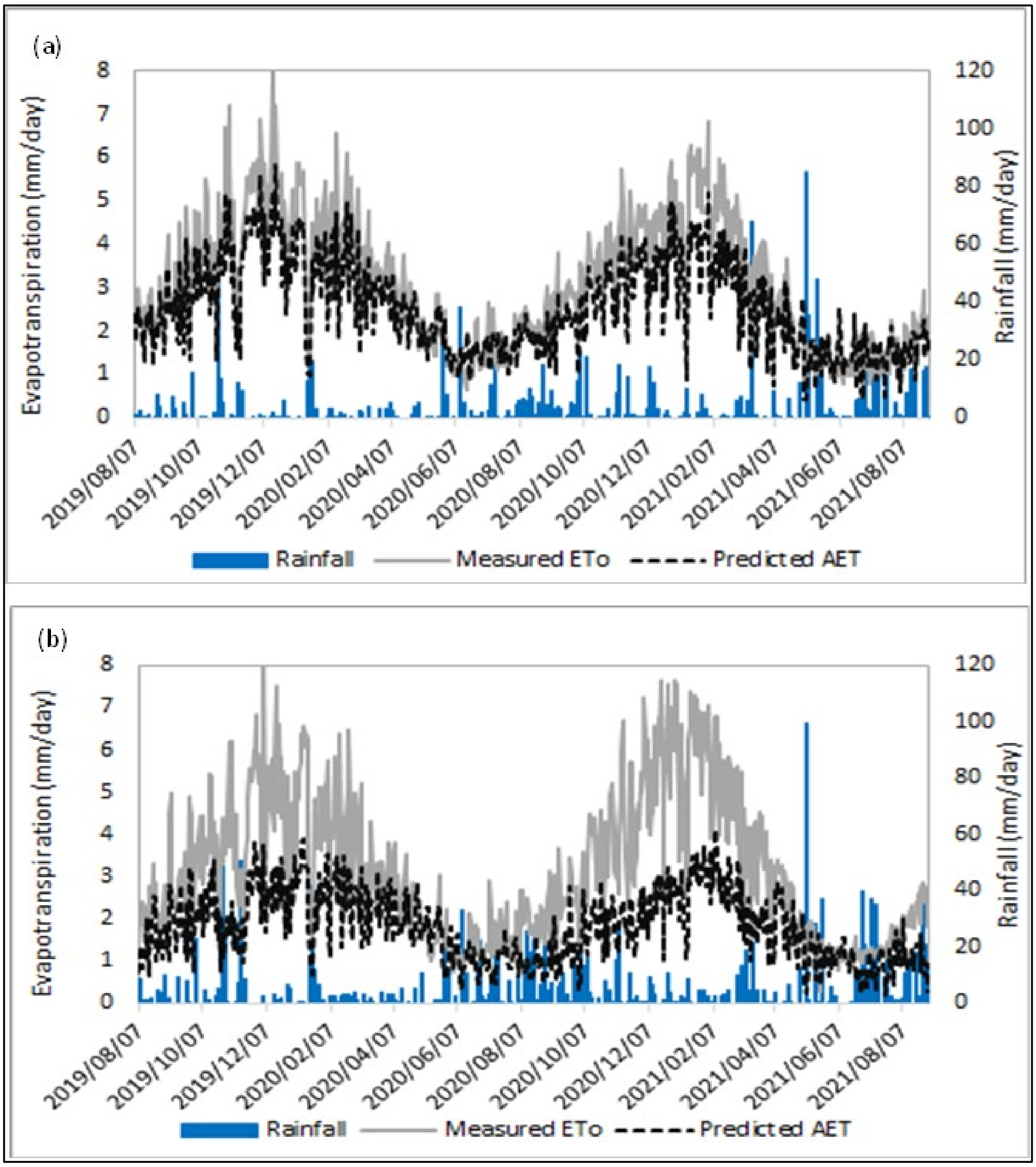


Figure 5.19: Daily estimated AET and the measured ETo at Moddervlei (a) and Sandfontein (b) from August 2019 to August 2021 using the two-later model.

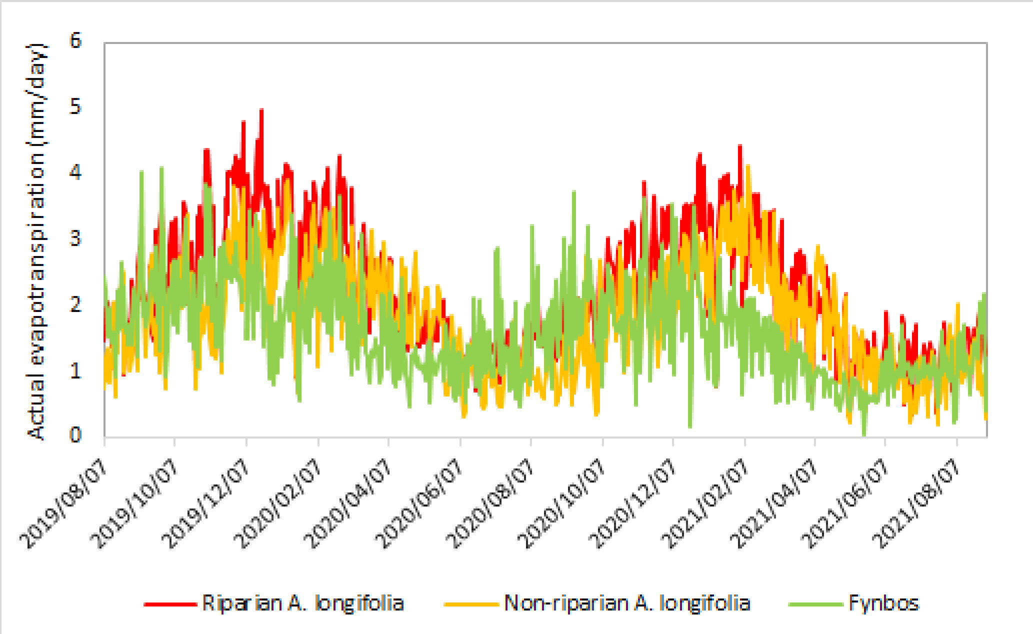


Figure 5.20: Daily actual evapotranspiration of *A. longifolia* and fynbos vegetation from August 2019 to August 2021

Table 5.5: Annual actual and reference evapotranspiration rates measured on invaded and fynbos sites.

	Model Predictions (mm/year)		**Measured (mm/year)**				**PBIAS (%)**	**R2**
	AET		AET		ETo			
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021		
Fynbos			696	509				
Riparian IAPs	1 060	879			1 243	1 071	28.7	0.93
Non-riparian IAPs	746	629			1 180	1 173	41.5	0.71

5.3.6 Spatial variations of actual evapotranspiration within the Nuwejaars Catchment.

Actual evapotranspiration (AET) estimated using the SEBS model show that the AET extracted from polygons along the riparian zones ranged between 5.47-7.03 mm/day, which was higher than AET estimated on hillslope IAPs (5.54-5.94 mm/day). SEBS AET did not show much variation between areas dominated by IAPs and fynbos. Such that lowland fynbos had AET ranging 4.79-6.98 mm/day and 5.64-6.79 mm/day was estimated from hillslope fynbos. Low AET rates were observed in areas that were cultivated. Cultivation on the lowlands had AET rates between 3.68-6.89 mm/day, and those on the hillslope had 4.37-6.49 mm/day (Figure 5.21). A similar observation was made during the summer season in December 2020, where areas covered by IAPs, fynbos, and water had higher AET rates (ranged between 5-6 mm/day) than the cultivated lands that had AET between 3-4 mm/day. As the result of low radiation and thus available energy during the winter season, less variation was observed in AET spatially. During the 2019 and 2021 winter seasons, AET rates were between 0-2 mm/day (Figure 5.22).

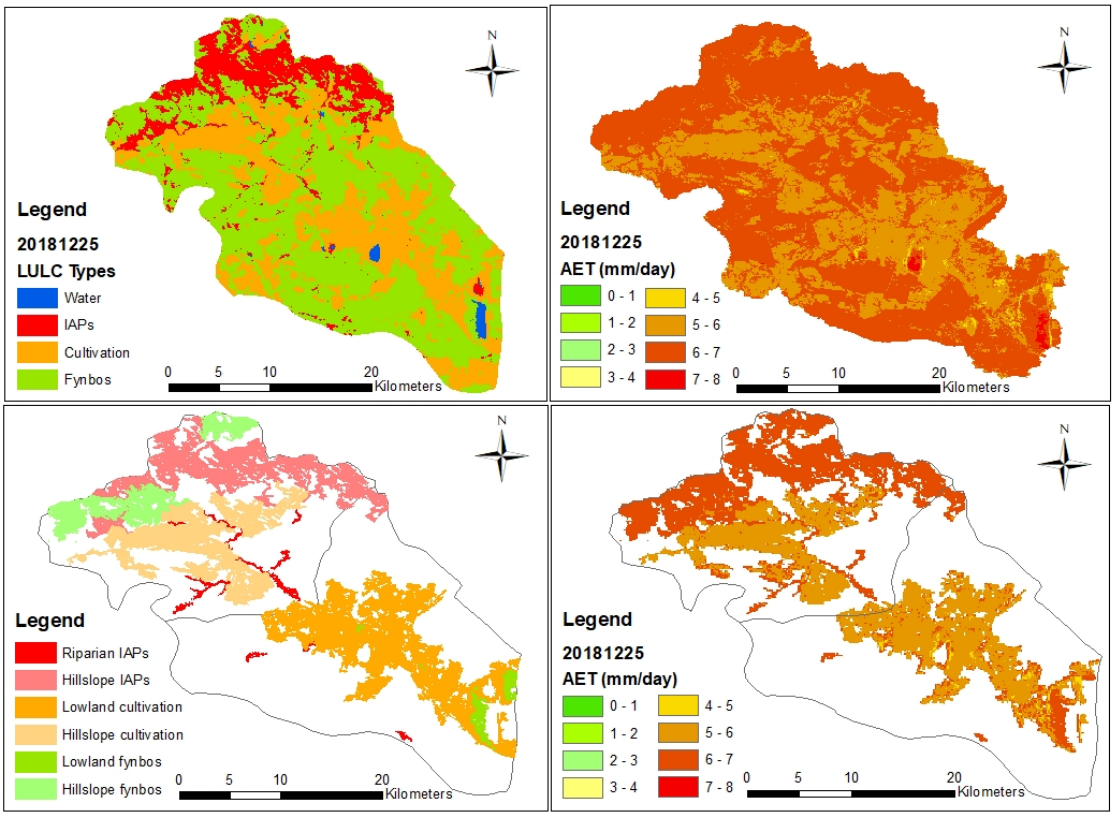


Figure 5.21: Spatial variation of AET across different land covers in the Nuwejaars Catchment (image source: Landsat 8; 20181225) using SEBS model. The shaded parts on the bottom images show polygons that were extracted from the land cover and AET images on top.

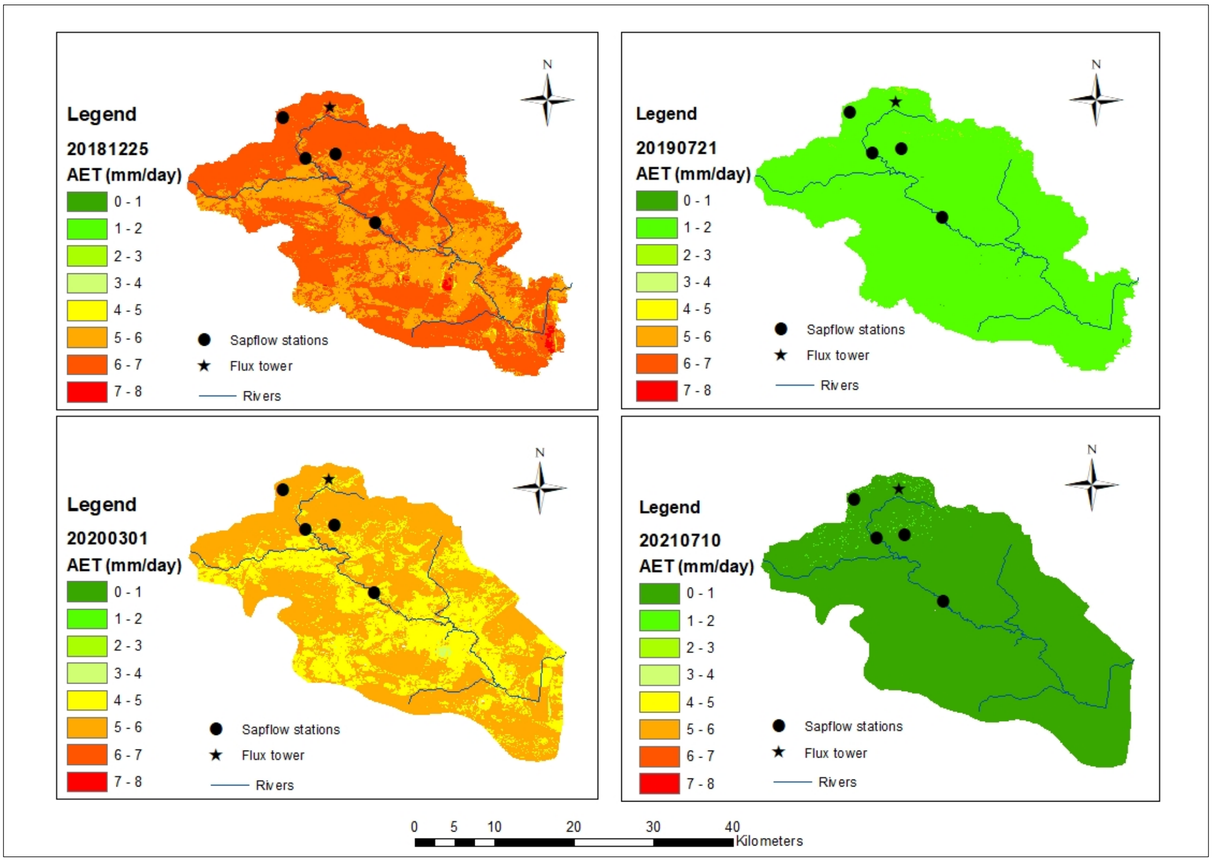


Figure 5.22: Spatial variation of evaporation across the catchment for three selected days, 21st July 2019, 10th July 2021 (representing wet season) and 25th December 2018, 1st March 2020 (representing dry season).

5.4 DISCUSSION & CONCLUSION

5.4.1 The extent of IAPs in the Catchment

Fynbos shrubs and cultivated lands are the dominant land covers in the Nuwejaars catchment. However, areas on the headwaters and along the riparian zones have been dominated by invasive alien plants. The headwaters receive slightly higher rainfalls than the lowlands, and the deep sandy riparian soils have also encouraged the invasion in riparian areas. As a way of controlling and reducing the negative impacts of IAPs on the invaded ecosystems (Le Maitre *et al.*, 2011), a national programme named “Working for Water” was established in 1995. Local farmers and landowners in the catchment also made efforts by establishing the Wetland Special Management Area forum in the catchment. These programs were interventions that have been employed to combat the spread and impact of these IAPs. Such that the extent of IAPs in the catchment has declined from 25% in 1973 to 11% in 2021. The land cover results show that areas that are invaded were mostly located on the north-western mountains and the riparian zones of the Nuwejaars River.

5.4.2 Transpiration dynamics by riparian and non-riparian A*. longifolia* stands along the topographic gradient

Acacia longifolia was identified as the dominant species occupying the hillslopes and riparian zones in the Nuwejaars Catchment (Mkunyana *et al.*, 2019). Therefore, this study sought to test the hypothesis that that IAPs act as groundwater "pumps" in invaded corridors. This was thought to be more likely during summer periods when transpiration is expected to be high and trees could potentially use groundwater to a point where the water table will become lower than stream levels, thus changing the river system to be a losing stream. In contrast, during winter, when transpiration rates are low, *A. longifolia* was expected to have minimal effect on the hydraulic gradient.

The reference evapotranspiration (representing the evaporative demand) increased from the headwaters to the lowlands. Across the catchment, reference evapotranspiration was more than the total rainfall received. Thus, showing the aridity of the catchment increased from the headwaters to lowlands. The increasing aridity also affected the transpiration dynamics along the gradient. *A. longifolia* stands on the headwaters had the highest rates of water use as a result of high rainfall in the area which in turn increased water availability for plants. At the riparian sites, Moddervlei and Jan Swartskraal, from June 2019, increased groundwater table and soil water content were observed. The rise in the water table and increased soil water content explained the high rates of water use at the riparian sites. On both-riparian sites, high transpiration rates were observed during periods when the sites received significant rainfalls that increased soil water contents in the deep soil layers. As a result, in 2020, transpiration by *A. longifolia* stand at Sandfontein (non-riparian) was greater than the stand transpiration rates at Moddervlei and Jan Swartskraal (riparian). In 2020, Sandfontein received relatively higher rainfalls and thus the water table at the site was close to the surface for extended periods, and this was evidence that soil water availability is a prevailing factor in tree water use by *A. longifolia* occurring in both riparian and non-riparian settings. The Sandfontein site is towards the lower end of sloping ground. The site receives groundwater from an upslope recharge zone, which provides additional water for plant use. The low transpiration rates during 2020 at the riparian site however was attributed to waterlogging at the site which is generally associated with lack of soil aeration, thus affecting the root system and the transporting of water.

The riparian invasions used substantially more water than non-riparian invasions as a result of high-water tables that increased soil moisture content in the capillary fringes. The shallow roots identified by Mkunyana et al. (2019) were consistent with the shallow water table depth that ranged between 1.4-2.2 meters below ground during 2019-2020 at Moddervlei. This supports the assumption in the literature that plants minimize energy use by developing the highest root densities and extracting most of their water from soil layers that are most consistently wet and have the highest available water potential (Amin et al., 2019). Thus, the shallow water table enables *A. longifolia* to thrive without a taproot system.

The extraction of groundwater by *A. longifolia* was also evident in the diurnal changes of the water table across all the sites. These diurnal variations of the water table due to extraction of groundwater by plants has been observed in other studies (Loheide et al., 2005; Butler et al., 2007). During the night, when transpiration significantly diminishes or ceases, the water table will recover because of groundwater inflow to the site (Loheide et al., 2005). This was observed in *A. longifolia* trees occurring in both riparian and non-riparian settings. Extracting of groundwater from the capillary fringes is a defence mechanism that most plants growing in semi-arid regions have adapted to avoid or minimize water stress during the dry season (Sun et al., 2011), whereby plants use shallow soil moisture preferentially when abundant and switch to groundwater or deeper soil layers as shallow layers become dry (Naumburg et al., 2005).

5.4.3 Comparative water use by invasive *A. longifolia* stands and the indigenous fynbos stand

The sap flow method of the heat pulse velocity technique quantified the water used (transpiration) by individual trees and was upscaled to stand level transpiration. A two-layer AET model was used to establish annual AET rates from the riparian and non-riparian invaded sites and the results from the model were compared with AET from the fynbos stand. The results showed that IAPs used substantially more water than the fynbos stand. Even though the model underestimated AET by *A. longifolia* stands, but the results from the model were validated by transpiration rates by *A. longifolia* at these sites which were already higher than AET from fynbos. The underestimation of AET using the model was greater on the non-riparian *A. longifolia* stand, and this was attributed to the sensitivity of the model to soil water content that was lower on non-riparian soils. This validates the hypothesis that IAPs use more water than the indigenous vegetation and thus the greater impacts are observed in areas that are favourable for their rapid growth, such as the riparian areas.

5.4.4 Actual evapotranspiration at the catchment scale

The spatial and seasonal variation in actual ET were observed across different land covers in the catchment. High AET was observed on the upland/headwaters of the catchment whereas low values occurred on the low-lying areas. On the headwaters, there were differences between areas with IAPs, cultivation, and fynbos. Areas with IAPs had high AET rates. Also, in the lowlands, corridors of high AET rates were observed along the rivers. These were associated with corridors of IAPs along the riparian zones. These results agreed with findings from previous studies that showed IAPs used more water than the indigenous vegetation (Calder and Dye, 2001; Dye *et al.*, 2001; Everson *et al.*, 2016; Scott-Shaw, Everson and Clulow, 2017; Gush, 2018). The seasonal variation in actual ET was also observed, with high AET rates during the dry season and low AET during the wet season. The impacts of the drought period in the Western Cape were also notable between the dry season AET rates. As a result, the dry season AET rates in 2018 were lower than the dry season AET rates in 2020. This was attributed to limited water for evaporation and transpiration during the drought season compared to 2020 when water was available for evaporation (AET). The wet season AET rates in 2019 were higher than AET rates observed in July 2021. These were consistent with the lower average temperature and higher total rainfalls in 2021 compared to 2019.

5.4.5 Implications of IAPs stands on GW-SW interaction

There is not enough evidence of the extent of impact by IAPs on groundwater-surface water interaction. However, results from this study show potential groundwater use by *A. longifolia* through capillary fringes. This was illustrated by the declining water table during the day when transpiration rates increased. The extraction of water in the unsaturated zone (shallow and deep soils) could potentially affect the proportion of rainfall that becomes runoff and groundwater recharge in invaded sites (Le Maitre *et al.*, 1999). This results from the dense canopies that increase canopy interception.

CHAPTER 6: SURFACE WATER-GROUNDWATER INTERACTIONS

6.1 HYDROGEOLOGICAL ASSESSMENT FOR SW-GW INTERACTION

The interaction between groundwater and surface water largely depends on the geological systems/structures such as faults, folds, and fractures. The regional fault system influences flow paths and direction of groundwater and interactions with surface water. Thus, an understanding of geological structures in a catchment is important. The Nuwejaars Catchment is located in the syntaxis domain and slightly on the southern branch of the Cape Fold Belt (CFB). The CFB is a largely east-west striking feature, consisting predominantly of sedimentary and metamorphic rocks that influence the flow direction of groundwater and river channel morphology. These rocks were exposed to intense pressure, especially from the south (Meyer, 2001) which resulted in a variety of geological features and structures that produced a wide range of aquifer characteristics peculiar to the region. Regionally, the following main geological formations underlain the Nuwejaars Catchment; Malmesbury Group; Table Mountain Group (TMG); Cape Granite Group; Bokkeveld Group and Bredasdorp Group (Figure 6.1). The presence of these rocks explains the occurrence of fractured rock aquifer systems that have groundwater with low EC.

The basement geology of the area is made up of the meta-sediments of the Malmesbury Group, while the Table Mountain, Bokkeveld and the others were deposited over the Malmesbury Group. The Nuwejaars Catchment is locally confined within the TMG and the Bokkeveld Groups of the Cape Supergroup and the Bredasdorp Group. This locally confined system is responsible for a confined aquifer system with high pressure resulting in artesian conditions in some boreholes in the study catchment, e.g. the 50 m borehole at Tussenberge which is artesian during the wet season. The Cape Supergroup has the TMG as the lowest component which forms the foundation of the Cape Fold Belt Mountains (Brown et al., 2003) producing fresh groundwater. Therefore, boreholes drilled in such formation had fresh water, e.g. EC for boreholes at Tussenberge in the uplands varied from 0.165 t0 0.416 mS/cm.

The tertiary to recent alluvium calcified dune sand and coastal limestone of the Bredasdorp group dominate along main river channels, floodplains of the Nuwejaars River and all the way to the Soetendalsvlei Lake and Heuningnes Estuary (Figure 6.1). The Bokkeveld Group dominates the middle subdivisions of the catchment consisting of fine-grained sandstones and shales that conformably overlie the TMG in an off-lapping succession (Thamm and Johnson, 2006). The shales and sandstones are products of the marine continental slope muds of early to mid-Devonian thereby explaining saline nature of the groundwater from such rocks (Gordon et al., 2011). Most of the boreholes drilled within the Nuwejaars River floodplain at Moddervlei intercepted sand up to 5-10 m deep, then sandstone 10-15 m, followed by shale extending up to the maximum drilling depth of 50 m. Groundwater at this location has very high salinity ranging from 2 to 24 mS/cm. The Bokkeveld Group is prone to weathering, occurrence of fractures and faulting and is intruded by the basement lithologies. Several faults also cut through the Napier and Bredasdorp Mountains in a north-east to south-west and east to north-west direction (Bickerton, 1984) (Figure 6.1). No studies exist to confirm whether or not the faults are barriers or non-barriers in the catchment. Fractures and faults are the secondary structures dominant in the area and seem to influence the main flow paths and direction in the catchment. Most springs in the area are closely linked to faults and have TMG formation geological group underlying them. The TMG formation has high yields due to faulting and fracturing features or characteristics. For example, the Elim settlement with a population of about 1,500 persons depends entirely on spring discharge for domestic water supply and dairying.

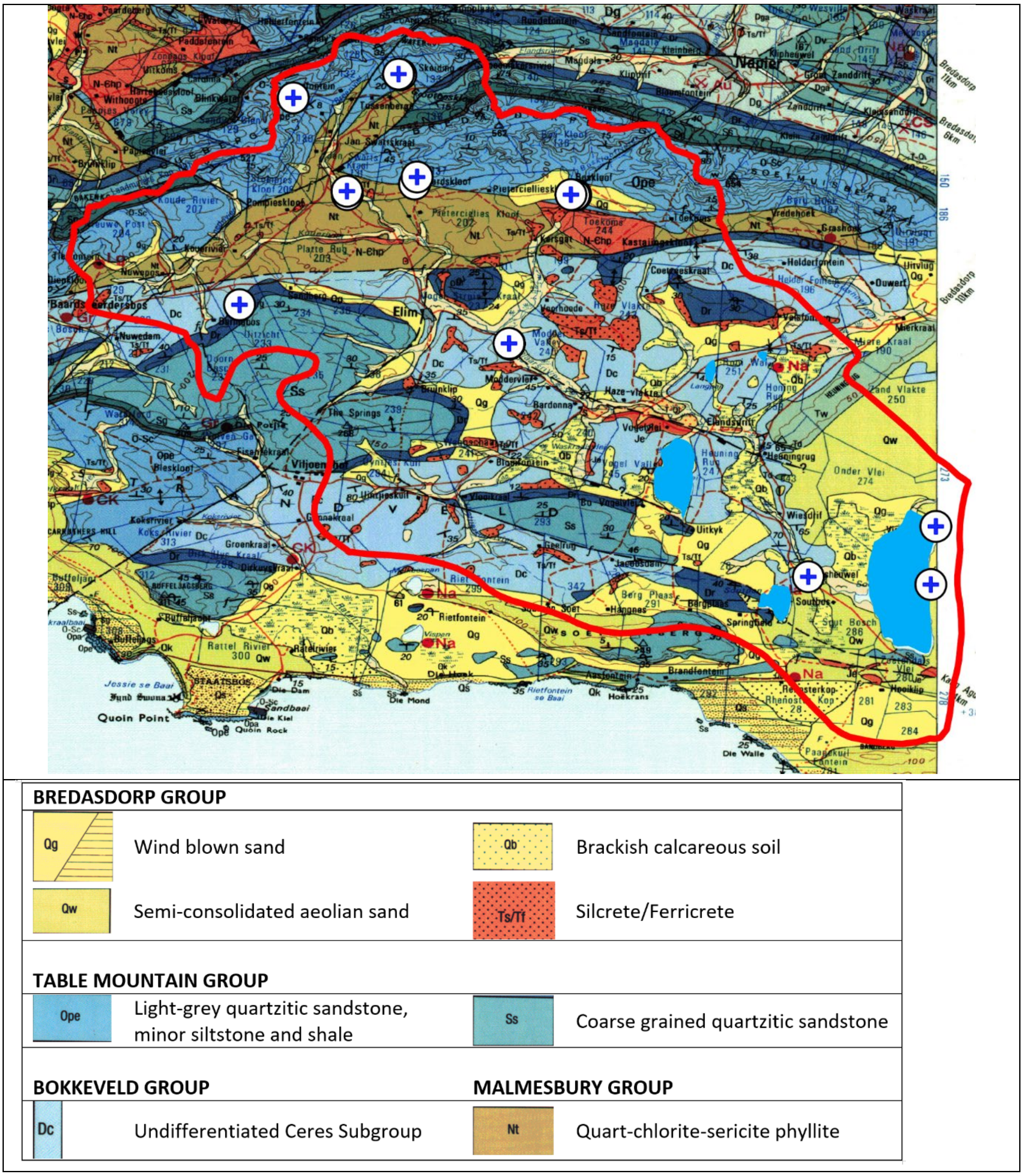


Figure 6.1: Geology of the Nuwejaars Catchment. White circles with blue crosses indicate locations of monitoring boreholes. Source: 3319 Worcester 1:250,000 Geological Series, Geological Survey of South Africa, Pretoria.

In general terms, the upper confined aquifers occur within tertiary and quaternary deposits of unconsolidated and weathered sand and shale with a thickness ranging between 10 to 25 m (Table 6.1). The second layer is a confined aquifer which extends from the top of the first layer to 100 m below the mean sea level, composed mainly of sandstones, shale and quartzite of the Cape Supergroup (Bokkeveld and Table Mountain). The bottom layer is underlain by an aquiclude comprising meta-sediments of the Malmesbury group at ~100m below the mean sea level (Kenotic, 2018).

Table 6.1: Hydro-stratigraphy of the study area (adapted from Mazvimavi, 2017)

Era	Period	Geological groups	Lithology	Hydro-stratigraphy
Xenozoic	Quaternary and Tertiary	Bredasdorp	Unconsolidated to semi-consolidated shelly, calcareous sand	Low yield primary porosity aquifers
Devonian	Palaeozoic	Bokkeveld	Shales and sandy shales	Low yield secondary porosity aquifers
Silurian-Ordovician	Palaeozoic	Table Mountain	Quartz, sandstone, shale, siltstone, and conglomerate	High yield secondary porosity, occurring at high depths
Pre-Cambrian		Cape granite suite	Basement rock	Aquiclude
		Malmesbury		

Groundwater flow in the study catchment explains the connectivity between surface water bodies and aquifer systems (Rotes et al., 2008). There are several springs that discharge into or form sources of streams in the uplands. Diffuse groundwater discharge occurs on several locations along slopes in the uplands. The shallow water tables are within reach of root systems making vegetation depending on groundwater as evidence of interaction. For example, at Boskloof, with an 8 m deep water table, Eucalyptus trees growing at this site had easy access to the groundwater (Mazvimavi, 2018). The water flowing downstream, to the rest of the catchment is significantly reduced because the invasive trees in the upper catchment tap shallow groundwater thereby contributing to observed reduced spring flow and interflow. The lowland part of the catchment has shallow water levels close to the river. The monitoring of water tables showed that the valley fill primary aquifers were in hydraulic connection with the rivers and it is expected that water tables will respond to changes in river flows (Mazvimavi, 2018). Change in hydraulic gradient will always affect the groundwater flow direction between the shallow aquifer and the river all through the season. Groundwater in the area is from regional flow [deep system], direct rainfall, seepage from rivers and wetlands while outflow of groundwater is through evaporation, flow to wetlands and streams, discharge into streams and groundwater flow across the south-eastern boundary. To the north-west and north-east are the Bredasdorp and Koue mountains respectively that surround the Nuwejaars river catchment. This gives way for tributaries of the catchment and subsequent groundwater recharge areas. Groundwater in the area flows from the high hydraulic heads in the northern and western part to the lower heads in the south-eastern part of the catchment. Therefore, it can be stated that groundwater flow within the Nuwejaars Catchment is partly influenced by surface conditions, geological structures such as springs and faults

Xaza (2020) used geology of the study area, recharge/discharge information, to develop a model illustrating groundwater flow (Figure 6.2). Groundwater flow in the lowlands is retarded mainly by the presence of the marine clay and the gently topographic slope. The discharge of groundwater from uplands through springs and into lowlying areas contributes to river flows. Several springs occur discharging into the ocean occur along the southern coastline (Figure 6.2).

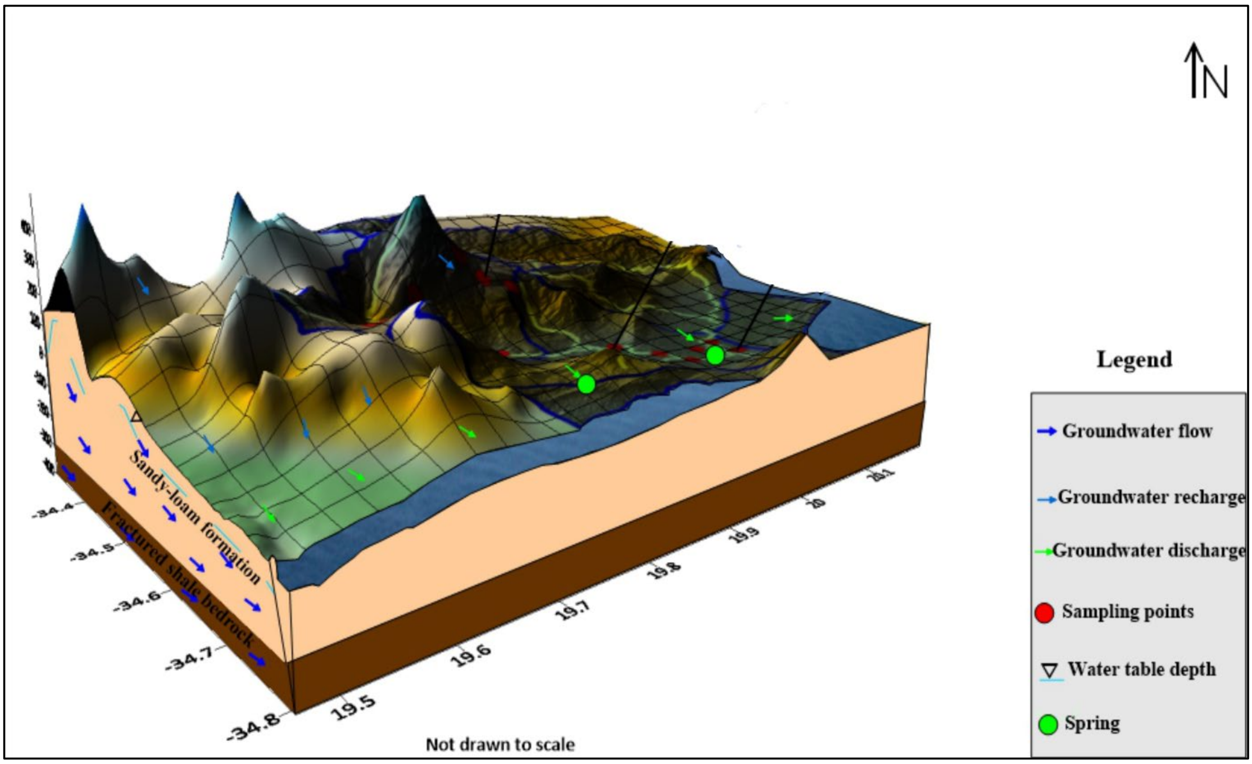


Figure 6.2: A 3D conceptual model for the Nuwejaars Catchment (Xaza, 2020)

6.2 SPRINGS

Several springs occur in the Nuwejaars Catchment, and as has already been explained contribute substantially to river flows (Figure 6.3).

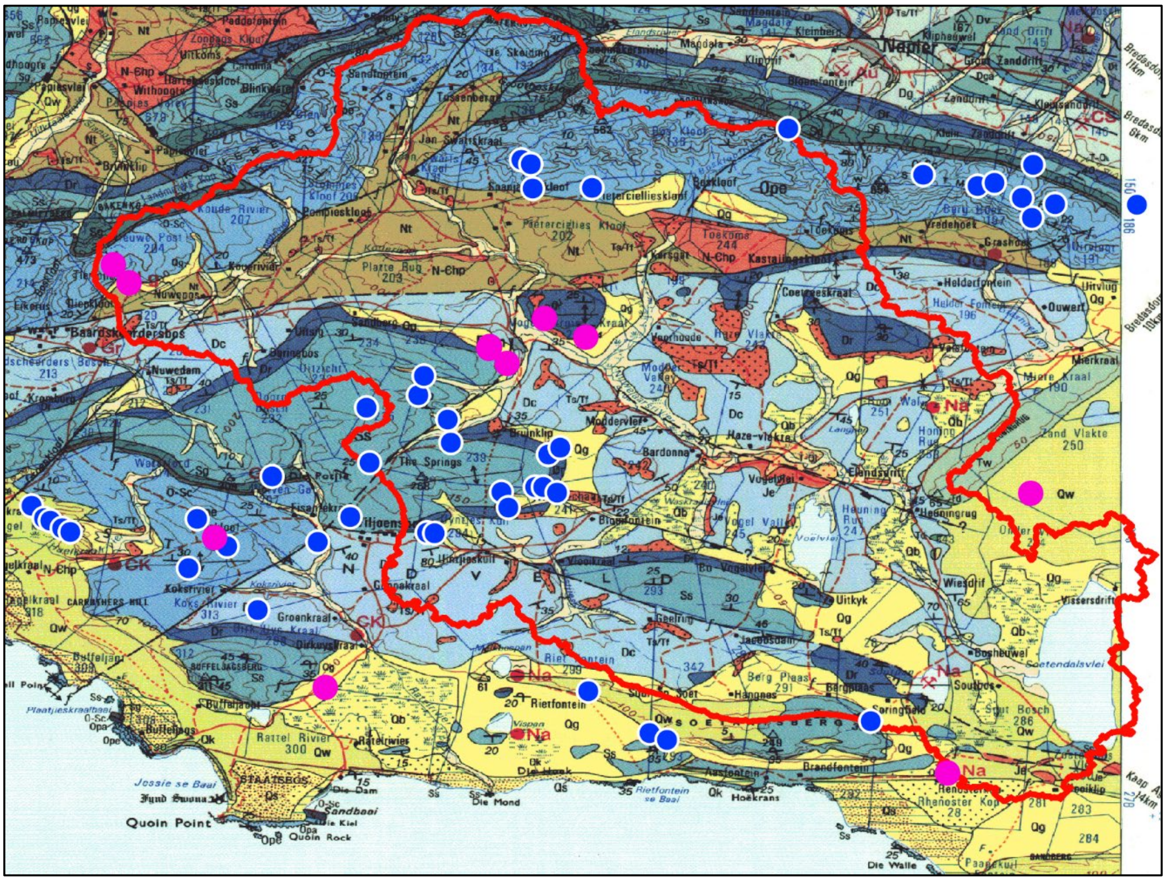


Figure 6.3: Locations of springs in the Nuwejaars Catchment.
Blue circle – springs occurring on the 3419C 3419D Gansbaai 3420C Bredasdorp 1963 Geological Map. Purple circles – springs identified by the Project Team. Base map 3319 Worcester 1:250,000 Geological Series, Geological Survey of South Africa, Pretoria

The origin of most springs is associated with the local presence of deep geological structures, such as folds, faults, and dykes. The regional and local groundwater flow systems which influence the occurrences of springs are controlled by lithology and faults. Most springs in the study area are associated with TMG formations and closely linked to fractures and faults (Figure 6.3 and 6.4). Three types of springs were identified in the study catchment as shallow circulating springs, lithology-controlled springs and fault-controlled springs. The work on detailed classification of springs is in progress. Suffice to reiterate that groundwater discharges via springs sustain surface water and confirms the existence of the SW-GW interaction in the study catchment.

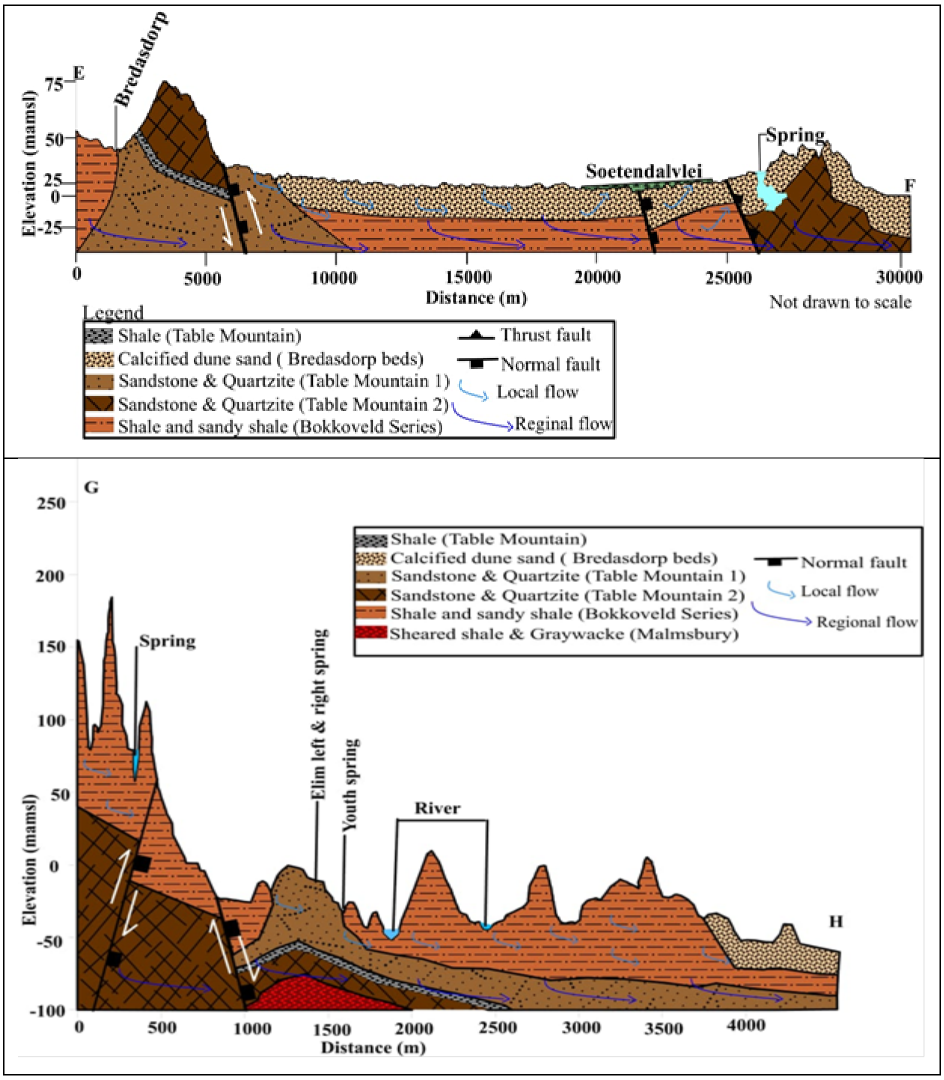


Figure 6.4: Influence of geological structures on groundwater flow system and the occurrence of springs

Groundwater discharge in the study catchment occurs through fractures and faulting of the geological formation. Such fractures are significant in the explaining flows and discharges of groundwater to rivers thereby showing the preferential pathways of surface waters in the catchment. Groundwater discharges through springs form permanent or intermittent river segments in the catchment (Uys and O'Keeffe, 1997). This observation confirms that groundwater discharges to the rivers forms important part of the water balance. Most streams in the uplands derive flows from groundwater discharges (Winter, 2007).

6.3 INFERENCE ON SW-GW INTERACTIONS

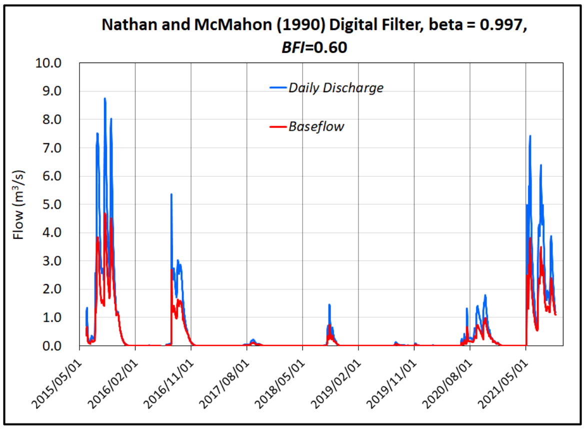
6.3.1 Hydrograph separation

Table 6.2 provides the estimated *BFI* for different parameter values of the two digital filters. The recession constant required for the Eckhardt (2005) filter was estimated from the recession curve by regressing *Q(t)* against *Q(t-1).* The recession constant for the Nuwejaars River (*α)* was 0.930

Table 6.2 Base flow indices obtained for different parameter values of the digital filters

Nathan and McMahon (1990) filter		Eckhardt (2005) filter	
β value	BFI	BFI_{max}	BFI
0.925	0.86	0.50	0.50
0.950	0.83	0.65	0.64
0.997	0.60	0.70	0.70

The Nathan and McMahon (1990), and the Eckhardt (2005) filters give baseflow values that are comparable (Figure 6.5) depending on the filter parameter values selected. The two filters estimate the baseflow contribution to be greater than 60% of total flows. Such high contributions are expected for perennial rivers. However, the Nuwejaars River dries up as is evident from the mean monthly flows and the flow duration curve presented in Figure 3.6. Thus, the baseflow contribution estimated using digital filters is considered to be unrealistic. Previous studies have found that most parts of the country have baseflow indices less than 0.30 (Smakhtin and Watkins, 1997, Le Maitre and Colvin, 2008; Schulze, 2012). This shows that the use of digital filters for baseflow separation on flows influenced by water storage in floodplain pools is not appropriate. After peak flows the slow drainage of water back into the main channel from floodplain pools is apportioned to baseflow by digital filters.



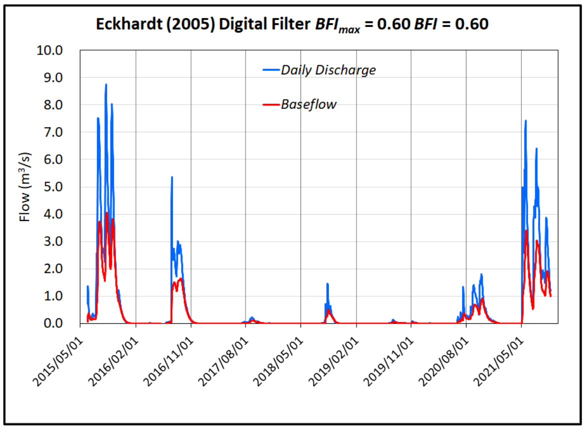


Figure 6.5: Baseflow separation using the Nathan and McMahon (1990) (left) and Eckhardt (2005) digital filters

Electrical conductivity (EC) of river water measured on an hourly basis at Moddervlei from February 2019 to October 2021 were used for hydrograph separation on a daily time interval. The study assumed that EC values measured during the wet season on streams in the headwaters, Tussenberge, are representative of rainwater EC, c_s in Equation (2.5). The average EC of headwater tributaries (Tussenberge Streams) c_s = 144 µS/cm during the June-August 2021 period was used to represent rainwater conductivity, while the peak flow EC of Nuwejaars River water at Moddervlei was 322 µS/cm. The average of the electrical conductivity of river water at Moddervlei during the low flow period from 5 January to 2 April 2021 was 732 µS/cm. During this period EC varied from 694 to 757 µS/cm. The average EC during this period was assumed representative of baseflows, c_b.

Table 6.3: Baseflow index (BFI) estimated using the conductivity mass balance hydrograph separation method

c_b (μS/cm)	c_s (μS/cm)	*BFI*
732	144	0.56
732	322	0.35
1000	144	0.38
1000	322	0.21

Hydrograph separation done using an estimate of rainwater conductivity (c_s = 144 μS/cm), and c_b = 732 μS/cm gave a *BFI* = 0.56 which seems too large for a river that dries up frequently. If the EC of the peak flows of the Nuwejaars River at Moddervlei, c_s = 322 μS/cm is used, the estimated baseflow index is 0.35 (Table 3.5, Figure 3.8). There have been suggestions that c_b be estimated from the maximum conductivity value measured (c_b =1000), and this provides BFI values of 0.21 and 0.35 depending on values assumed to be representative of surface water (Table 3.5).

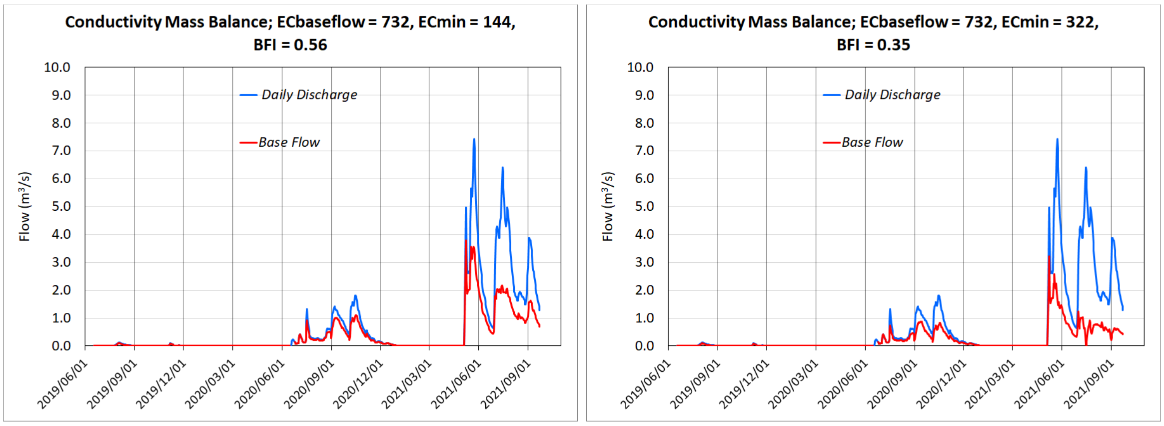


Figure 6.6: Comparison of conductivity mass balance hydrograph separation using the EC of rainfall (cs = 144 μS/cm) and EC of peak flows of the Nuwejaars River at Moddervlei EC (cs = 322 μS/cm) to represent surface runoff.

The value of the baseflow index (21% to 35%) estimated using the conductivity mass balance method is of the order of magnitude expected for rivers with geological formations similar to the Nuwejaars River. The WR2021 estimated the baseflow index to be 0.28.

6.3.2 Hydrochemical analysis

Major ions are very essential in monitoring water resources. The major cations include Ca2+, Mg2+, Na+ and K+ while major anions are, HCO3-, SO42- and Cl-. The analysis of these ions was done using data collected in October 2018, March 2018, December 2020, January 2021, February 2021, March 2021, May 2021, July 2021, and September 2021 as these months contain both groundwater and surface water data. In both surface and groundwater, a similar pattern is presented by the concentrations of cations with the range from high to low in order Na>Mg>Ca>K and from high to low concentrations of anions in order Cl>SO4>HCO3. Schoeller diagrams were plotted for groundwater and river water samples located closer to each other. The Schoeller plot is a semi-logarithmic diagram representing concentration of major ions in mEq/l. This allows major ions of many samples to be represented on a single graph from which samples having similar patterns can be differentiated. The results from the concentrations of major ions for river water and groundwater are shown in Figures 6.7 and 6.8 respectively.

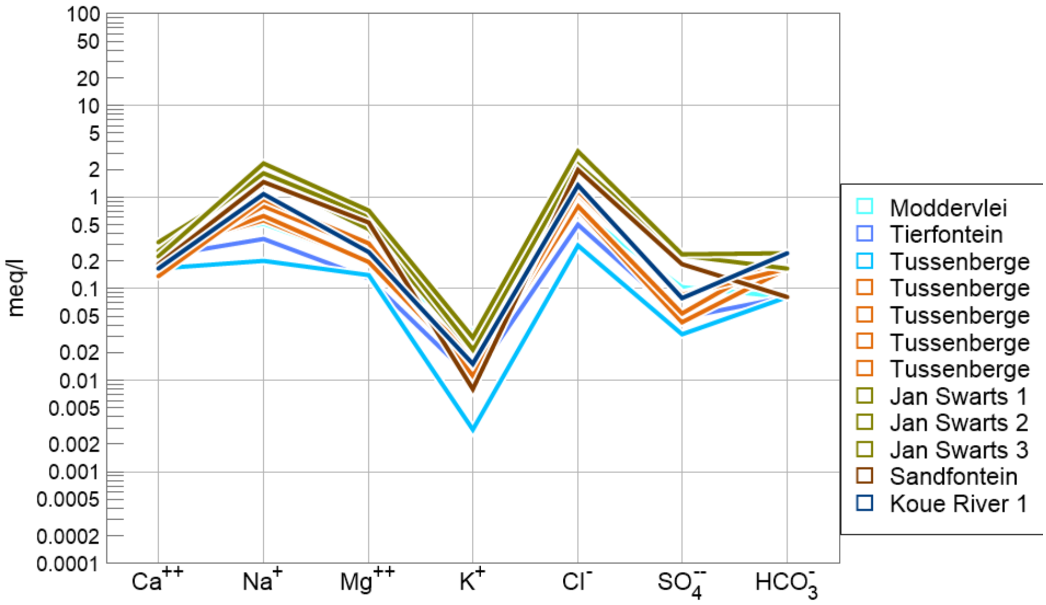


Figure 6.7: Schoeller showing river water samples at various locations

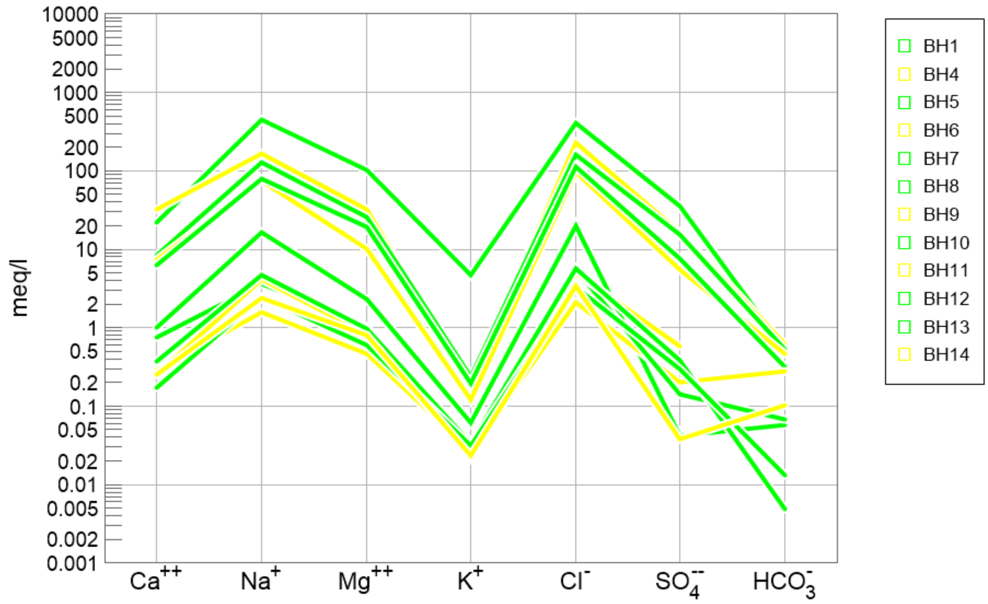


Figure 6.8: Schoeller showing groundwater samples at various locations

The results indicate that the concentration of major ions are higher in groundwater in both the wet shallow and deep boreholes (Figure 6.8). However, wherever there is a rise in concentration of a particular ion in groundwater (Figure 6.8) there is also such a rise of that particular ion in surface water (Figure 6.7). The fall in the ion concentration is also similar for groundwater and surface water. The same type of variation in major ion concentrations between the two water sources implies possible interaction between groundwater and surface water. In general, both water sources have high concentrations of Na and Cl. Therefore, the chemical characteristics of river water is generally influenced by the groundwater characteristics.

6.3.3 Comparison of water tables and riverbed levels

This section presents a comparison of the elevation of the water table in monitoring boreholes with that of the riverbed nearest to the respective sites. If the water table is above the riverbed, i.e. positive hydraulic head, this indicates that if there is hydraulic connectivity between the aquifer and the nearest river, then groundwater will discharge into this river. This will be a case of a gaining river. Where the water table is below the riverbed, negative hydraulic head, then groundwater will not discharge into such a river, a potential exists for the river to recharge groundwater, and therefore be a losing stream. While a positive head may exist, groundwater may not discharge into the nearest river bed, but discharges at a distant location, e.g. a topographically low point in the catchment. Similarly, a riverbed could be above the water table, however the underlying clay or any other relatively impermeable material may limit the movement of river water into groundwater.

6.3.3.1 *Tussenberge*

The three monitoring boreholes at Tussenberge in the uplands have altitudes of 202-209 m above sea level, and are 160 m away from a nearby stream with an altitude of 192 m. These boreholes were drilled into sandstone and have depths of 12, 30, and 50 m. The level of the water tables of both the shallow and deep aquifers are always above the river bed (Figure 6.9).

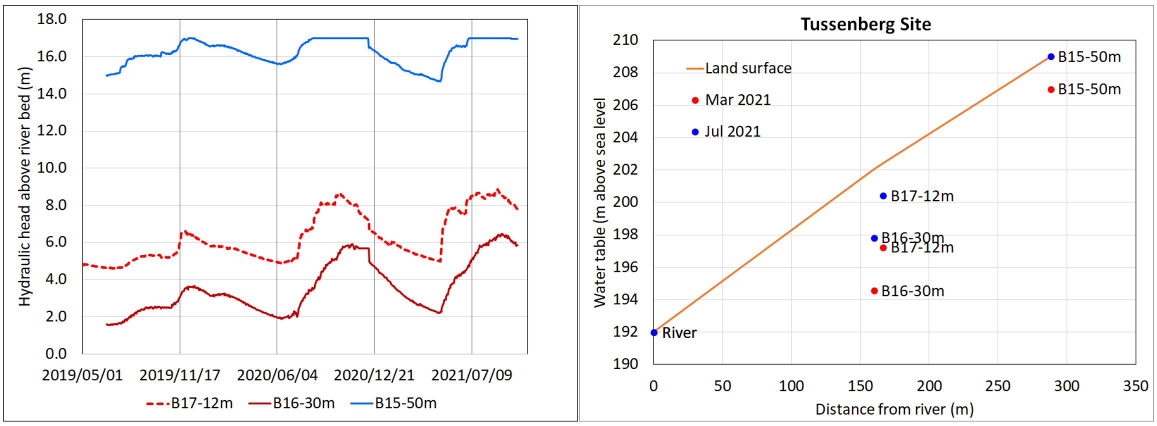


Figure 6.9: Relationship between water table and riverbed level at Tussenberge.

The deep aquifer intercepted by the 50 m borehole at Tussenberge has the highest hydraulic head and becomes artesian during the wet season. Surfacing of the water table during wet periods may results in some of the seepage flowing directly to the nearest stream. In addition, the wetting of the surface increases the proportion of rainfall that forms runoff, thereby enhancing surface flows. The shallow aquifer also has a positive hydraulic head throughout the year, creating conditions conducive for groundwater discharge into the nearby stream. The adjacent stream is perennial confirming that this is a gaining stream.

6.3.3.2 *Sandfontein*

This site is in the uplands and has two monitoring boreholes, 11 and 30 m deep, and at 228 m above sea level while the stream which is 60 m away is at 222 m. This site was also used for tree water use monitoring. The water tables in both boreholes were always above the riverbed level (Figure 6.10).

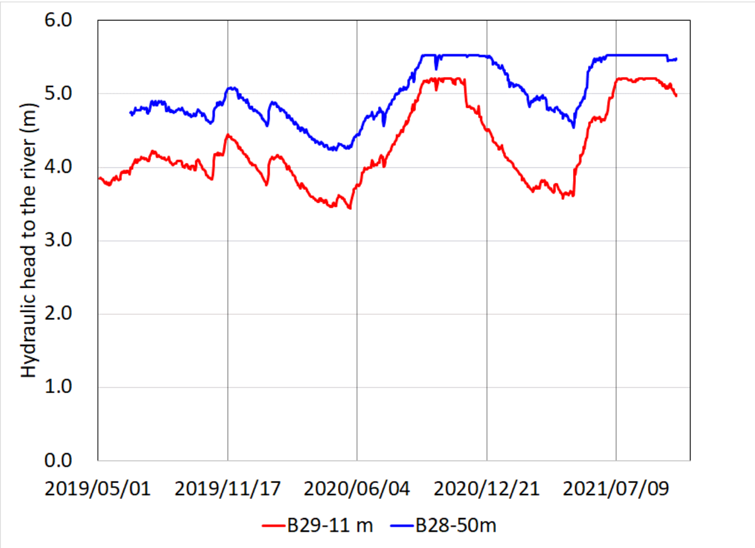


Figure 6.10: Relationship between water table and riverbed levels at Sandfontein

The stream at Sandfontein has the potential to be gaining water from groundwater discharge (Figure 6.10 and 6.11).

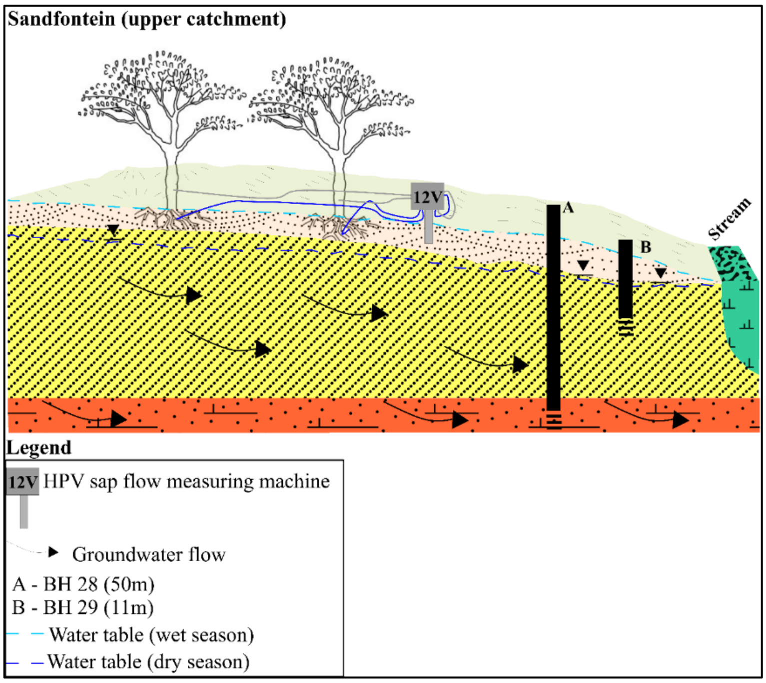


Figure 6.11: Conceptual model for tree water use and surface water-groundwater interactions at the Sandfontein site in the upper part of the Nuwejaars Catchment

The Sandfontein boreholes are located towards the bottom of a slope which has the highest point being 1.0 km away at about 400 m above sea level. Waterlogging frequently occurs during the wet season as a result of resurfacing of groundwater moving downslope. The Sandfontein stream can therefore be classified as a gaining stream. The results of tree water use monitoring showed that trees do abstract water from the shallow aquifer. This water use will not affect groundwater discharge from the deep aquifer to the stream.

6.3.3.3 *Jan Swartskraal (mid catchment)*

The Jan Swartskraal site has two boreholes, 7 and 50 m deep, and sandstone occurs up to 2 m deep, followed by shale throughout. The boreholes are at an altitude of 67 m while the stream which is 34 m away has an altitude of 65 m. The water table in the 50 m borehole has been 0.5 to 3.5 m below the riverbed (Figure 6.12, 6.13). The shallow borehole (7 m) dries up during the dry season. This part of the Jan Swartskraal River is considered to be a losing stream

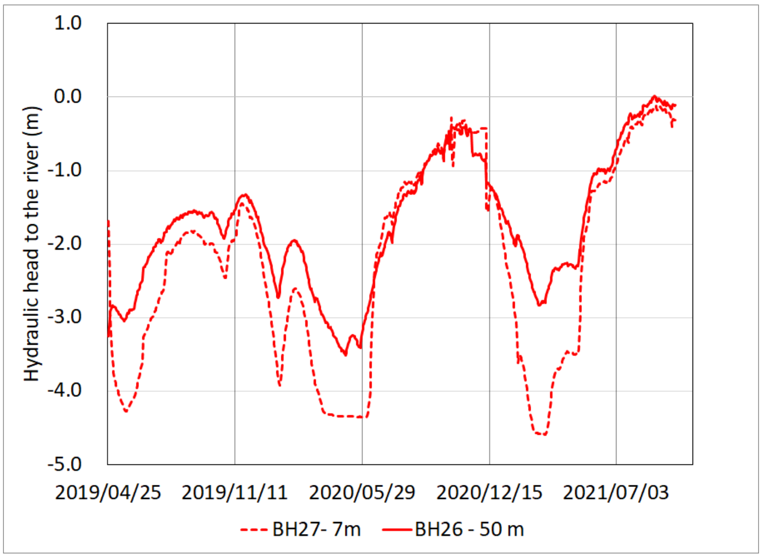


Figure 6.12: Water table always below the riverbed at Jan Swartskraal site

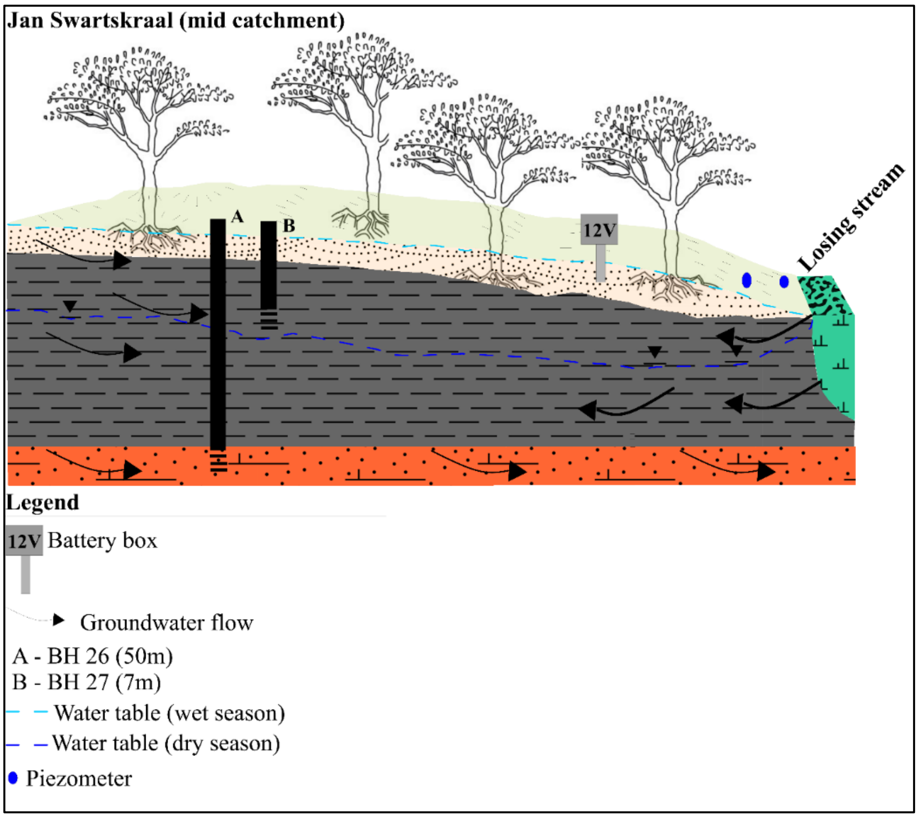


Figure 6.13: Groundwater flow at Jan Swartskraal which is a losing stream.

The midslope region of the Jan Swartskraal River has dense invasive *Acacia sp* along the riparian zone and. palmiet. Water use by the IAPS reduces flows in this river section which dries up during the dry season.

6.3.3.4 *Boskloof*

The Boskloof site has 6 boreholes with depths ranging from 6 to 100 m. The boreholes are on a 225 m long transect with altitude varying from 111 to 129 m, while the stream that is located 88 m from the nearest borehole has an altitude of 108 m above sea level. The site has sandy clay up 4 m followed by sandstone up to 100 m deep. Only two boreholes have water level recorders. Monthly measurements of the water table were done in all the boreholes. The water tables in boreholes at the top of the slope, BH11 (60 m) and BH12 (20 m) is always above the riverbed (Figure 6.14)

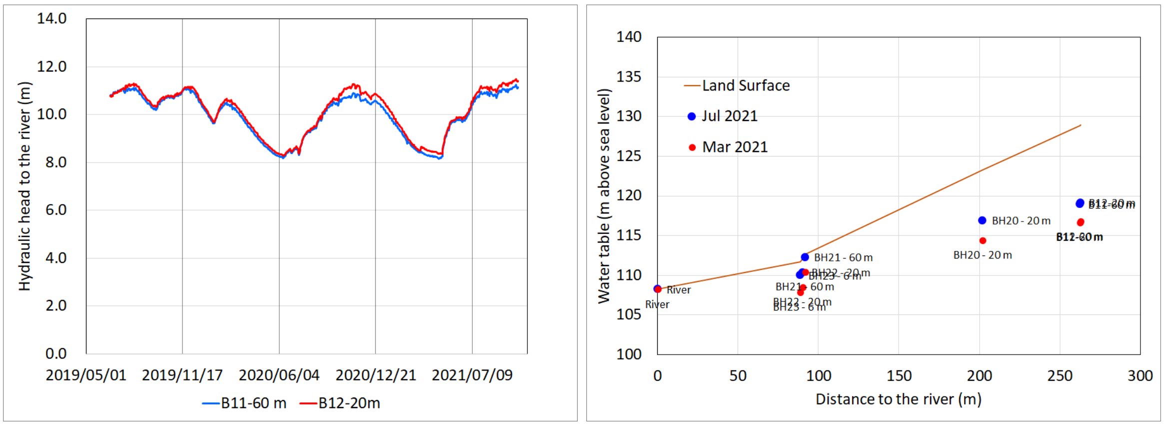


Figure 6.14: Relationship between water tables and riverbed at Boskloof

During the dry season, the water table in shallow boreholes at the bottom of the slope, BH22 (20 m) and BH23 (6 m) was slightly below the riverbed (Figure 6.14). Thus, the shallow aquifer does not contribute to river flows during the dry season. During the wet season, the bottom valley becomes waterlogged due to surfacing of deep groundwater, e.g. BH21 (60 m). The Boskloof site has therefore interesting surface water-groundwater interactions. The deep aquifer has the potentially to discharge to the stream throughout the year, while this is restricted to the wet period for the shallow aquifer.

6.3.3.5 *Moddervlei*

The Moddervlei site which is at the starting point of the Nuwejaars River floodplain has 8 boreholes with 6 of these being on the right bank and 2 on the left bank. The boreholes have depths varying from 8 to 60 m. The site has very low gradient, and the borehole altitudes are 21.5-22.9 m while that of the river is 19.3 m.

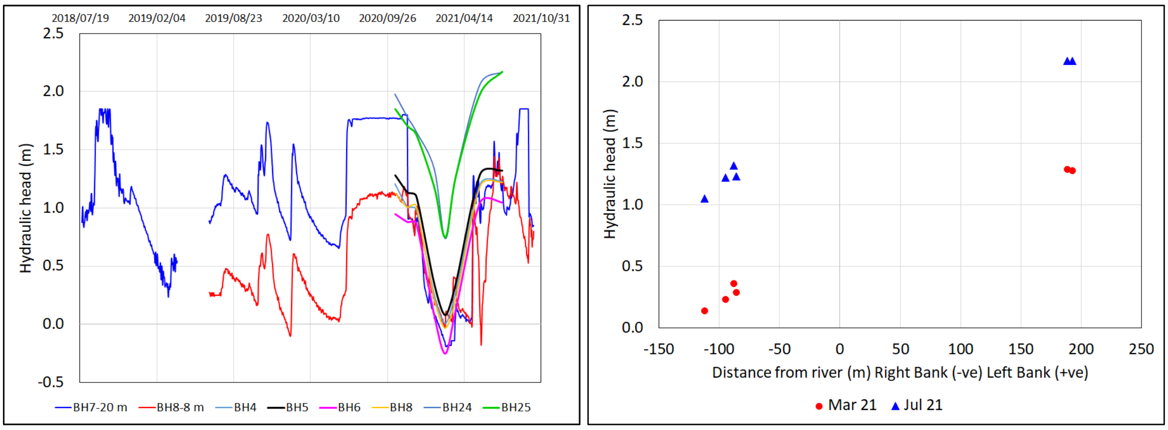


Figure 6.15: Relationship between water table depth and riverbed level at the Moddervlei site within the lowlands

Water tables in all the boreholes are generally 0.5-1.8 m above the riverbed level on the right bank, and 1.0-2.0 m on the left bank at Moddervlei (Figure 6.15). The left bank has an altitude about 1.4 m higher than the right bank, hence the greater hydraulic head. During February 2021, the water table declined to below the riverbed level on the right bank. This suggests that the potential for groundwater discharge to the Nuwejaars River occurs on the right bank mostly during the wet period and may be absent during the dry season. The channel has the potential to gain water from groundwater flow from the left bank. During the drilling of the left bank boreholes, dark brown soil was encountered up to 7 m followed by grey clay up to 21 m, and then shale up to 60 m. With very low gradient and grey clay on the left bank, groundwater movement into the river may be very limited, despite the existence of a positive hydraulic head. In general, the low gradient in the lowlands will constrain groundwater discharges into the Nuwejaars River within the lowlands. The high salinity of groundwater in this region is indicative of sluggish flow, hence limited discharge to the river.

6.3.4 Stable isotope analysis

Samples of groundwater and surface water were collected on a monthly interval from March 2018 to March 2021, and for precipitation from May 2020 to December 2020 for stable isotope analysis.

Rainwater samples at the three weather stations (Tussenberge, Tiersfontein & Moddervlei) had -30.5 to 1.7 ‰ for $\delta^{2}H$ and -6.49 to -1.43‰ for $\delta^{18}O$. Isotopically depleted values were observed during winter (May-August) which has high rainfall and low air temperatures. Rainwater became gradually enriched during summer which could be due to evaporation of rain drops falling through a warm atmosphere. The number of rainwater samples was not sufficient for identifying the influence of the environmental/geographical factors (climate, altitude, precipitation amount, continentality) on the isotopic composition of the precipitation.

Isotope values of stream water ranged from -25.8 to 41.1‰, and from -5.5 to 9.3 ‰ for $\delta^{2}H$ and $\delta^{18}O$ respectively. The isotopic composition of river water varied seasonally with heavier isotopes (isotopically enriched) in summer and lighter isotopes (isotopically depleted) in winter. The headwater streams (Tussenberge, Sandfontein & Upper Koue River) had the most depleted values with average values of -16.21 ±3.6‰ and -4.20 ±0.43‰ for $\delta^{2}H$ and $\delta^{18}O$, respectively. The isotopic composition of river water from the midslope zone was generally intermediate (mean: -14.33 ±4.3‰ and -3.72 ±0.71‰ for $\delta^{2}H$ and $\delta^{18}O$, respectively), while river water in the lower catchment had the most enriched isotopic values with an average value of 0.31 ±12.1‰ and -1.21 ±2.28‰ for $\delta^{2}H$ and $\delta^{18}O$ respectively. The lower catchment had also highly variable isotope values, ranging from -15.0 to 32.50‰ and -3.57 to 5.29‰ for $\delta^{2}H$ and $\delta^{18}O$, respectively.

Table 6.4: Summary of surface water isotope composition in the Nuwejaars Catchment

Sampling period	$\delta^{18}O$, in ‰		$\delta^{2}H$, in ‰	
	Min	Max	Min	Max
Mar-18	-5.1	7.1	-22.9	38.8
Jul-18	-4.9	0.9	-21.1	9.0
Feb-19	-5.3	9.3	-22.1	39.6
Jul-19	-5.3	-3.7	-23.9	-13.5
Oct-19	-5.5	1.7	-25.0	12.0
Dec-19	-5.0	-3.2	-24.1	-13.2
Oct-20	-4.7	-0.1	-17.0	7.2
Nov-20	-4.5	1.9	-20.3	16.4
Dec-20	-4.6	1.2	-20.5	14.3
Jan-21	-5.3	3.2	-21.7	24.3
Feb-21	-4.6	5.3	-20.4	32.5
Mar-21	-5.2	6.8	-25.8	41.1

Most of the stream water samples plot along the LMWL suggesting that recent rainfall was a significant contributor to streamflows. Two of the midslope streams (Spanjaardskloof spring and Elim flow diversion) which receive significant spring discharges had more depleted isotopic composition compared to the other midslope streams. There was a gradual enrichment in the isotopic values of the river water as the summer season progressed. This was evident for samples collected from the Nuwejaars River and its tributaries on the lower catchment such as Blomkraals River and Voëlvlei outlet that plot below the LMWL until they eventually dry up. There was a progressive increase in $\delta^{18}O$ and $\delta^{2}H$ values in the river water with distance downstream, demonstrating the cumulative effects of evaporation.

The isotopic composition of groundwater had low variability ranging from -5,77 to -0.34‰ and -27,8 to 2,5 ‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively with mean values of -3,87 and -17,74‰ for $\delta^{18}O$ and $\delta^{2}H$. Most of the groundwater samples plot on or close to the LMWL. Groundwater samples from the headwaters have depleted isotope values which suggests that groundwater recharge is mainly from meteoric waters. There were few groundwater samples from shallow boreholes (< 20m depth) located primarily in the lower catchment that were enriched. Their isotope values ranged from -22,6 to 2.5‰ (mean: -10,35‰) and -4,22 to -0,34‰ (mean: -2,22‰) in the lower catchment, and -23,5 to -10,2‰ (mean: -18,8‰) and -5,24 to -3,16‰ (mean: -4,35‰) in the headwater for ^{2}H and ^{18}O, respectively. The mean values indicate an enrichment of the heavy isotopes in this part of the catchment. A similar trend is observed for deep groundwater (>20 m depth) where headwater groundwater is isotopically depleted (mean: -5.00‰ for $\delta^{18}O$) compared to groundwater in the lower catchment (mean: -2.71‰ for $\delta^{18}O$). The isotopic composition for deep groundwater in the midslope region is intermediate with a mean value of -4.45‰ for $\delta^{18}O$, and seems reflect seasonal recharge during specific periods when heavy rainfall is particularly depleted during the winter period (May-August) and enriched in the summer period (September-April).

Table 6.5: Summary of groundwater isotope compositions within the Nuwejaars Catchment

	$\delta^{18}O$, in ‰		$\delta^{2}H$, in ‰	
Sampling period	Min	Max	Min	Max
Mar-18	-5.2	-1.7	-24.0	-5.9
Jul-18	-4.8	-2.2	-23.4	-8.9
Feb-19	-5.5	-2.5	-22.5	-9.8
Jul-19	-5.5	-0.4	-25.6	1.6
Oct-19	-6.0	-0.4	-28.0	-0.2
Dec-19	-5.5	-0.9	-25.9	-3.3
Oct-20	-5.2	-0.3	-25.2	2.5
Nov-20	-5.3	-0.6	-25.2	-1.4
Dec-20	-5.4	-1.4	-25.5	-4.4
Jan-21	-4.8	-0.5	-24.7	-0.5
Feb-21	-5.7	-1.1	-27.1	-6.0
Mar-21	-5.8	-0.8	-27.8	-2.1

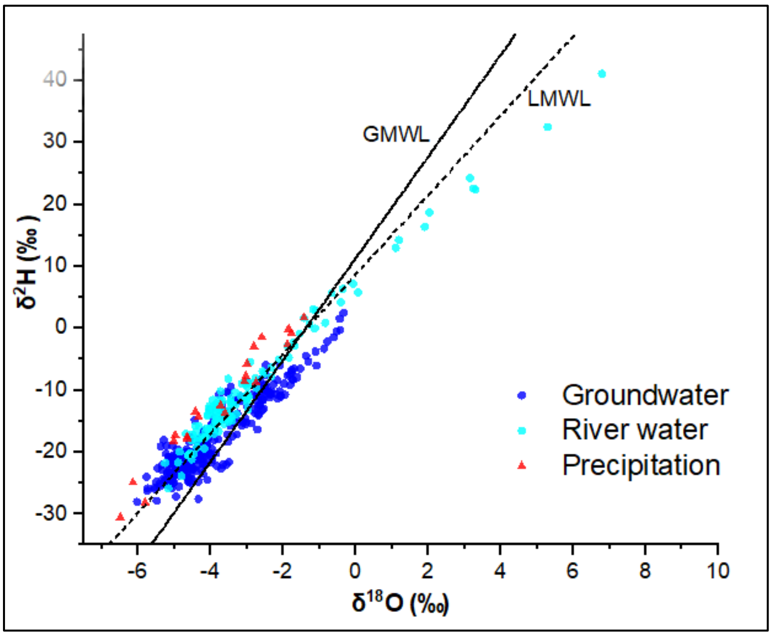


Figure 6.16: Dual plot pf precipitation, groundwater, and river water samples in relation to Global Meteoric Water Line of Rozanski et al. (1993) ($\delta^2H=8.20\ \delta^{18}O+11.27‰$) and the Cape Meteoric Water Line of Harris et al. (1999) ($\delta^2H=6.41\ \delta^{18}O+8.66‰$)

River water samples from the headwaters had an isotopic composition similar to the proximal groundwater during both the wet and dry periods, suggesting that groundwater is a dominant source of water for these streams (Figure 6.16). This is evident in the mean values of the shallow groundwater (-18.18 and -4.35‰ for δ^2H) and surface water (-16.21 and -4.20‰ for $\delta^{18}O$) at Sandfontein and Tussenberge. These values indicate the existence of a hydraulic connection between the groundwater and surface water system in the headwater region. The same observation was made for Boskloof River located in the midslope region. All the headwater and midslope streams are perennial with isotopic composition consistently depleted throughout the year which suggests that most of the streamflows are of groundwater origin.

Water samples Jan Swartskraal River at a midslope site had an isotopic composition dissimilar to the proximal groundwater isotopes (BH24 and BH25). The mean values of the river water isotopes (-3.52‰ for ^{18}O) and groundwater isotopes (-4.57 ‰ and -4.76‰ for ^{18}O) for shallow and deep groundwater were different suggesting that there is no interaction between them at this site. During the March to May period, the Jan Swartskraal River had no flows at the site close to the sampled boreholes, and therefore not receiving any groundwater discharge.

River water and groundwater samples within lowlands had clear difference in isotopic composition, suggesting little to no connection between the river and aquifer in these parts of the catchment. Groundwater had more depleted values compared to nearby enriched river samples, indicating that there was no groundwater recharge from the river samples. The disparity in EC values is also worth mentioning for these water sources with groundwater having high EC values compared to the adjacent river water of the Nuwejaars River having low EC values.

6.3.5 Radon data

The importance of the knowledge regarding radon in water is not only confined for radiation protection issues but also in its use for studying geological and hydrogeological characteristics of the environment (Mvelase, 2010). The difference in radon concentration between groundwater and surface water can be used to assess the existence of groundwater-surface water interactions.

Radium, the predecessor of radon, decays to radon that is embedded in rocks and dissolves in water occupying fracture spaces. Radon occurs naturally in all groundwater with varying concentrations depending on lithology and geological structure. This is evident in all the groundwater samples analysed as it ranged between 1081 to 332250 Bq/m³ (Figure 6.17). Radon is a gas and will travel as a dissolved gas as well as through the soil profile. It will only be present in surface water once groundwater enters the surface water body.

The concentration of radon in 23 surface water samples in the Nuwejaars Catchment ranged from 905 Bq/m³ to 64550 Bq/m³ (Figure 6.17). The higher radon concertation in headwater streams (Sandfontein, Koue River) implies that there is higher proportion of groundwater contribution (discharge) to the river, inferring that these parts of the river are gaining (Cook *et al.,* 2003). In the middle section of the catchment the radon concentration decreases compared to the headwaters which implies connectivity but at a lesser scale than upstream. However, Nuwejaars River 2 (Moddervlei) contains higher concentration of radon than any other points along the same river. This is due to inflows from the upstream Boskloof River and Pieterseilieskloof River both of which are gaining streams.

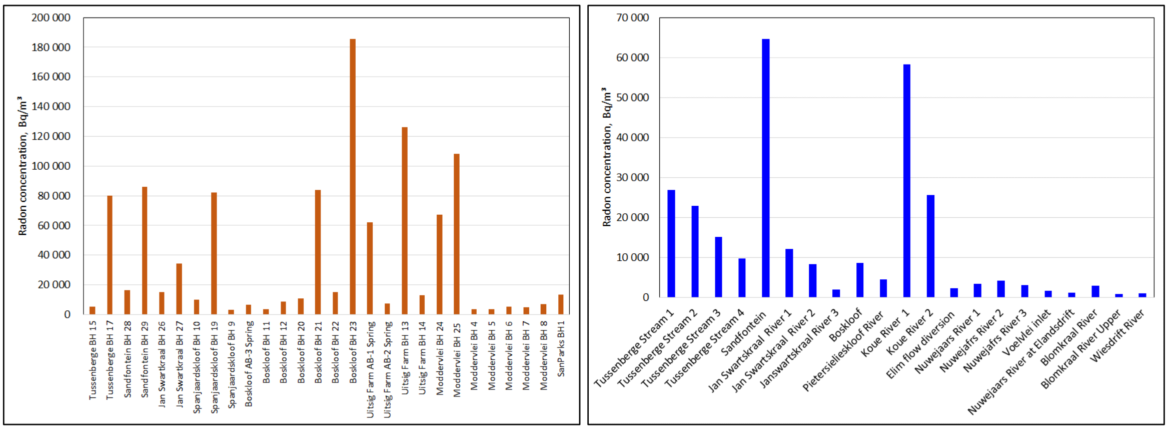


Figure 6.16: Radon concentration in boreholes (left) and rivers (right). River sites are plotted generally from upstream to downstream, except for Sandfontein and Koue River 1 which are both located in the uplands close to river sources

The radon results show that headwater stream gain from groundwater. These finding are similar to those of Bank *et al.* (2011). Radon was detected in streams within the midslope region which indicates the occurrence of groundwater discharge. In general, there is connectivity between surface water bodies and the subsurface evident by the varying radon concentration in all the sampled streams.

6.4 DISCUSSION

Considering the chemical composition of the various components of the hydrological cycle in an integrated manner, gives us insight into the interaction between the various components. The pH and Electrical Conductivity in both surface and groundwater show similar trends of gradual increases from the upper parts of the catchment towards the lower part of the catchment. This is due to the geological environment in the upper part of the catchment, the TMG which imparts acidity from silica as well as the pH of rainfall being slightly acidic. The observed increase in EC with distance from the upper part of the catchment for both groundwater and surface water is a function of natural processes of mineralization and evaporation which occur during dry periods. This is supported by the isotopic signatures with the lowlands having isotopic enrichment due to evaporative processes, causing lighter isotopes to be preferentially evaporated leading to more heavy isotopes. Changes in pH along the flow path are due to a change in lithology including the occurrences of calcareous dune sands especially in the lowlying part of the catchment.

Plotting of trilinear piper diagrams using data from groundwater (both deep and shallow), surface water from the entire catchment as well as rainfall showed that most data points, plot in the Na-Cl quadrant of the piper diagram. This implies that all the water samples originate from a similar geological environment. A few samples, i.e. rainfall and one shallow borehole, plot separately from the other samples, which suggests that rainfall may not be the main input to the surface water bodies as the ratios of ionic compounds present do not reflect that of the rainfall. However, one of the shallow boreholes reflect these ionic ratios. This leads to the consideration of the possibility of interaction between the groundwater and surface water in the catchment, as the ionic ratios are similar/the same. However, further use of tracers would need to be used to assess or confirm this.

Considering stable isotopes, one can consider points that cluster together as having the same or similar isotopic signatures, and this infers the same recharge source, or interaction of resources. When all points were plotted together, many of the points plot under the meteoric water line, this implies that evaporation occurs prior to infiltration or recharge. All upper catchment samples of deep groundwater, shallow groundwater and surface water plot in a cluster which relates to the same source and interaction between these sources. The lower catchment is significantly different in that evaporative processes impact largely on the surface water signatures, an evaporative signature is also seen in the shallow groundwater, however the level of enrichment of heavy isotopes is not as large as that of the surface water.

Radon 222 isotope concentration was considered as a tracer for deep circulating groundwater. Radon sources can be linked to the geological environment present in the study area, namely TMG and shales. Radon is a gas, hence it would not be present in large quantities or at all in surface water, unless a subsurface source of radon is interacting with the surface water. During the study, large concentrations of radon were detected in both surface and groundwater in the upper parts of the catchment. This supports what was found while considering the piper diagram results as well as the stable isotope signatures for the upper part of the catchment. The radon 222 data further showed that there is some degree of interaction in the lowlands as well.

CHAPTER 7: CATCHMENT MANAGEMENT

7.1 INTRODUCTIONS

The results presented in the previous chapters show that the Nuwejaars Catchment can be divided into the following three regions that reflect different hydrological responses, and surface water-groundwater interactions;

- *Uplands or headwater region* with elevation ranging from 100-650 m, covering 38% of the catchment, and with average rainfall of 600-800 mm/year.
- *Midslopes* with altitude of 50-100 m, comprising about 27% of the catchment and rainfall in the 500-600 mm/year range.
- *Lowlands* varying from 7 to 50 m above sea level, constituting 35% of the catchment, and average rainfall of 450-500 mm/year.

Both altitude and rainfall increase from the southern to the northern parts of the catchment. Uplands generally have slopes greater than 10%, while lowlands are flat especially along the Nuwejaars River. Consequently, the Nuwejaars River has wide floodplains with in- and off-channel pools. Several pans occur in the lowland region. The above catchment characteristics affect hydrological and hydrogeological behaviour and characteristics which affect spatio-temporal availability of water resources, potential threats to these resources, and possible land and water management interventions.

Previous chapters have shown that due to relatively high rainfall in the uplands and moderate to steep slopes (>10%), the uplands generate significant surface water during the wet season which benefits both the midslopes and lowlands. In contrast, lowlands do not contribute significantly to river flows as most of the rainfall is ponded because of low gradient. In the uplands, groundwater discharge in the form of springs and seepage contributes to surface flows during both the wet and dry seasons, hence streams such as Koue, Jan Swartskraal, and Pieterseilieskloof are perennial. Parts of the catchment with altitude greater than 200 m (or rainfall > 650 mm/year) and moderate to steep slopes (>10%) can be considered, within the context of the Nuwejaars Catchment, to be strategic water source areas (Figure 7.1). These parts which constitute the strategic water source area cover about 110 km^2 or 14% of the catchment.

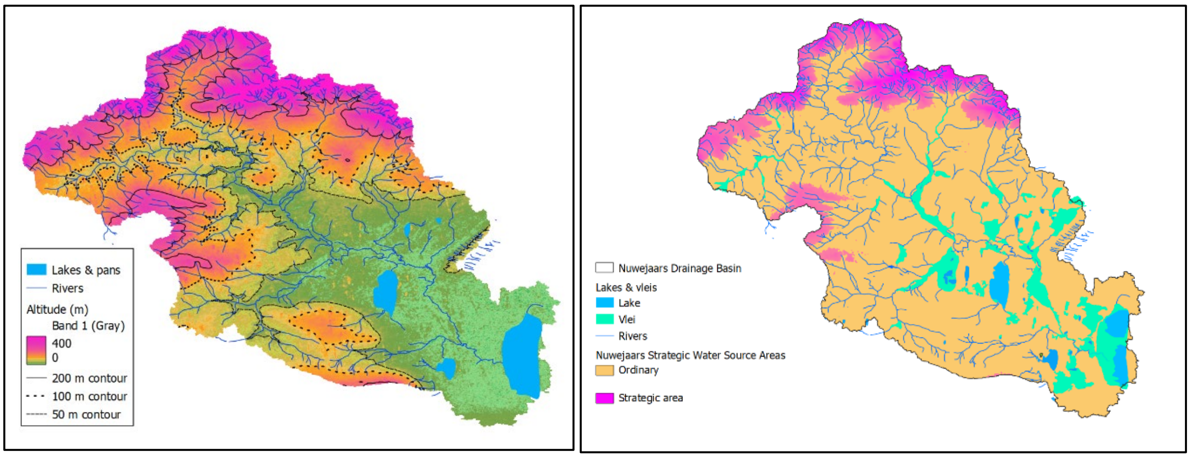


Figure 7.1: Spatial variation of altitude within the Nuwejaars Catchment (Right), and regions considered to be strategic water source areas for both surface water and groundwater (Left).

Groundwater discharge into streams within the uplands has already been highlighted as being important during both the wet and dry seasons. Groundwater discharging in backslope and footslope locations originates from recharge zones on upper parts of the catchment. Thus, these upper parts are also strategic groundwater recharge zones within the catchment (Figure 7.1).

Hydrochemical analysis revealed that the streamflows in uplands or strategic water source areas have very low electrical conductivity and are slightly acidic. However, electrical conductivity increases significantly from 13 milliSiemens/m in headwaters to 200 milliSiemens/m in lowlands. Therefore, the strategic water source areas do have significant influences on both the quantity and quality of water in midslopes and lowlands of the Nuwejaars Catchment. Catchment management has to reflect the linkages between the uplands and lowlands. Below is an outline of potential threats to these linkages

7.2 INVASIVE ALIEN PLANTS

Invasive alien plants have covered areas varying from 25% in the 1970s to the current 11% of the Nuwejaars Catchment. Most of affected parts occur in the uplands constituting strategic water source areas, and riparian zones throughout the catchment (Figure 7.2).

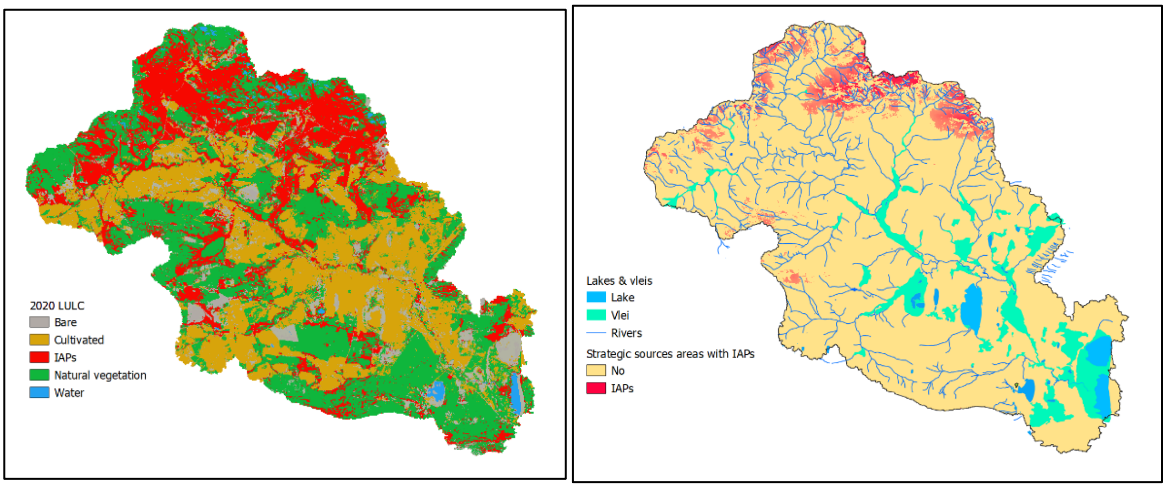


Figure 7.2: Areas affected by IAPs (Right), and strategic water source areas affected by IAPS (left).

Previous chapters have shown that IAPs in uplands and riparian zones consume twice as much water as those occurring on relatively dry locations. Water consumed by IAPs especially during the dry season has the potential to reduce groundwater discharge to streams and, therefore, reducing dry season flows. High densities of IAPs along and within channels of the Jan Swartskraal and Koue Rivers in the midslope region obstruct the flow of water. Water consumption by these IAPs also contribute towards these sections of the rivers frequently drying during years with below average rainfall. Thus the occurrence of riparian and in-channel IAPs affect the overall availability of water resources particularly the linkages between uplands and lowlands.

7.3 IMPOUNDMENT AND ABSTRACTION OF WATER

There are about 240 farm dams mostly located on the central part of the upper part of the Nuwejaars Catchment (Figure 7.3), with 70% of them being very small having diameters less than 30 m. Most of the farm dams have never been surveyed but, based on their surface areas estimated from Google Earth images, the total water storage could be 2 million m^3, equivalent to 10% of the catchment Mean Annual Runoff for quaternary catchments G50B and G50C.

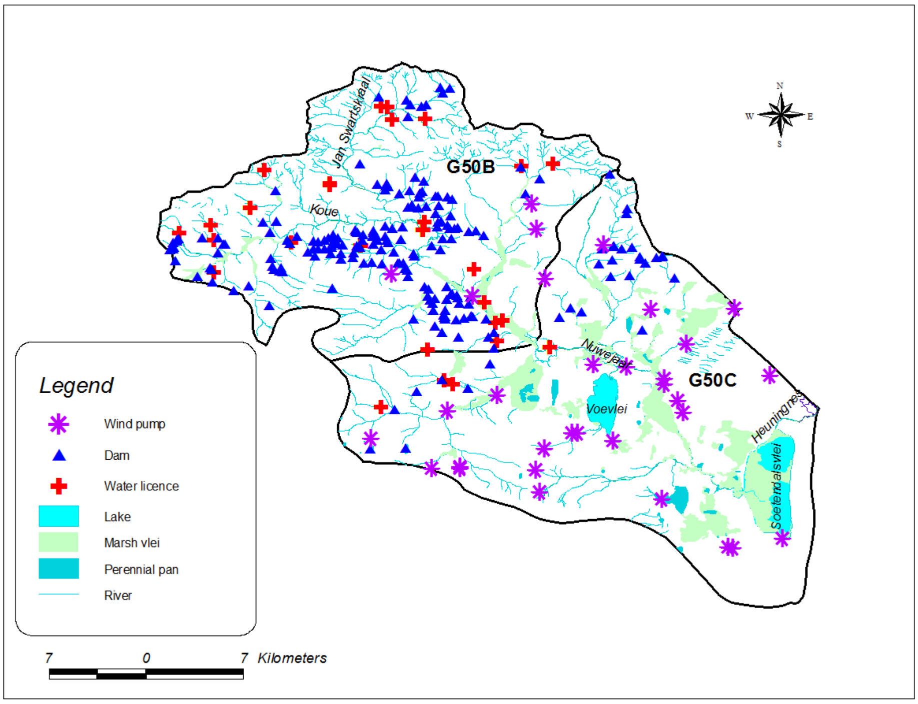


Figure 7.3: Farm dams and water licences within the Nuwejaars Catchment.

During years with above average rainfall these dams will fill and would have no significant effect on downstream availability of water. However, during years with below average rainfall, the farm dams may have a noticeable localized impact on downstream flows. .

The Nuwejaars Catchment has about 63 registered water use licences (Figure 7.3) with direct abstraction from the river accounting for 57% of the licences, springs 29%, and boreholes 10%. The total volume of water allocated is 4.7 Mm^3 of which 87% is for crop irrigation, 12% domestic uses and the remainder for livestock watering. The total volume of water allocated is about 20% of the mean annual runoff (MAR) at the outlet of the Nuwejaars Catchment. The abstraction of water for crop irrigation is not likely to have significant effects during the wet season because of low irrigation water requirements. During summer with both low flows and high evaporation rates resulting in relatively high crop water requirements, direct river abstraction for irrigation may have significant effects on those sections of the river where such demands are made on the river stretch.

7.4 WATER RESOURCES MANAGEMENT OBJECTIVES FOR THE NUWEJAARS CATCHMENT

The current water resources management objectives for the Nuwejaars Catchment are stated in the following:

- Water Resources Classes and Resources Quality Objectives for the Breede-Gouritz Water Management Area gazetted by the Minister of the Department of Water and Sanitation in 2020.
- The Breede-Gouritz Water Management Area Catchment Management Strategy gazetted in 2020 and which should be reviewed every 5 years (BGCMA, 2017).

The Nuwejaars Catchment was part of the studies done by the Department of Water and Sanitation on the Determination of Classes of Water Resources and Resources Quality Objectives (RQOs) for the Breede-Gouritz Water Management Area (DWS, 2017). The proposed classes and RQOs were gazetted in 2020 after invitations were extended to the public for comments in 2018. The site in the Nuwejaars Catchment used for these studies is on the Nuwejaars River at the R43 Bredasdorp-Elim Road Bridge, which is on the lower part of the catchment and at the end of the 12 km long and 0.8 km wide floodplain wetland.

Water resources for the Nuwejaars Catchment were gazetted as belonging to the Water Resources Class II which means that the resources are moderately utilized and require moderate protection. The Recommended Ecological Category is C/D implying that the aim is to have a catchment with ecosystems that are moderately to heavily impacted Table 7.1 provides the gazetted RQOs for the river.

Table 7.1: Resource Quality Objectives for the Nuwejaars River in lower part of the catchment.

Component	Resource Quality Objective (RQO)
Quantity of river flows	River flows should be adequate for maintaining an Ecological Category C/D. 13% (approximately 1.6 Mm^3/year) of the MAR is allocated to satisfy Total Ecological Water Requirements. Maintenance Low Flows 3.93% (0.490 Mm^3/year) of MAR, Drought Low Flows 1.68% (0.210 Mm^3/year) of MAR, and Maintenance High Flows 9.11% (1.136 Mm^3/year) of MAR.
Quality of river flows	Nutrient levels should ensure that the river continues to be in a mesotrophic state.
	Salt concentrations should be maintained at current levels (< 170 milliSiemens/metre).
	$6.5 \leq pH \leq 8.5$
Habitats	Geomorphology – maintain Category D. Significant morphological changes have occurred as a result of overgrazing, livestock tramping, farm dams and furrows.
	Riparian vegetation – maintain current Category E. Highly disturbed by livestock. Invasive alien plants should be cleared.
Biota	Fish – maintain Category E. Disturbed due to habitat loss and introduction of alien invasive fish species.
	Macro invertebrates – maintain current Category E. Impacted by loss of habitats and salinity.

The overall objective of the resource quality objectives for the river is to stabilise the current condition and avoid any further deterioration. It should, however, be highlighted that the achievement of the RQOs highly depends on what happens in the upper parts of the catchment. Table 7.2 provides the Groundwater RQOs gazetted for the Nuwejaars Catchment.

Table 7.2: Groundwater Resource Quality Objectives for the Nuwejaars Catchment

Component	Resource Quality Objective (RQO)
Quantity, discharge	Groundwater abstractions should allow water tables to recover during both wet and dry seasons. Groundwater use should be sustainable.
	The natural hydraulic gradient between surface water and groundwater should be maintained.

Component	Resource Quality Objective (RQO)
	There should not be any groundwater abstraction within 250 from a wetland, and Freshwater Ecosystem Priority Area. The Nuwejaars River including the floodplains have been classified as Wetland Freshwater Ecosystem Priority Areas (FEPAs).
	Groundwater discharge to rivers should ensure that the Maintenance Low Flow 3.93% (0.490 Mm^3/year) of MAR, for the river are sustained.
Quality (Xenozoic Coastal Deposits)	Nitrates (NO3) < 10 mg/l Electrical conductivity < 280 milliSiemens/metre
Quality (Bokkeveld Group)	Nitrates (NO3) < 3.6 mg/l Electrical conductivity < 74 milliSiemens/metre
Quality (Table Mountain Group)	Nitrates (NO3) < 3.8 mg/l Electrical conductivity < 117 milliSiemens/metre

Catchment management measures should aim to achieve at least the gazetted river and groundwater resource quality objectives. The possible approaches for achieving this considering surface water-groundwater interactions within the Nuwejaars Catchment are presented below.

7.5 CATCHMENT MANAGEMENT TO ACHIEVE RESOURCE QUALITY OBJECTIVES.

Previous chapters have demonstrated that the quantity and quality of water resources, including their spatiotemporal variations throughout the Nuwejaars Catchment, greatly depend on the connectivity between the uplands, midslopes and the lowlands. The uplands are strategic source areas for both surface water and groundwater resources. Human-induced changes of the status of strategic water source areas and movement of both surface water and groundwater downstream towards the midslopes and the lowlands will adversely affect the achievement of resource quality objectives with result being reduction in the fitness for purpose of the resources and effectively impacting the water security of the catchment. Catchment management measures should therefore be directed at managing the following threats within the Nuwejaars Catchment;

a) the spread of invasive alien plants,
b) uncontrolled abstractions of surface water and groundwater, and
c) changes in and/or expansion of land use land cover activities such as crop production and pastures.

7.5.1 Control of invasive alien plants

The expansion of areas infested with IAPs in strategic water sources areas, hillslopes, riparian zones, and within channels is a major threat to the achievement of resource quality objectives especially those related to quantity aspects. Current clearing of IAPs by the Working for Water Programme, the Nuwejaars Wetlands Special Management Area (NWSMA) forum, and other landowners should continue, and cover parts of the catchment hitherto not reached by these efforts and programmes. Planning of clearing operations should adopt an integrated catchment management approach (ICM) which recognises the linkages between all parts of the catchment. Thus, clearing should not only prioritise wetlands in lowlands, but include IAPs on top of the hills and hillslopes which are the strategic water source areas. Currently, there are some parts of the catchment such as the midslope sections of the Jan Swartskraal that are heavily infested with IAPs where there is reduction of the movement of flows generated in the uplands to the lowlands. A major challenge in planning and managing the clearing is the asymmetrical relationship between upstream and downstream landowners. Upstream landowners incur costs for clearing IAPs, and the downstream landowners derive the benefits from the clearing done in the upper catchment, e.g. increased water availability and ecological integrity, tourism. There is need for DWS, BGCMA, and landowners to explore options for incentivising upstream landowners, e.g. benefit sharing mechanisms. It is highly recommended that an integrated catchment management approach is adopted for clearing of IAPS.

7.5.2 Water abstractions

Current abstractions of both surface water and groundwater do not cause a threat to water resources and ecological integrity. However, any future significant changes in either impoundments and/or abstractions could have adverse effects particularly during the dry season, from November to April. Any impoundment with a carry-over storage located in the strategic water source areas will have adverse effects on recharge and flow quantity components. Abstractions of river water for irrigation in the lowlands especially during the dry season has the potential to affect the achievement of RQOs. An integrated water resources management (IWRM) approach which considers linkages between upstream and downstream relationships of water resources and ecosystems should be adopted when considering applications for water licences. This will contribute towards achieving the RQOs. Any groundwater abstractions close to riparian zones should be avoided in line with RQOs.

7.5.3 Balancing utilisation of green and blue water

Dryland crop production and pastures cover 23% of the catchment area and utilise about 19% of the rainfall in the form of green water. Any changes in the proportion of rainfall that becomes green water arising from expansion of cultivated crops will affect blue water. The achievement of a sustainable balance between green and blue water requires integrated land and water management. The 5 yearly review of the Breede-Gouritz Catchment Management Strategy should emphasise the incorporation of ICM to achieve this balance.

7.5.4 Management of riverine habitats

During the determination of the river RQOs, overgrazing and trampling of floodplains and riverbanks was identified as a threat towards ecological habitats. While management of livestock is a responsibility of the agricultural sector, this should be incorporated in the catchment management strategy for the attainment of river RQOs including the determination of natural carrying capacities of landscapes.

Previous studies within the Nuwejaars Catchment showed that wastewater from dairies had adverse effects on the quality of water resources. The achievement of the river RQOs requires maintaining nutrients and EC within specified safe levels. An ICM approach is required to manage dairies as their cumulative effects can be significant.

CHAPTER 8: CONCLUSIONS & RECOMMENDATIONS

8.1 CONCLUSIONS

The study integrated several methods to investigate the occurrence and nature of SW-GW interactions within the Nuwejaars Catchment. These methods combined data on river flows, water tables, hydrochemical characteristics, stable isotopes and radon for both surface water and groundwater. The different methods complimented each other and increase confidence in inferences made about SW-GW interactions. The analysis of different data sets enabled the identification of parts of the catchment or river stretches where SW-GW interactions were very significant or of minor importance.

All the streams in the following upland areas were gaining from groundwater; Tiersfontein, Tussenberge, Spanjaardskloof, and Boskloof. SW-GW interactions occurred through spring discharge into most of the streams, diffuse seepage into river channels, and diffuse seepage of groundwater onto the surface especially towards the lower end of slopes. Diffuse groundwater seepage onto the surface occurred when the water table rose to the surface during the wet season. When rain falls on such areas that are already saturated, a high proportion of this rainfall will form surface runoff.

The middle stretches of the Koue and Jan Swartskraal Rivers do not receive groundwater and often dry during the year. The water table was found to be below the river bed at the site in the riparian zone of Jan Swartskraal River with one of the shallow boreholes drying up. The middle stretches of these two rivers have very dense invasions of woody invasive plants which partly contribute to lowering of the water table through transpiration.

SW-GW interactions are spatially and temporally variable within the lowlands. At the Moddervlei site, the potential exists for groundwater discharge into the river during the wet season. However, during the dry season, the water table is below the river bed on the right bank, but above on the left bank. Thus, groundwater discharge into the river may occur one the left bank, while this may be limited on the right bank. The existence of clay and very low gradient may limit any significant SW-GW interactions along some river stretches. Radon data however showed some groundwater contributions to river flows.

SW-GW interactions within the Nuwejaars Catchment have influenced aquatic ecosystems. Four fish species exist in upland streams that are groundwater fed and perennial. Stretches of the river within lowlands had no fish species. Upland streams had also higher species diversity than the lowland parts.

Groundwater discharges to rivers in the uplands are important for domestic and agricultural water supply. Three farm dams at Tussenberge have all year round water used for irrigating protea flowers and pastures. These dams benefit from spring discharges and diffuse groundwater seepage into their streams. The Elim settlement depends entirely on spring discharge for domestic and dairying water supply.

8.2 RECOMMENDATIONS

Spring discharge into rivers has been found to be an important form of SW-GW interactions in the catchment. The springs in the catchment contribute significantly to the availability of water resources particularly in the upland areas. There is however no information about the rates of discharges by springs. In addition, there is no information regarding factors accounting for the occurrences of springs at specific locations. The recharge areas of the springs are not clearly known.

A study aimed at improving information about the contribution of springs in different settings to water resources within the Nuwejaars Catchment is much needed. Anecdotal information from land owners suggests that invasive alien plants reduce spring discharges. All the factors affecting the availability of water from springs need to be understood. Most studies on springs have focused on dolomitic regions, and very little is known outside these regions. The existing research infrastructure in the Nuwejaars Catchment will assist in a study on springs.

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APPENDIX 1: Boreholes for Groundwater Monitoring (as per Chapter 2.2)

Borehole ID	Site Name	Latitude (°S)	Longitude (°E)	Elevation (m)	Borehole Depth (mbgl)	Screen Length
BH4	Moddervlei	-34.60535	19.79761	21.46	50	11.2
BH5		-34.60535	19.79758	21.69	20	11.2
BH6		-34.60561	19.79758	21.11	50	8.4
BH7		-34.60561	19.79753	21.11	20	11.2
BH8		-34.60531	19.79741	21.56	8	5.6
BH9	Spanjaardskloof	-34.52958	19.75255	145.55	60	11.2
BH10		-34.52961	19.75252	145.41	20	11.2
BH11	Boskloof	-34.53489	19.82909	128.9	60	14
BH12		-34.53485	19.8291	128.95	20	11.2
BH13	Uitsig	-34.58694	19.66944	152.45	55	16.8
BH14		-34.58694	19.66944	152.24	20	11.2
BH15	Tussenberge	-34.477446	19.74491	202.03	50	
BH16		-34.477418	19.744954	209.01	12	
BH17		-34.47683	19.74601	202.42	30	
BH18	Spanjaardskloof	-34.477418	19.744954	179.1	50	
BH19		-34.52628	19.75374	179.6	20	6
BH20	Boskloof	-34.534917	19.828389	123.29	100	
BH21		-34.534661	19.826799	112.63	60	
BH22		-34.534655	19.826733	112.12	20	
BH23		-34.53467	19.720556	111.73	6	
BH24	Moddervlei	-34.60375	19.799861	22.86	60	10
BH25		-34.603705	19.799722	22.78	7	3
BH26	JanSwartskraal	-34.533078	19.720556	67.73	50	
BH27		-34.53302	19.72043	67.73	7	3
BH28	Sandfontein	-34.488722	19.695	228.03	50	
BH29		-34.488722	19.694972	228.35	11	