FINDING "NEW" WATER TO ADDRESS CONFLICTING AND COMPETING WATER DEMANDS IN THE NUWEJAARS CATCHMENT, CAPE AGULHAS

Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

E.1 Motivation

The Heuningnes Catchment, which is 1 401 km^2, is located in Cape Agulhas. It is managed by the Breede-Gouritz Catchment Management Agency (BGCMA). This catchment is not covered by the networks of river flow and groundwater monitoring stations of the South African Department of Water and Sanitation. Consequently, there are uncertainties regarding the potential and limitations of the available water resources. The goal of the National Water Resources Strategy that "Water is efficiently and effectively managed for equitable and sustainable growth and development" (DWA, 2013), cannot be achieved in the absence of information about the available water, and the extent of its utilisation in this catchment. The Heuningnes Catchment is made up of areas drained by the Kars River and the Nuwejaars River on the eastern and western parts respectively. The rapid spreading of invasive alien plants on hillslopes, and in riparian zones in the lowlands, is a major threat to water resources and habitats in the Nuwejaars River Catchment.

The lowest 25 km stretch of the Nuwejaars River has floodplain wetlands that reach a maximum width of about 0.8 km, and, together with the numerous pans and lakes, provide a wealth of habitats resulting in this area having high biodiversity. The Nuwejaars River flows into the Soetendalsvlei, which is the largest freshwater lake in South Africa that drains into the Indian Ocean. It drains through the Heuningnes Estuary, a Ramsar site. Several tourist activities, such as bird watching, depend upon the rich biodiversity supported by the Nuwejaars River. A Nuwejaars Wetlands Special Management Area (NWSMA) was formed by 26 landowners and the Elim community with the objective of protecting water and biodiversity, and implementing sustainable farming practices. These landowners registered the Nuwejaars River Nature Reserve under Section 21 of the South African Companies Act to advance the goals of the NWSMA.

The Nuwejaars River Catchment is increasingly becoming important for vineyards for wine production, and tourism. Some vineyard owners wish to be allocated water from the Nuwejaars River to increase production of wine and table grapes. Owners of farms located on the headwaters consider the non-allocation of water on the basis that all the river flow generated on their lands is required for downstream biodiversity conservation within the floodplain wetlands as irrational. They are of the view that most of the water flowing downstream is supporting invasive alien plants, and not the maintenance of biodiversity in floodplain wetlands. Landowners who are actively clearing invasive alien plants on their properties share the view that "new" water could be made available if all landowners cleared these plants.

With the above conflicting (e.g. increasing grape production through irrigation versus conservation of wetlands) and competing demands for water (e.g. invasive alien plants versus irrigation of crops), the BGCMA requires reliable information about water resources so that they can put in place measures that will contribute towards achieving the goals of the National Water Resources Strategy. In addition, there is an increasing number of emerging farmers who wish to be considered for water allocation. When such a demand is not realised, these farmers may perceive that previous inequitable allocation of water is being perpetuated. Such a demand could be addressed by identifying new water sources. The identification of such new water sources requires information about the availability and limitations of both the quantity and quality of water resources in the Heuningnes Catchment. The Institute for Water Studies at the University of the Western Cape and the BGCMA agreed to collaborate in improving information about water resources in the Heuningnes Catchment so as to contribute towards sustainable water resources management.

E.2 Aims

The following aims were set for this project:

1. To determine the contribution of sub-catchments of the Heuningnes River to inflows into the Soetendalsvlei.
2. To establish the effects of land use and water use on the quantity and quality of inflows into the Soetendalsvlei.
3. To establish the extent to which floodplain wetlands occurring along stretches of the Nuwejaars River affect river flows.
4. To determine how river inflows and the interactions between surface water and groundwater affect the water balance of Soetendalsvlei, and outflows into the Heuningnes Estuary.

E.3 Methodology

E.3.1 Study area

The study area is the Nuwejaars Catchment, comprising quaternary catchments G50B and G50C, with a total area of 760 km^2. The Nuwejaars Catchment has headwaters in the Koue and Bredasdorp Mountains with altitudes ranging from 400 to 650 m above sea level. Altitude decreases rapidly within the first 5 km, along tributaries, to about 80–100 m. The rest of the catchment is made up of lowlands that are 5–60 m above sea level, and with several lakes and pans. The major tributaries are the Koue, Jan Swartskraal, Pietersielieskloof, Bloomkraal, and Voëlvlei rivers.

The dominant land cover type is fynbos, on 41% of the area. Crop cultivation occurs on 39% of the area, with the major crops being barley, wheat and canola, on 6 570 hectares. Table and wine grapes, and olives, are produced under irrigation on 228 hectares. Most of the land is privately owned by farmers involved in both livestock (cattle, sheep) and crop production. The major settlement is the historical Moravian Mission, Elim, established in 1824. Elim had a population of 1 412 at the time of the 2011 Census.

E.3.2 Establishment of a hydrological monitoring system

This study established a catchment monitoring system comprising the following:

- 5 weather stations
- 13 river water level measuring stations
- 2 lake level measuring stations
- 14 monitoring boreholes

- 26 piezometers
- 2 sap flow monitoring systems.

The study installed the heat pulse velocity system for transpiration monitoring of the invasive alien *Acacia longifolia* (long-leaved wattle) at a site in a riparian zone and at another site on a hillslope. Based on the total area in the Nuwejaars Catchment affected by invasive alien plants and the measured transpiration rates, the volume of water used by these plants was determined.

Secondary data on areas under different crops on each farm, and on the livestock population, were obtained from the Department of Agriculture of the Western Cape Province, and used to estimate water use for dryland and irrigated crop production, and livestock watering.

E.4 Results

E.4.1 Contribution of sub-catchments to the flow of the Nuwejaars River

The project collected weather data, on a continuous basis from December 2014–March 2015, from the five weather stations that were established. During the wet season, June–September, rainfall occurred on 10–15 days per month; during the dry season, January–February, the number of rainy days was 5–7 days per month. The year 2015 received about 130% of the long-term rainfall. Rainfall increases from the near coastal south-east to the mountainous northern parts. The upper part of the Nuwejaars Catchment received about 20% more rainfall than the lower part. In 2015, the uplands received about 630 mm, while the south-eastern lowlands got 558 mm/yr. The 2017 drought has been more severe in the southern part of the Nuwejaars Catchment which received about 50% of the 2015 rainfall.

The rainfall received in 2016 was close to the long-term average of the catchment. The estimated 2016 annual runoff for the Nuwejaars Catchment is 15.66 Mm^3, which is close to 18.78 Mm^3/yr, the long-term mean annual runoff estimated during the WR2012 water resources assessment of South Africa (http://waterresourceswr2012.co.za/resource-centre/). Quaternary catchment G50B contributed 70% of the flow of the whole Nuwejaars Catchment. The individual sub-catchments contribute 16 to 28% of the catchment runoff, depending on size, location and gradient. Groundwater in the upper catchment is well connected to the surface water systems with shallow interflow from the hilly areas providing base flows. Springs from the upper catchment provide water derived from deep groundwater flow systems, and maintain constant base flows throughout the year on the Koue, Jan Swartskraal, and Pietersielieskloof rivers. The spring at Spanjaardskloof and the other at Elim support year-round water supply for domestic use and maintain dry season flows of rivers they drain into. However, these rivers dry up along the transition from the headwaters to the lowlands, due to dense invasive alien plants occurring along them.

The lower part of the Nuwejaars Catchment, comprising most of Quaternary Catchment G50C, has a poorly developed drainage network, due to the low gradient and numerous vleis and water bodies of varying sizes. Groundwater is not well connected to surface water, due to the low yielding formations and low gradients limiting the exchange of water. Most of the groundwater contributions are expected to be localised to regional fault systems.

E.4.2 Effects of land use and water use on the quantity and quality of water

The major concern in the catchment is the spreading of invasive alien plants, mainly Acacia species, along riparian zones and on hillslopes. These plants cover 261 km^2 or 34% of the catchment area. We investigated water use rates of *Acacia longifolia* on a hillslope site and in a riparian zone. The total transpiration rate of the selected trees, during the study period from June 2016 to June 2017, was 241 mm on the hillslope compared to 596 mm at the riparian site. These results show, as expected, that the riparian trees used more water than the hillslope trees. The prevailing drought situation led to substantial drying of the soil at the riparian site and transpiration rates declined as the soil water content decreased. Unstressed transpiration rates were estimated to be 596 mm for the hillslope and 1348 mm in the riparian zone. Based on the national invasive plant survey by Kotzé *et al.* (2010), the area in the whole of the Nuwejaars Catchment invaded by invasive alien plants is equivalent to 7 930 hectares at 100% density of these plants. If other invasive alien plants in the Nuwejaars River, which are mainly Acacia species, have similar transpiration rates to those obtained in this study, then the invasive plants in the Nuwejaars Catchment were using 20.5 Mm^3/yr. Unstressed transpiration rates show that the amount of water used by these trees could be as high as 49 Mm^3/yr depending on prevailing soil water content.

Dryland crop production of barley, canola, and wheat on 6 570 hectares was estimated to use 18.9 Mm^3/yr. Seasonal pastures on 10 033 hectares use about 40.5 Mm^3/yr. Green water use for rainfed crop and pasture production is, therefore, the dominant water use in the catchment.

The underlying geology and floodplain wetlands have the most influence on water quality. River flows in the upland area are mostly acidic, due to the quarzitic Table Mountain Group (TMG). After passing through the floodplain wetland along the Nuwejaars River, the water becomes slightly alkaline, due to photosynthetic influence and changes in geology to shale and greywacke. Total dissolved solids increase as the water flows from the upper TMG, downstream through this floodplain wetlands and the Soetendalsvlei, correlating with changes in geology and groundwater inflows. A reduction in dissolved oxygen occurs as the water passes the floodplain wetland, suggesting subsurface flow conditions in reducing wetland conditions where peat material breaks down. Nutrient concentrations increased immediately downstream of the dairy located close to the Nuwejaars River at Weisdrif. Nutrient concentration decreased as the water passed through Soetendalsvlei which suggests that phragmites covering almost half of the western part of this lake are taking up these nutrients.

E.4.3 Influence of floodplain wetlands on river flow

The study has shown that, following a major rainfall event at the beginning of the wet season in 2016 when most of the channels along the Nuwejaars River and floodplain wetland had low water levels, a substantial amount of water, up to about 5.8 Mm^3, was stored in the channels and pools occurring along the 12 km long stretch downstream of Elim, referred to as Moddervlei. Consequently, peak flows from 20–35 m^3/s were reduced to 5 m^3/s when exiting this wetland. Peak flows took about 26 hours to travel this stretch of the river. At the end of the wet season, drainage of water stored in this wetland sustained downstream flows from October to December 2016 after which the river dried up. Thus, the main effect of the floodplain wetland was to reduce flood flows and sustain dry season flows.

E.4.4 Water balance of the Soetendalsvlei

A bathymetric survey of the Soetendalsvlei established that this lake has a maximum depth of 2.3 m, with a surface area of 15.5 km^2, and storage capacity of 20 million cubic metres. Using the results of the bathymetric survey, Nuwejaars River inflows measured at Elandsdrift, and weather data, a linear reservoir model was able to represent the change in water storage on a daily basis. The estimated flow of the Nuwejaars River into Soetendalsvlei was 43.885 Mm^3 and 15.662 Mm^3 in 2015 and 2016, respectively. River inflows contributed 80 to 88% of the volume of water, with the remainder coming from rainfall over the lake. In order for the lake to discharge flows into the downstream Heuningnes River, a minimum storage of 11.258 million cubic metres should have been attained. In a year with high lake levels, such as in 2015, surface outflows constituted 66% of the losses, while the remainder was in the form of evaporation. However, in 2016, when there were low water levels, loss of water by evaporation comprised 78% of the losses, with the remainder being surface outflows. An analysis of 1989–2016 Landsat images revealed that the Soetendalsvlei lake levels were below the threshold for discharging flows into the downstream Heuningnes River for some varying periods during 72% of these years. Cessation of downstream discharges from the Soetendalsvlei affects the level of salinity in this river, and movement of fish between this lake and the estuary.

No significant influence of groundwater on lake water storage is expected because of limited gradient in the immediate vicinity of the lake. Similarly, discharge from deep ground water systems is unlikely, due to the limited hydraulic gradients.

E.4.5 Water use

The Water Authorisation and Registration Management System (WARMS) database showed that in 2014, there were 61 water users who had registered their water storage and abstraction in the Nuwejaars Catchment. The total volume of water registered was 4.7 Mm^3, with most of the registrations being for abstracting river and spring water for agricultural purposes. The majority of registrations are on the upper part of the catchment in Quaternary Catchment G50B. There are 239 farm dams, again mostly in G50B. Based on the surface areas of these farm dams, the total volume of water which can be stored is about 2.1 Mm^3. Most of the farm dams are excavations on sloping ground, and without a conventional dam wall.

Rain-fed crop production and pastures cover 17 291 hectares and are using about 18.9 Mm^3/yr of rain water. Wine grapes, table grapes, olives and protea are being grown under irrigation on 440 hectares with an estimated crop water requirement of 3.4 Mm^3/yr. Most of this irrigation is from springs and groundwater abstraction associated with TMG Group Quartzite ridges.

Water for domestic water supply is mainly from springs. For example, Elim, with a population of 1 412 people, depends on a spring and a borehole. The total volume of water used by Elim was estimated to be 0.028 million m^3/yr. The Spanjaardskloof community (150 persons) is supplied with water from a spring by the Cape Agulhas Municipality, and the annual water consumption for this community is 7 300 m^3/yr. The estimated human population on farms is about 1000 persons. The combined use of water for domestic use and livestock watering is 0.3 Mm^3/yr.

E.4.6 Water balance and implications for "new" water

The average annual water balance of the Nuwejaars Catchment has been derived using the mean annual rainfall and mean annual runoff in the WR2012, and the estimated water use for dryland crop production, pastures, irrigation, invasive alien plants, and storage in farm dams. These estimates are summarised below.

Water Balance Component	Input (Mm^3/yr)	Output (Mm^3/yr)	Output as % of Rainfall
Rainfall	319.3		
Mean annual runoff		18.8	5.9
Groundwater recharge		4.2	1.3
Dryland cultivation		18.9	5.9
Pastures		40.5	12.7
Irrigated crops		3.4	1.1
Invasive alien plants		20.5	6.4
Farm dams		2.**1**	0.7
Domestic use and livestock watering		0.3	0.1
Total	319.3	108.7	34.0
Actual evapotranspiration (shrublands, etc.)		210.1	66.0

The current water use is dominated by green water for rainfed crop and pasture production. New water or additional water is not likely to become available by adjusting green water use for agriculture. New water is likely to be made available by clearing invasive alien trees. If we assume that all the invasive alien trees transpire at rates similar to those measured in this study, then these trees were using 20.5 Mm^3/yr from June 2016 to June 2017 which was a relatively dry period. When unstressed transpiration rates are assumed, the water use by these trees can be as high as 49 Mm^3/yr. Unstressed water use refers to potential transpiration rates had water supply to the trees not been limited by the drought which occurred during the study period. The riparian areas of most rivers, including the floodplains in the Nuwejaars Catchment, would have had grasses as the natural vegetation. The actual measured and unstressed transpiration rates are, respectively, 18% and 168% greater than the water use rates for perennial grasslands. The alien trees also block river channels. This study did not monitor water use by the fynbos vegetation occurring on hillslopes. Assuming that the water use rates of fynbos on non-riparian areas will be similar to seasonal pastures (442 mm/yr), the unstressed water use rate is 36%, or 11.6 Mm^3/yr, greater than that of fynbos. In an average year without severe water stress, the incremental water use or new water that can be salvaged by clearing invasive alien trees from riparian and non-riparian areas will be about 15 Mm^3/yr. Thus, clearing of invasive alien trees presents an opportunity to make "new" water available, and at the same time contribute towards enhancing the biodiversity of this catchment.

The groundwater assessment has tentatively identified faults occurring in the Nuwejaars Catchment as being important for regional groundwater flow. There is a potential that these faults, especially in the lower part of the catchment, are an important source of additional groundwater which could complement existing water sources. Further investigations to verify this preliminary observation need to be undertaken.

E.5 Capacity building and knowledge dissemination

Funding from the Water Research Commission (WRC) and other sources enabled the establishment of the catchment monitoring system used as a living laboratory. The WRC project directly supported four MSc students and one PhD student. An additional 33 honours and MSc students benefited from the research infrastructure developed.

Six conference and two peer-reviewed papers have been presented, highlighting findings from studies in the Heuningnes Catchment. A research open day was held during which research findings were presented to the local community and other stakeholders.

E.6 Recommendations

The study has established a living laboratory for studies on various aspects of water resources. Maintenance of the monitoring system developed is critical for continued beneficial use of this living laboratory. The following recommendations are made to maximise the use of the infrastructure already developed and improve decision making in the catchment:

i. It was not possible to measure the full range of magnitude of river flows during the study period. Continued river flow measurement is necessary to improve rating curves for the gauging stations established.
ii. Water table depths collected monthly did not allow an understanding of surface water–groundwater interactions in the floodplain wetland of the Nuwejaars River, and around the Soetendalsvlei and Voëlvlei. In 2017, new monitoring boreholes were developed and equipped with continuous water level recorders. Further studies need to be undertaken to address the following objectives:
    a. To establish the nature of surface water–groundwater interactions from headwaters to lowlands.
    b. 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.
    c. To examine how surface water–groundwater interactions influence ecosystems from headwaters to lowlands.
iii. The spread of invasive alien plants is a major concern. This study measured sap flow rates on a hillslope and riparian site of *Acacia longifolia*. Further studies to evaluate if other invasive alien tree species have similar water use rates need to be undertaken. Such a study will improve estimation of catchment-scale benefits of clearing these plants, and which locations should be prioritised in order to maximise the benefits.

E.7 Achievement of project objectives

The study has largely achieved all the project objectives. Low rainfall in 2016 and 2017 reduced the number of flow events that could be examined to improve assessment of the spatio-temporal variability of both the quantity and quality of river flows in the study catchment. The following was achieved:

i. A functional hydrological monitoring system providing continuous data on weather elements, rainfall, river flows, and groundwater is in place and operational.
ii. The contribution of the Nuwejaars River to inflows into the Soetendalsvlei was determined for 2015, 2016 and up to 2017.
iii. The effects of the major land use, crop and livestock production, on water resources have been determined.
iv. Transpiration rates of one of the dominant invasive alien trees have been estimated for both riparian and non-riparian areas.
v. Preliminary effects of floodplain wetlands on river flows were determined. Low rainfall in 2016 and 2017 limited the number of flow events that were analysed.
vi. The influences of rainfall, evaporation and surface inflows and outflows on water storage in the Soetendalsvlei were determined from 2015 to 2017. The effects of groundwater on water storage in this lake are likely to be minor. However, the study was not able to accurately determine groundwater influence on water storage in this lake.

E.8 Data archiving

The Institute for Water Studies at the University of the Western Cape has established a data archiving system. All the data collected by the research team, including the students, are archived on a) Google Drive, and b) a server of the institute. Data that are specific to research projects of individual students will be available to other users when the respective students have completed their studies. An agreement has been reached with the South African Environment Observation Network (SAEON) that data collected in this and other projects are also archived on their system.

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Mr Jannie van Staden, Breede-Gouritz Catchment Management Agency

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- National Research Foundation (NRF) Alliance for Collaboration in Climate & Earth Systems Science (ACCESS) Programme (Student support and mobility)
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- Netherlands Initiative for Capacity Development in Higher Education (NICHE) of the Netherlands Organisation for International Cooperation in Higher Education (NUFFIC)

The study presented in this report is an outcome of the partnership between the BGCMA and the Institute for Water Studies at the University of the Western Cape. BGCMA identified the Heuningnes Catchment as a priority for water resource research, hence the study reported in this report. The following colleagues supervised research by students working in the Heuningnes Catchment:

- Dr Michael Grenfell: fluvial geomorphology, land cover mapping, processing of bathymetric survey data
- Dr Suzanne Grenfell: remote sensing and wetlands ecology
- Dr Thokozani Kanyerere: groundwater
- Dr Jaco Nel: groundwater
- Dr Evison Kapangaziwiri (CSIR): hydrological modelling
- Dr Sebinasi Dzikiti (CSIR): plant water use
- Prof Nebo Jovanovic (CSIR): estimation of actual evapotranspiration from satellite data
- Prof Jenny Day: water chemistry
- Prof Chris Mannaerts (ITC, University of Twente, The Netherlands): estuary studies and bathymetric survey
- Prof Maciek Lubczynski (ITC, University of Twente, The Netherlands): integrated modelling

A considerable part of the work presented in this report forms part of on-going or recently completed MSc and PhD studies by the following students:

Eugene Maswanganye	Validation of satellite-derived rainfall estimates
Damian Hans	River flow measurement and effects of floodplain wetlands on river flow
Daniel Mehl	River flow measurement and effects of floodplain wetlands on river flow
Kinsley Manyama	Groundwater
Tamsyn Booysen	Water quality
Mandy Carolissen	Water balance of the Soetendalsvlei
Yonela Mkunyana	Water use by invasive alien trees
Seymour Siwa	Water use for crop production, livestock watering and domestic supply

We are extremely grateful to members of the Nuwejaars Wetlands Special Management Area, and other landowners within the Heuningnes Catchment, for granting us permission to install our monitoring equipment on their properties. The Chairperson of the Nuwejaars Wetlands Special Management Area, Mr Dirk Human, and their officers, Eugene Hahndiek and Erica Carla Brink, assisted in so many ways during our studies.

Our late friend and colleague, Lewis Jonker, was very instrumental in the formulation of this study, and getting the support of various stakeholders. We greatly miss, and continue to be inspired by, his enthusiasm and passion for UWC to establish a living laboratory in the Heuningnes Catchment.

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ABBREVIATIONS

BGCMA	Breede-Gourtiz Catchment Management Agency
BH	Borehole
CHIRPS	Climate Hazards Group Infrared Precipitation with Stations
CSI	Critical Success Index
DO	Dissolved oxygen
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
ETo	Reference Evapotranspiration
FAR	False Alarm Ratio
Mm^3	Million Cubic Metres
HPV	Heat Pulse Velocity
MAR	Mean Annual Runoff
MNDWI	Modified Normalised Difference Water Index
MODIS	Moderate Resolution Imaging Spectroradiometer
NRNR	Nuwejaars River Nature Reserve
NWSMA	Nuwejaars Wetlands Special Management Area
POD	Possibility of Detection
POFD	Possibility of False Detection
SAPWAT	South African Procedure for Estimating Irrigation Water Requirements
TAMSAT	Tropical Applications of Meteorology using SATellite

TDS	Total Dissolved Solids
TMG	Table Mountain Group
UWC	University of the Western Cape
WARMS	Water Authorisation and Registration Management System
WR2012	Water Resources of South Africa, 2012 study
yr	year

1 INTRODUCTION

1.1 Motivation

The Heuningnes Catchment, which is 1 401 km^2, is located in Cape Agulhas. The catchment is managed by the Breede-Gouritz Catchment Management Agency (BGCMA). The catchment is not covered by the Department of Water and Sanitation's networks of river flow and groundwater monitoring stations. There have not been any routine flow measurements in this catchment, except on the Kars River during the 1953–1960 period. Consequently, there are uncertainties regarding the potential and limitations of the available water resources. The goal of the National Water Resources Strategy that "Water is efficiently and effectively managed for equitable and sustainable growth and development" (DWA, 2013), cannot be achieved in the Heuningnes Catchment due to the absence of information about the available water, and the extent of utilisation of this resource. BGCMA is therefore constrained in developing and implementing sustainable water resources management practices.

The middle and lower parts of the Nuwejaars River have floodplain wetlands that reach a maximum width of about 0.8 km. These wetlands, together with the numerous pans and lakes, provide a range of habitats, resulting in this area having high biodiversity. The Nuwejaars River flows into the Soetendalsvlei, which is the largest freshwater lake in South Africa that drains into the Indian Ocean. It drains through the Heuningnes Estuary, a Ramsar site. Ecosystems occurring within the Soetendalsvlei and this estuary depend on maintaining the natural spatio-temporal variability of the flow of the Nuwejaars River. In addition, several tourist activities such as bird watching depend upon the rich biodiversity supported by the flow of this river. Realising the importance of the biodiversity of the Nuwejaars River wetlands to livelihoods in this region, 26 landowners and the Elim community formed a Nuwejaars Wetlands Special Management Area (NWSMA), with the objective of protecting water and biodiversity, and implementing sustainable farming practices. These landowners registered the Nuwejaars River Nature Reserve under Section 21 of the South African Companies Act to advance the goals of the NWSMA. The achievement of the objective of the NWSMA requires accurate information about the spatio-temporal variabilities of surface water and groundwater in this catchment.

There are several threats to biodiversity supported by the Nuwejaars River. The rapid spreading of invasive alien woody plants on hillslopes and riparian zones is a major threat to water resources and habitats in the Nuwejaars River catchment. Residents report that river channels are blocked, and river flows have, over time, been depleted by the growth of these invasive alien plants. Some of the landowners are involved in clearing invasive alien plants. However, due to the absence of river flow monitoring, the incremental benefits of these clearing operations are not known. Furthermore, there is inadequate information about which locations within the Nuwejaars Catchment should be prioritised for clearing. Such prioritisation should ideally take into account the benefits, in terms of water resources and biodiversity, to be realised from the clearing.

Clearing, by upstream landowners, of invasive alien plants that are growing in the headwaters, creates an asymmetrical relationship with downstream landowners in terms of benefits arising from reduction of water uptake by these plants and the resultant increase of downstream flows. Upstream landowners bear a cost that benefits downstream landowners. If there are no opportunities for the upstream landowners to benefit from the “saved” water, such as through additional water allocation, then some of them may perceive that they are incurring a cost without any benefit. Since the downstream stretches of the rivers are heavily invaded by alien plants, the non-allocation of part of the “saved” water is considered to be irrational as some of the water flowing downstream is supporting invasive alien plants. A considerable proportion of the landowners are of the view that, if an effective programme for clearing invasive alien plants is implemented, there will be opportunities to consider allocating some of the “saved” or “new” water to existing or new water users. The determination of such potential benefits requires information about rates of water use by invasive alien plants on hillslopes and riparian zones, and prevailing river flows. This information is lacking in the Nuwejaars Catchment.

The catchment of the Nuwejaars River is increasingly becoming important for wine production, and tourism. The increase in the area under vineyards is considered to have potential to boost agricultural production and tourism in this region. However, an increase in the area under vineyards will require an increased use of surface water and groundwater, which has the potential to adversely affect ecosystems and related livelihoods along the Nuwejaars River. Since there is inadequate information about available water resources, the BGCMA is not in a position to accurately assess the feasibility of providing additional water for irrigation.

The floodplains of the Nuwejaars River support livestock and dairy activities. There is a major concern that dairy activities located in the floodplain contribute to water contamination, and therefore adversely affect biodiversity along this river. There is, however, inadequate information about whether these activities do significantly affect water quality.

With all the above conflicting (e.g. increasing grape production through irrigation vs conservation of wetlands) and competing demands for water (e.g. invasive alien plants vs irrigation of crops), the BGCMA requires reliable information about the spatio-temporal variability of water resources so that they can put in place measures that will contribute towards achieving the goals of the National Water Resources Strategy. In addition, there is an increasing number of emerging farmers who wish to be considered for water allocation. When such a demand is not realised, these farmers may perceive that the previous inequitable allocation of water practised during the apartheid era is still being perpetuated. Such a demand could be addressed by identifying new water sources. The identification of such new water sources requires information about the availability and limitations of both the quantity and quality of water resources in the Heuningnes Catchment. The Institute for Water Studies at the University of the Western Cape and BGCMA agreed to collaborate in improving information about water resources in the Heuningnes Catchment.

1.2 Aims

a) To determine the contributions of sub-catchments of the Nuwejaars River to inflows into the Soetendalsvlei.

b) To establish effects of land use and water use on quantity and quality of inflows into the Soetendalsvlei.
c) To establish the extent to which floodplain wetlands occurring along stretches of the Nuwejaars River affect river flows.
d) To determine how river inflows and the interactions between surface water and groundwater affect the water balance of Soetendalsvlei, and outflows into the Heuningnes Estuary.

1.3 Outline of the report

Chapter 2 presents a description of the study area, and an outline of the methodology used in the study. Detailed descriptions of methods used for the various aspects of the study are given in the relevant chapter dealing with the relevant hydrological variables.

Chapter 3 describes the establishment of a weather monitoring system for collecting data that contributes towards achieving all the aims of the study.

Chapter 4 presents the assessment of groundwater which is required to achieve all the research aims.

Chapter 5 describes the development of a river flow monitoring system for providing information required for the achievement of all the research aims. The chapter also examines the contribution of sub-catchments to river flows and the effects of floodplain wetlands on these flows, which are the first and third aims of the study.

Chapter 6 on water quality assessment contributes to the achievement of the second aim of the study.

Chapter 7 covers the last aim of the study dealing with the water balance of the Soetendalsvlei.

Chapter 8 investigates water use by invasive alien trees and their impact on water resources. This chapter contributes to the achievement of the second aim of the study dealing with effects of land uses on water resources.

Chapter 9 examines water uses in the catchment and how they impact on water resources. This chapter contributes towards achieving the second aim of the study.

2 STUDY AREA AND APPROACH TO THE STUDY

2.1 Location and topography

The study area is the 760 km^2 catchment of the Nuwejaars River, which is a tributary of the Heuningnes River. This catchment is located on the southern-most part of South Africa and falls within the Breede-Gouritz water management area. The catchment of the Nuwejaars River covers quaternary catchments G50B and G50C (Figure 2.1). The study area falls within the Cape Agulhas Municipality which is part of the Overberg Region. The Koue Mountains, with elevation ranging from 400–526 m above sea level, form the north-western watershed. The northern part of the watershed is made up of the Bredasdorp Mountains (altitude 450–655 mm). The Koue and Bredasdorp Mountains are underlain by sandstone, and thereafter, the rivers pass through an area with sheared shale and fine-grained greywacke. The middle to lower part of the catchment has shale and sandy shale. The lowest part of the catchment up to the coast has calcified dune sand.

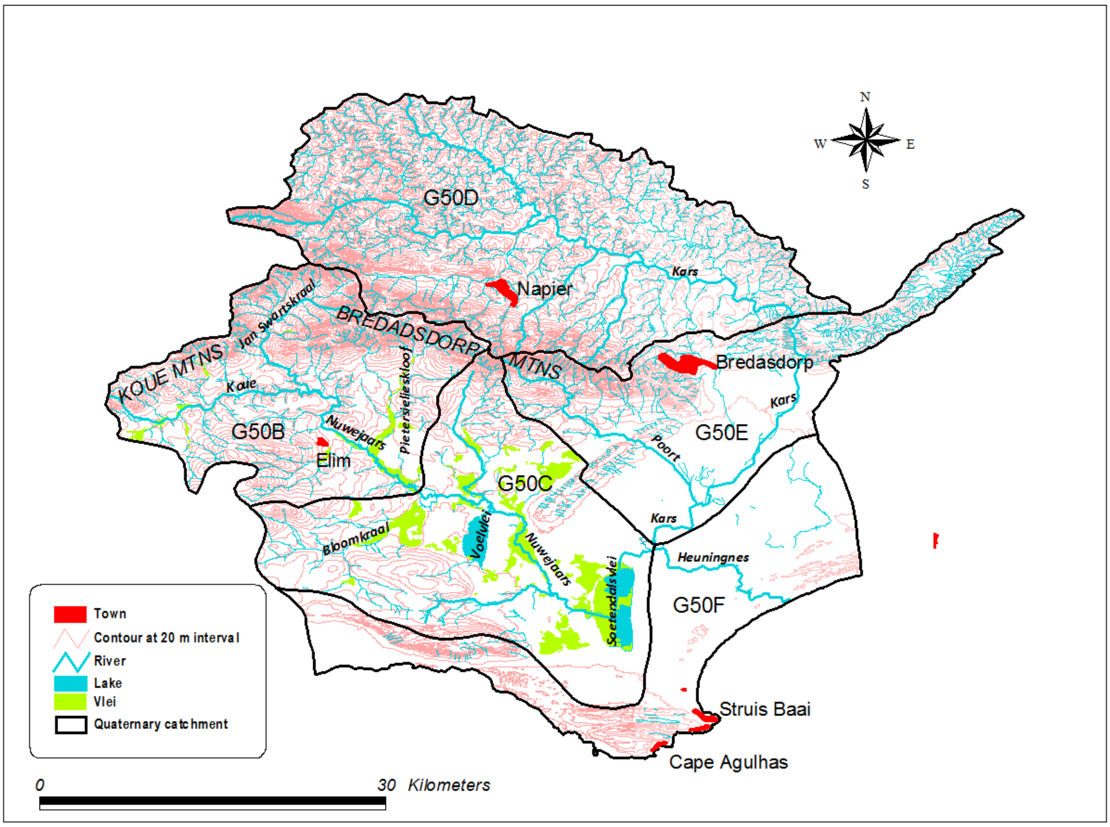


Figure 2.1: The study area is made up of quaternary catchments G50B and G50C which make up the catchment of the Nuwejaars River, which is a tributary of the Heuningnes River

The main tributaries of the Nuwejaars River are the Koue River on the north-west, Jan Swartskraal on the upper northern part, and Pietersielieskloof, on the central northern part. The Bloomkraal and Voelvlei rivers drain the lower western part of the Nuwejaars Catchment (Figure 2.1). The length of the Nuwejaars River up to Soetendalsvlei is 48 km. The headwaters are characterised by a rapid decrease of altitude from about 400–600 m to about 150 m within the first 4 km along the main tributaries. After the confluences of the Koue, Jan Swartskraal and Pietersielieskloof rivers, the Nuwejaars River passes through a lowland with altitude decreasing from 30 to 7 m over a distance of 20 km.

The occurrence of lakes and pans, especially on the lower part in quaternary G50C, is a characteristic feature of the Nuwejaars Catchment. The largest lake is the Soetendalsvlei which is about 3 km wide and 8 km long. Other lakes occurring in this catchment are the Voëlvlei (4 km by 1.7 km), Soutpan (1.3 km by 1.9 km), Longpan (1 km by 0.5 km), and Roundepan (0.6 km by 0.4 km). The Soetendalsvlei drains into the 18 km-long Heuningnes River which discharges into the Indian Ocean. The Kars River joins the Heuningnes River 3 km downstream of Soetendalsvlei. Tidal activity affects the Heuningnes River, which has a permanently open mouth with the sea due to human intervention. Under natural conditions, the river mouth used to close for some years due to deposition of sand from the sea (Bickerton, 1984). When the river mouth closed, damming of water in the Heuningnes River resulted in inundation of adjacent farmlands. During the 1940s, owners of farmlands that were frequently flooded requested the government to put in place measures to prevent sand accumulation and closure of the river mouth. Thus, the mouth of the Heuningnes River is permanently open due to human intervention. The Heuningnes Estuary is a Ramsar site and one of the ecologically important estuaries in South Africa.

2.2 Climate and runoff

The study area lies in a region which receives its highest rainfall during winter. During summer, from December to March, average maximum temperatures are about 25°C, and 18°C in winter, June to August (Figure 2.2). Average minimum temperatures during the winter months are about 9°C. Sub-zero temperatures are rarely experienced due to the warming influence of winds from the Indian Ocean.

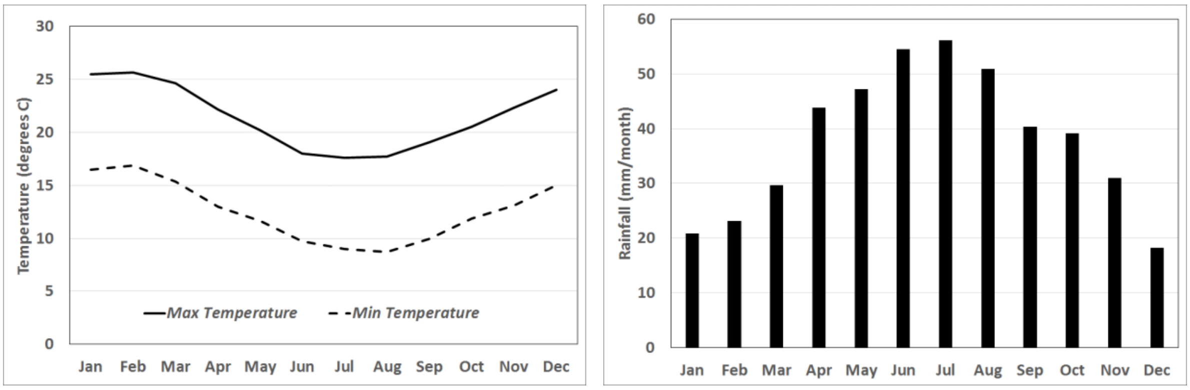


Figure 2.2: Variation in average monthly maximum and minimum temperatures at the Agulhas Wine Farm, and average monthly rainfall at Zeekoevlei. Both locations fall within the Nuwejaars Catchment.

Rainfall is received throughout the year (Figure 2.2). The winter months, June to August, receive the highest rainfall, of about 50–56 mm/month. From December to February, average monthly rainfall is about 18–23 mm/month. The average annual rainfall varies from 455 mm/year in the lower part to about 600 mm/year in the northern mountainous area.

The WR2012 estimates of water resources of South Africa (http://waterresourceswr2012.co.za/resource-centre/) show that the mean annual runoff for the quaternary catchments within the Heuningnes Catchment varies from 15 to 37 mm/year (Table 2.1). The Nuwejaars Catchment (quaternary catchments G50B and G50C) contributes an average of 19 million cubic metres per year to the Heuningnes River flow, while the Kars River (quaternary catchments G50D and G50E) contributes 22 million cubic metres per year.

Table 2.1: Mean annual runoff of quaternary catchments within the Heuningnes Catchment

Quaternary catchment	Area (km^2)	Mean Annual Rainfall (mm/yr)	Mean Annual Runoff (mm/yr)
G50B	339	492	37
G50C	421	362	15
G50D	572	439	27
G50E	313	394	20

Streams in the mountainous parts have acidic water which becomes alkaline in the low-lying areas with vleis and pans (Bickerton, 1984). Gordon *et al*. (2011) found water in the Waskraalsvlei, Voëlvlei and Soetendalsvlei to be alkaline (pH 8–9). Water in the Heuningnes Estuary has high salinity during summer as a result of tidal activity and reduced inflows (Bickerton, 1984). Overflows from Soetendalsvlei and flows from the Kars River lower salinity in the estuary during winter.

2.3 Land uses and land cover

Fynbos shrublands are dominant and cover 41% of the Heuningnes Catchment (Figure 2.3 and Table 2.2). These are followed by cultivated lands which cover 39% of the catchment (Table 2.2). Surface water bodies such as pans and lakes cover a significant part, especially of the Nuwejaars Catchment. Bare land occurs mostly on top of the mountains, as rock outcrops.

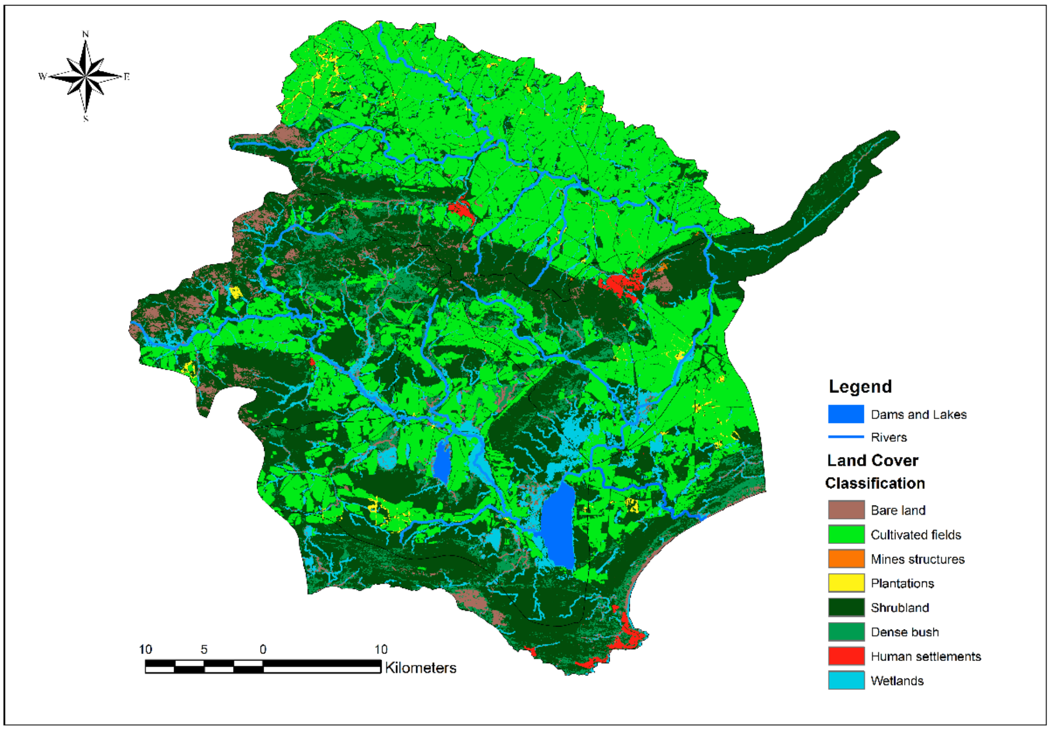


Figure 2.3: Land use and land cover types in the Heuningnes Catchment. (Cape Nature, 2016)

Table 2.2: Percentage area under the various land use and land cover types in the whole of the Heuningnes Catchment, and in its sub-catchment, Nuwejaars River

	Heuningnes (%)	**Nuwejaars** (%)
Dense bush	6.86	7.7
Cultivated land	38.75	25.5
Plantations	0.61	0.4
Human settlements	0.71	0.1
Water bodies	8.67	13.1
Bare land	3.84	5.6
Shrubland	40.56	47.5
	100.00	100.0

Sandstone fynbos occurs on the Koue and Bredasdorp Mountains. Most parts of the Nuwejaars Catchment have Elim ferricrete fynbos. Limestone fynbos and sand fynbos occur on the lower part that is underlain with limestone and calcified dune sand.

Almost all the land in the Nuwejaars Catchment is privately owned in the form of farms practising crop and livestock production. The main crops are barley, canola, and wheat. The growing of grapes, especially for wine making, is an important land use in the Nuwejaars

Catchment. Livestock production in the form of cattle and/or sheep is practised on most of the farms. Dairying is being practised at a small number of farms.

The major settlements are Bredasdorp, Napier and Elim. During the 2011 census, Bredasdorp had a population of 15 524 persons, Napier 4 214 persons, and Elim 1 412 persons. Most of the farms are large-scale commercial farms with very low population numbers. There are about 90 farm homesteads in the Nuwejaars Catchment, with a population of about 1 800 persons. Most of the farmers owning land adjacent to the Nuwejaars River and its tributaries are members of the Nuwejaars Wetland Special Management Area (Figure 2.4) that has the objective to promote sustainable farming practices and protection of wetlands and water resources.

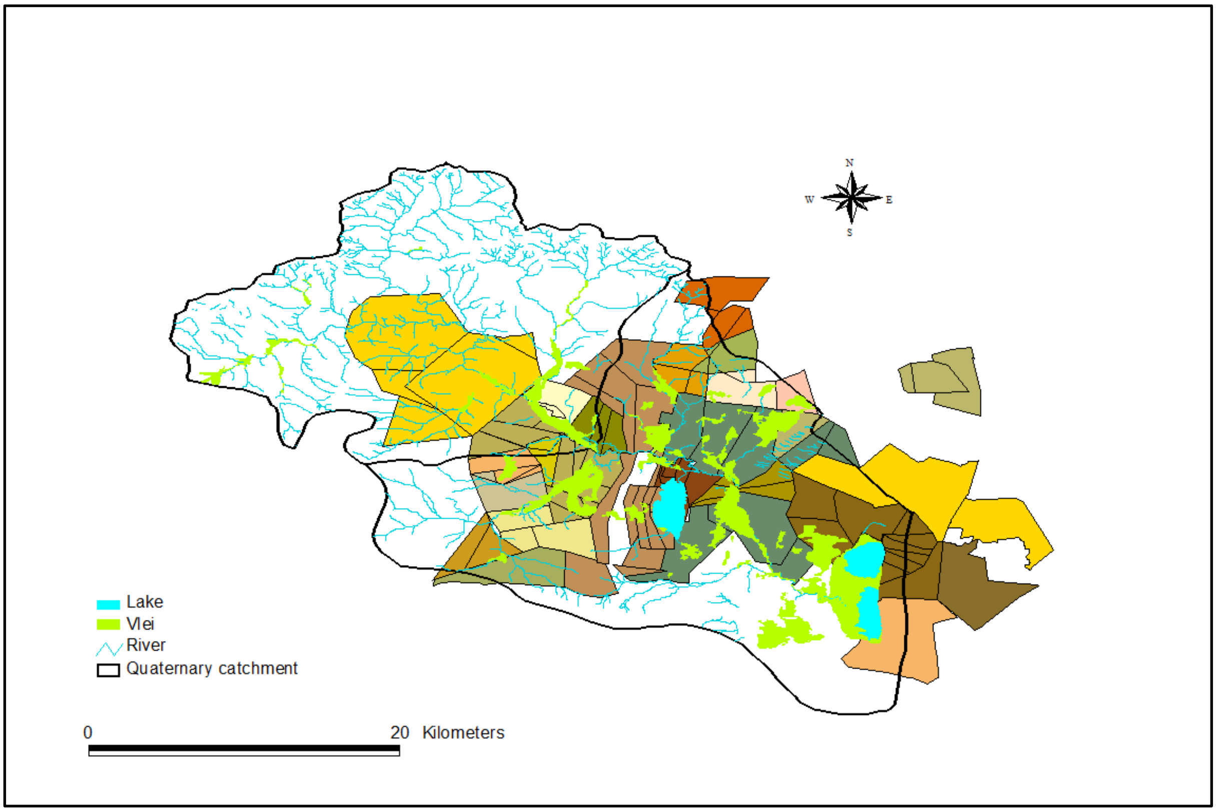


Figure 2.4: Farms belonging to the Nuwejaars Wetland Special Management Area

2.4 Approach to the study

This study required an analysis of data relating to the various elements of the water cycle within the Nuwejaars Catchment. Methods appropriate for collecting and analysing these various data types were employed in this study. The specific methods used for each aspect of this study are described in the relevant chapters of this report. In this section, an overview of the approaches used in the study is presented.

2.4.1 Assessment of surface water and groundwater

Prior to this study, the Nuwejaars Catchment was ungauged. Therefore, the development of a hydrological monitoring system to determine both the quantity and quality of water resources in the main sub-catchments was undertaken. This involved selecting sites for the establishment of weather and rainfall stations. Weather stations were required to collect data for estimation of reference evapotranspiration rates.

Stations for continuous monitoring of water levels on the main tributaries, and lake levels, were established. Monitoring equipment was installed at these sites. Regular river discharge measurements had to be undertaken at sites where river water levels were being monitored. The discharge measurements were used to develop stage-discharge relationships for converting water level measurements to discharges.

Several boreholes and piezometers were drilled for monitoring spatial and temporal variations of depths of the water table within floodplains and around selected lakes and pans. Measurement of the depth to the water table was done on a monthly basis in piezometers, and continuously in boreholes, using data loggers.

2.4.2 Assessment of effects of land use and water use on water resources

Discussions with the community in the Nuwejaars Catchment and other stakeholders revealed that the major land use and/or land cover change with potential significant effects on water resources was the spreading of alien invasive plants. There had been no major conversions of natural land cover to cultivation during the recent past. Consequently, the study focused on determining water use rates of invasive alien plants occurring on hillslopes and riparian zones. Transpiration rates of selected invasive alien plants at a hillslope and a riparian site were monitored using the heat pulse velocity method.

Data for areas under rainfed and irrigated crops were used to estimate water used for crop production. The South African Procedure for Estimating Irrigation Water Requirements, SAPWAT4 (van Heerden and Walker, 2016), was used for estimating crop water requirements.

2.4.3 Influence of floodplain wetlands on river flows

The influence of the floodplain wetlands occurring along the Nuwejaars River on river flows was determined by monitoring and comparing inflows and outflows of one of these wetlands. River flow data for tributaries of the Nuwejaars River were used to estimate inflows. Effects of the floodplain wetland on flow travel time, attenuation of peak flows, and storage and release of water were then analysed.

2.4.4 Water balance of the Soetendalsvlei

A bathymetric survey of the Soetendalsvlei was carried out to collect data for derivation of the relationships between lake levels, volume of water stored, and surface area of the lake. Measured inflows into the lake, weather elements at the lake, and a reservoir model were used to determine the contributions of river inflows and outflows, rainfall and evaporation to changes in water storage in this lake.

3 RAINFALL AND EVAPOTRANSPIRATION

3.1 Development of the weather monitoring system

Prior to this project, Agulhas Wines was the only weather station located within the Nuwejaars Catchment (Table 3.1). The existing stations in the Heuningnes Catchment were not adequate to represent the spatial variation of weather elements, including rainfall and evapotranspiration rates. The study aimed to establish a rainfall station in each of the catchments of the main tributaries of the Nuwejaars River, i.e. the Koue, Jan Swartskraal, Blomkraal and Pietersilieskloof rivers. In addition, the project aimed to assess possible changes in both weather and rainfall from the coast to inland locations. This required having a station on the low, middle and upper parts of the Nuwejaars Catchment. The specific locations of a weather or rainfall station depended on the landowner granting the research team permission to regularly visit a station.

Table 3.1: Stations with historical weather data in the Heuningnes Catchment

Name of Station	Type of Data Available	Period of Record
Agulhas Wines (ARC)	Radiation, temperature, rainfall, wind speed, relative humidity	2003–present
Prinskraal (ARC)	Radiation, temperature, rainfall, wind speed, relative humidity	2006–present
Cape Agulhas (SAWS)	Radiation, temperature, rainfall, wind speed, relative humidity	1970–present
Struis Bay (SAWS)	Radiation, temperature, rainfall, wind speed, relative humidity	1996–present
Bredasdorp	Rainfall	1878–present
Zeekoevlei	Rainfall	1910–2016

ARC – Agricultural Research Council; SAWS – South African Weather Service

The project established five weather stations and two rainfall stations in the study area (Table 3.2; Figure 3.1). All these stations are on privately owned land.

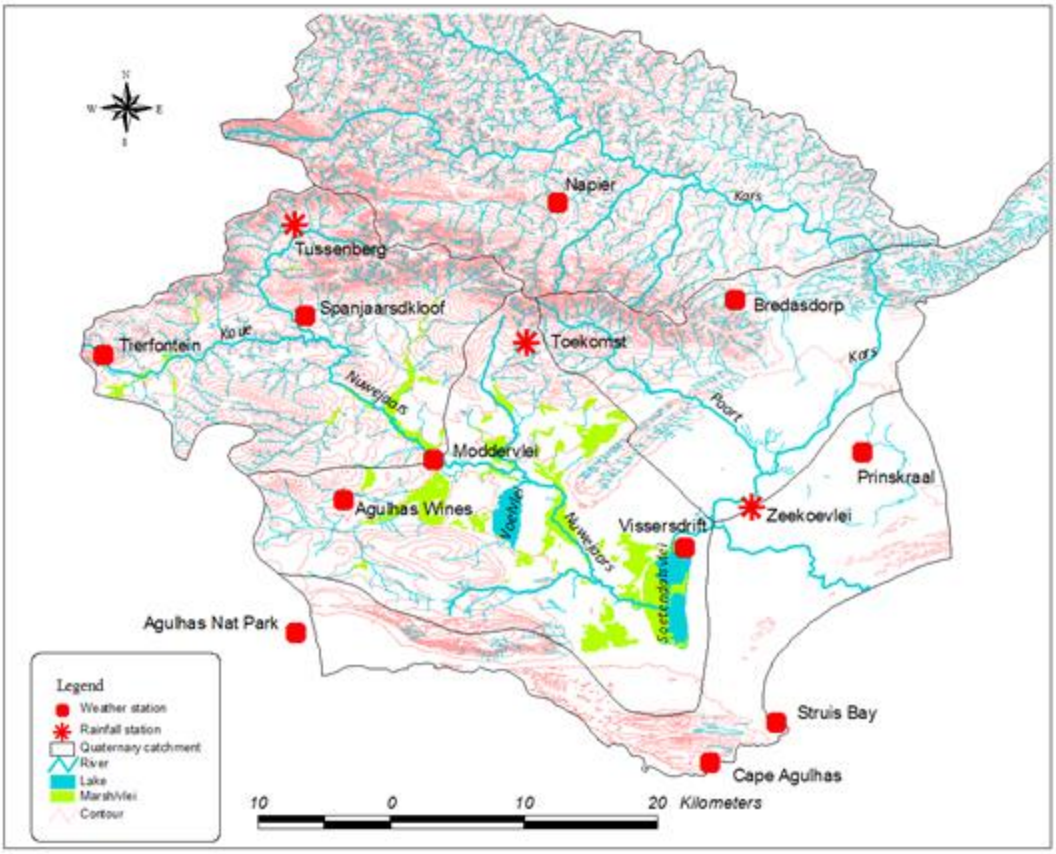


Figure 3:1 Locations of the UWC weather stations (Tierfontein, Spanjaardskloof, Moddervlei, Napier, Vissersdrift), and rain gauges (Tussenberg, Toekomst) in the Nuwejaars River Catchment

Table 3.2: Locations of automatic weather and rainfall stations established by the University of the Western Cape in the Heuningnes Catchment

Location	**Coordinates**	**Altitude (m)**	**Type of Equipment**	**Date Started**
		Weather Stations		
Spanjaardskloof	34.5400° S, 19.7396° E	159	HOBO US30	20 Dec 2014
Vissersdrift	34.6880° S, 19.9955° E	7	HOBO US30	21 Dec 2014
Tierfontein	34.5650° S, 19.6033° E	197	HOBO US30	20 Dec 2014
Napier at Sensako Farm	34.46778° S, 19.9099° E	159	HOBO US30	12 Feb 2015
Moddervlei	34.6051° S, 19.7963° E	25	Campbell Scientific with CR1000 Data Logger	17 June 2016
		Rainfall Stations		
Tussenberg	34.474363° S, 19.743775° E	231	HOBO 0.2 mm with Event Data Logger	4 June 2015
Toekomst	34.556116° S, 19.890188° E	162	HOBO 0.2 mm with Event Data Logger	4 June 2015

Weather and rainfall stations record data every 15 minutes. By the end of September 2017, these stations had collected data with record lengths ranging from 650 to 1 117 days (Figure 3.2).

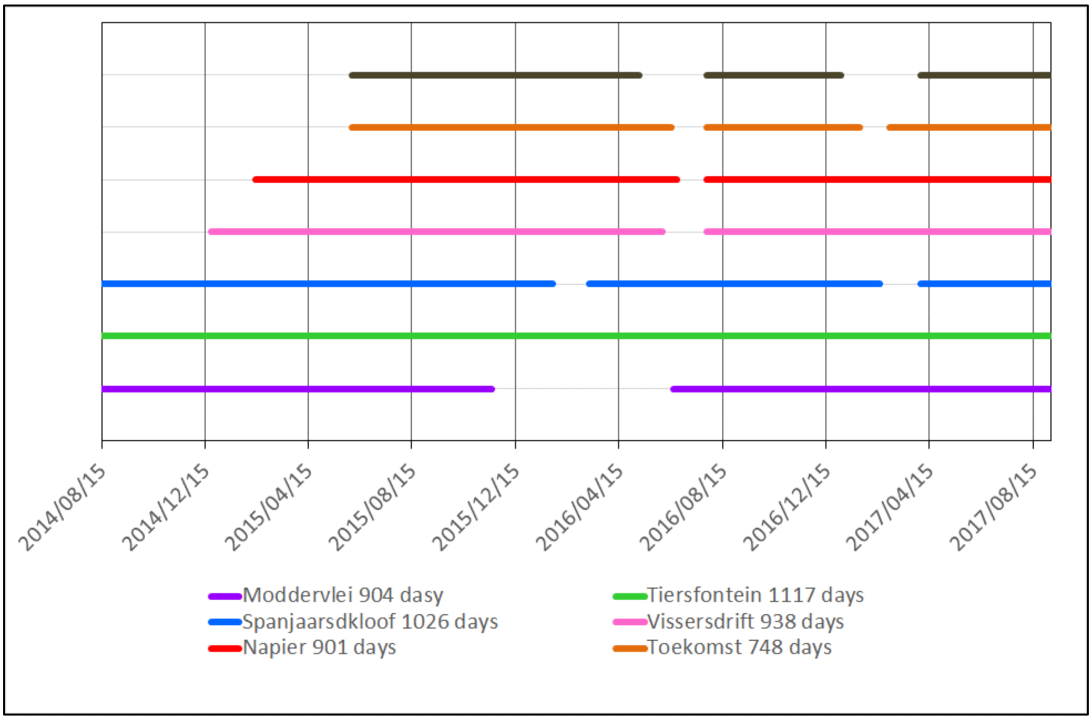


Figure 3.2: Record length of weather data collected at the stations established in the Heuningnes Catchment

3.2 Meteorological parameters

A summary of the meteorological elements measured during the January 2015 to August 2017 period is presented in Figure 3.3. The December to January period received the highest irradiance with an average of 26–28 MJ/m^2/day (Figure 3.3; Appendix 3.1). There were some days that received 35 MJ/m^2/day of irradiance. As expected, the month of June had the lowest mean monthly irradiance, 8 MJ/m^2/day. There were no major differences in irradiance received at the four weather stations. These values are comparable to those estimated by Schulze *et. al*. (1997) for the Western Cape Province. The five weather stations had also similar values of monthly average maximum and minimum temperatures (Figure 3.3). The monthly average maximum temperatures were 26–28°C during the December–January period, and 17–19°C during winter, June–August. There were a few occasions when maximum temperatures reached 40°C, especially at Napier (Appendix 3.2). The monthly average minimum temperatures were in the 6–8°C range during winter, and 10–16°C in summer (Figure 3.3). The Vissersdrift weather station which is on the shoreline of the Soetendalsvlei had 1–3 days during winter with a minimum temperature just below 0°C (Appendix 3.3).

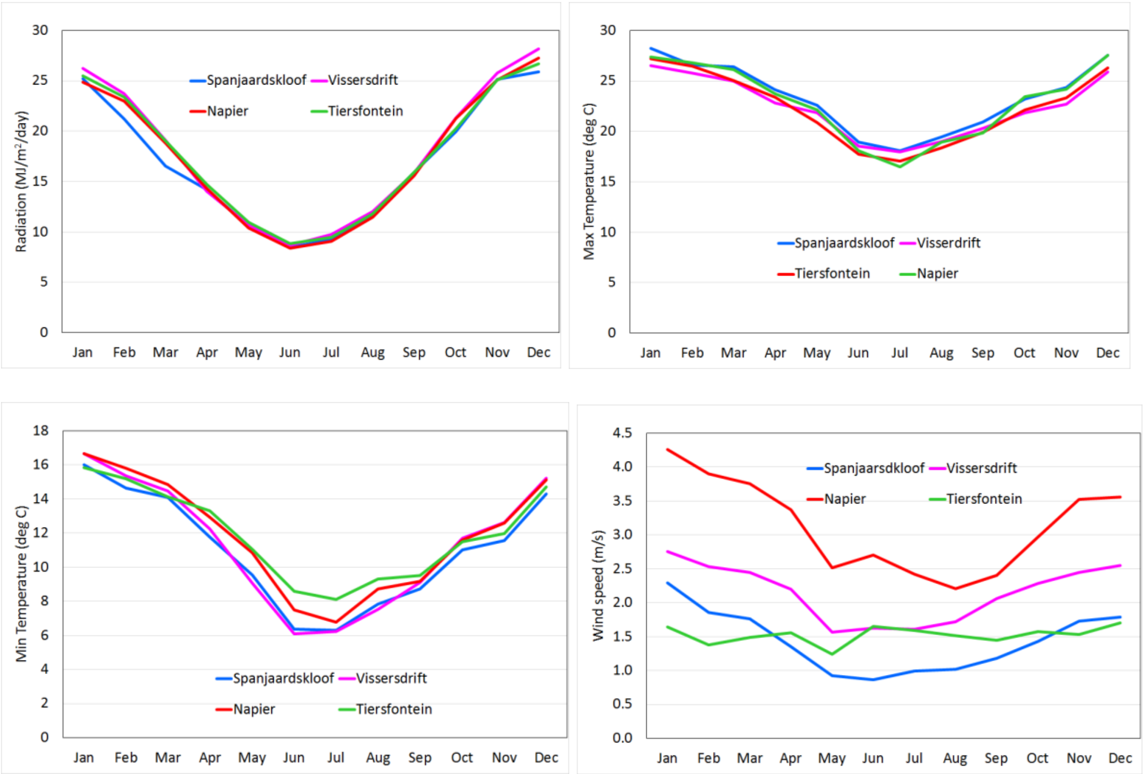


Figure 3.3: Mean monthly values of solar radiation, maximum and minimum temperatures, and wind speed at weather stations established in the Heuningnes Catchment

Wind speeds differ significantly at the five stations. The weather station in Napier is located just outside the town on a very exposed site in Sensako Farm, and had the highest wind speeds during all the months (Figure 3.3). Wind speeds in the 5–10 m/s range frequently occurred at this location, while the other stations rarely experienced such wind speeds (Appendix 3.4). The weather station at Moddervlei did record some very high wind speeds, up to 12 m/s. This floodplain site is very exposed and in a valley that tends to funnel south-easterly winds, hence the high wind speeds. The May to August period had the lowest wind speeds, 1–3 m/s, while January and February had the highest wind speeds. The Tierfontein station is on a south-facing hillslope of the Koue Mountains which seems to explain the lack of a discernible seasonal pattern in the wind speed.

3.3 Reference evapotranspiration rates

The collected weather data were used to estimate the reference evapotranspiration (ETo), using the modified Penman-Monteith equation (Table 3.3, Appendix 3.5) (Allen *et al.*, 1998). Tierfontein had the lowest daily ETo rates throughout the monitoring period, 2015–2017. Napier had the highest daily ETo rates which occasionally reached 8–10 mm/day. During the summer months of November to February, daily ETo rates were generally 5–7 mm/day, while these were 1–2 mm/day during the winter months (May to August).

Table 3.3: Monthly average reference evapotranspiration rates (mm/month) during the 2015 to 2017 period at weather stations in the Heuningnes Catchment

	Spanjaardskloof	Vissersdrift	Napier	Tierfontein
Jan	171.4	191.8	204.7	186.8
Feb	126.9	151.8	169.2	149.4
Mar	122.4	135.5	157.9	132.4
Apr	79.9	90.5	109.2	92.1
May	52.2	64.1	78.5	62.4
Jun	34.8	45.9	56.8	47.8
Jul	39.8	52.0	55.7	51.9
Aug	56.1	68.7	71.2	69.0
Sep	82.4	97.4	101.9	96.3
Oct	112.4	135.1	150.9	132.4
Nov	134.9	161.3	179.9	161.3
Dec	161.7	197.7	216.7	188.0
Total	1175.1	1391.7	1552.7	1369.9

Napier, as expected, had the highest total annual ETo of 1 553 mm/yr. Vissersdrift, which is on the shoreline of Soetendalsvlei (1 391 mm/yr), and Tierfontein (1 369.9 mm/yr) have comparable evapotranspiration rates. Spanjaardskloof has the lowest ETo rates. This location has the lowest wind speeds which accounts for the relatively low ETo rates. The high ETo rates at Napier are due to the relatively high wind speeds.

3.4 Rainfall

The Nuwejaars Catchment received rainfall throughout the year during 2015 and 2016 (Figure 3.4). June 2015 had very high rainfall ranging from 100 to 140 mm/month. This was a result of 80 to 122 mm of rainfall received from 30 May to 2 June 2015. Most of this rain (70–111 mm) occurred during the 2–3 June 2015 period. November of 2015 had also relatively high rainfall in comparison to October and December of the same year. There has been a tendency for March receiving relatively high rainfall in comparison to February, April and May (Figure 3.4). The December to January period received the lowest rainfall.

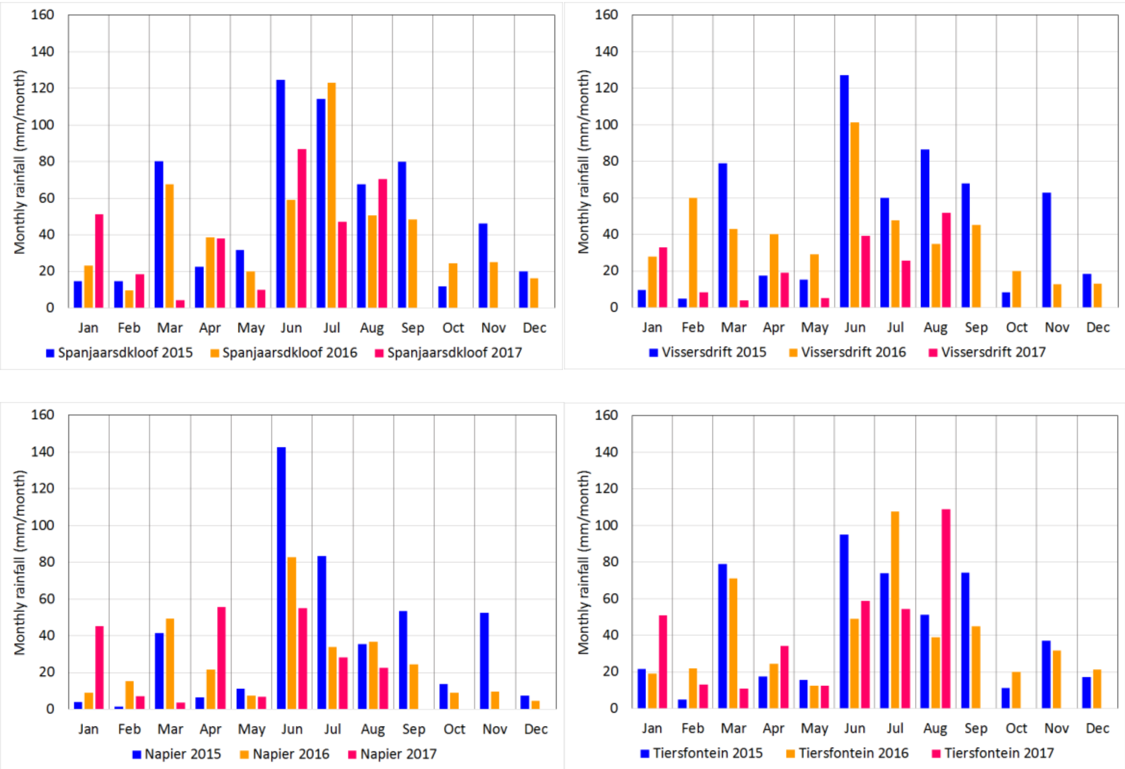


Figure 3.4: Monthly rainfall from January 2015 to August 2017 at the weather stations in the Heuningnes Catchment. At the time of compiling the report, rainfall data from 1 September 2017 had not been downloaded from the stations.

The annual rainfall for 2015 varied from 454 mm/yr at Napier to 629 mm/yr at Spanjaardskloof (Table 3.4). Although rainfall for 2016 was lower (334 to 563 mm/yr) than in 2015, the spatial distribution among the stations was similar.

Table 3.4: Annual rainfall for 2015 and 2016 at the weather stations in the Heuningnes Catchment, and a comparison of the January to August 2017 rainfall with rainfall received during the same period in 2015 and 2016

	Spanjaardskloof	Vissersdrift	Napier	Tierfontein
		Total Annual Rainfall (mm/yr)		
2015	628.6	558.4	453.7	499.2
2016	563.2	471.8	334.2	463.4
Jan–Aug 2017 Total Rainfall (mm) as a ***percentage of 2015 and 2016*** *rainfall for the same period*				
2015	70.3	46.5	78.5	95.7
2016	73.7	49.0	89.5	99.7

Rainfall data show that the 2017 drought has been more severe on the southern part of this catchment than the upland areas. Vissersdrift received in 2017 about 50% of the rainfall received in both 2015 and 2016 during the same period (Table 3.4).

During the wet winter period, May to August, rainfall occurs on about 10 to 12 days in a month (Table 3.5). Rainfall occurs on about 2-to-7 days in a month during the summer months, December to January. Although 2017 has been relatively dry, the number of rainy days per month was similar to those that occurred during a wet year, 2015. This implies that the drought in 2017 is not due to infrequent rainfall, but the low magnitude of rainfall received on rainy days.

Table 3.5: Number of rainy days occurring in each month in 2015 and 2017

	2015			**2017**		
Month	Vissers-drift	Spanjaardskloof	Tierfontein	Vissersdrift	Spanjaardskloof	Tierfontein
Jan	2	3	5	7	9	9
Feb	5	9	5	5	4	7
Mar	9	11	9	5	0	9
Apr	10	13	10	6	7	9
May	10	11	8	8	5	7
Jun	11	12	10	12	13	14
Jul	13	12	13	11	11	7
Aug	8	11	12	15	15	15
Sep	12	13	14			
Oct	7	7	6			
Nov	9	10	11			
Dec	7	7	7			
Annual total	**103**	**119**	**110**			
Jan–Aug	**68**	**82**	**72**	**69**	**64**	**77**

There is a high correlation between the daily rainfall of the different rainfall stations (Table 3.6). The distance between stations did not seem to have a major influence on the correlation of the daily rainfall. Daily rainfall at Toekomst has a weaker correlation with other stations. Toekomst is on the north-eastern part of the catchment, but this is not likely to be the reason for the weak correlation.

Table 3.6: Correlation between daily rainfall at stations established by this project. The upper part of the matrix shows correlation coefficients while the lower part of the matrix, which is shaded, shows distances between stations.

	Moddervlei	Tierfontein	Spanjaardskloof	Vissersdrift	Napier	Toekomst	Tussenberg
Moddervlei	1.00	0.80	0.90	0.89	0.85	0.61	0.88
Tierfontein	18.3	1.0	0.81	0.80	0.82	0.67	0.84
Spanjaardskloof	9.0	12.5	1.00	0.81	0.85	0.74	0.86
Vissersdrift	20.2	38.7	28.5	1.00	0.83	0.61	0.83
Napier	18.5	17.6	17.6	24.0	1.00	0.59	0.91
Toekomst	10.0	26.3	13.9	16.2	9.9	1.00	0.61
Tussenberg	14.4	16.2	7.4	32.0	15.3	16.2	1.00

3.5 Evaluation of satellite-derived rainfall estimates

This part of the study evaluated whether rainfall estimates derived from satellite data do realistically represent rainfall received at a station in the Nuwejaars Catchment. The study evaluated the following two satellite-derived rainfall estimates: a) Climate Hazards Group Infra-red Precipitation with Stations (CHIRPS), and b) Tropical Applications of Meteorology using SATellite (TAMSAT) (Table 3.7). A comparison was done between the rain gauge data for Spanjaardskloof, and the satellite-derived rainfall estimated for the pixel in which the rain gauge is located.

Table 3.7: Properties of the satellite-derived products used in the Nuwejaars Catchment

Product	Main principles data	Resolution	Spatial coverage	Gauge	Minimum time step interval	Producer
TAMSAT	Meteosat thermal-IR	4km	Africa	No	Daily	NOAA
CHIRPS	IR estimate and gauge	1km	50°N-50°S	Yes	Monthly	USGS

Total rainfall, for the March 2015 to February 2016 period, estimated by CHIRPS and TAMSAT, was compared with rain gauge data for the Spanjaardskloof station. The total rainfall for this period, based on rain gauge data, was 633 mm/year, while CHIRPS estimated 532 mm/year, and TAMSAT 114 mm/year. Thus, rainfall estimates based on remotely-sensed data underestimated rainfall by 16% for CHIRPS, and 82% for TAMSAT.

CHIRPS rainfall estimates did realistically capture the seasonal variation of rainfall (Figure 3.5). However, TAMSAT did not capture much of the seasonal variation of rainfall.

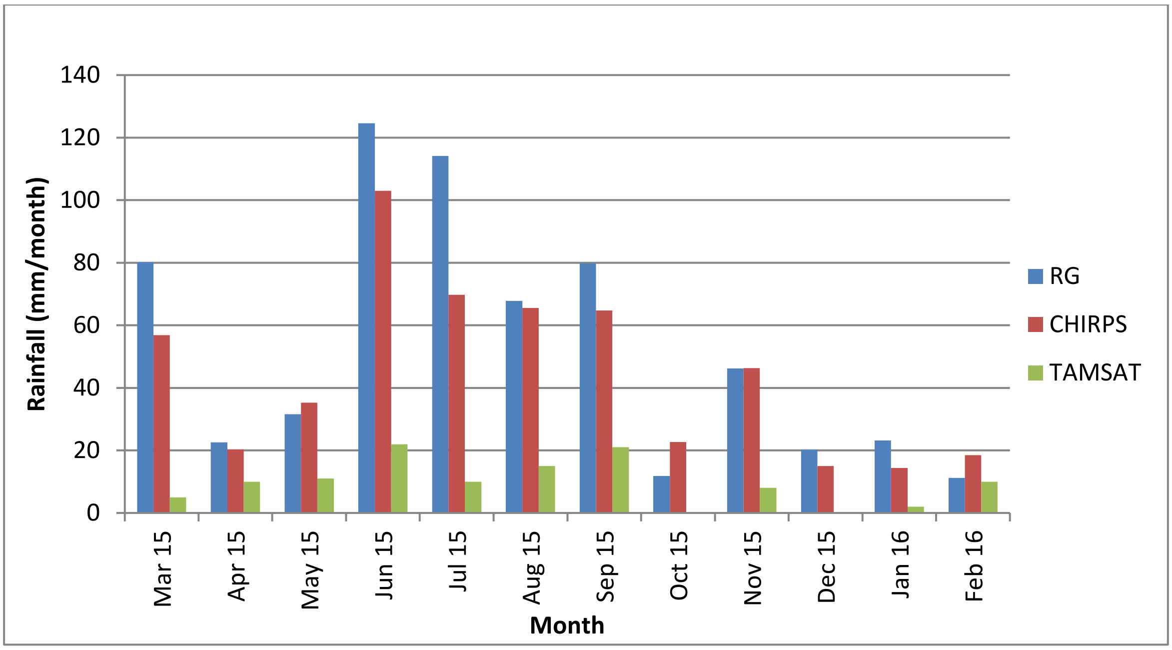


Figure 3.5: A comparison of monthly estimated rainfall by CHIRPS and TAMSAT with rain gauge (RG) data for the March 2015 to February 2016 period at Spanjaardskloof

TAMSAT underestimated considerably the June and July rainfall, by 103 and 104 mm respectively, while CHIRPS underestimated by 21.6 and 44 mm for the same months (Figure 3.5). However, there is general underestimation by both products. The better performance of CHIRPS is due to the fact that rain gauge data are incorporated in this method, while TAMSAT uses satellite data only.

An assessment of the ability of CHIRPS and TAMSAT to detect rainy and non-rainy days was also undertaken. A rainy day was defined as when 1 mm/day of rainfall was received. The days were categorised as hits, misses, false alarms and null. Hits are days when rainfall was estimated to occur, and occurred. Misses are days when rainfall occurred but was estimated not to occur. False Alarms are days when rainfall was estimated to occur and did not occur. Null days are days when rainfall was estimated not to occur and did not occur. This was then used to calculate the accuracy, bias, possibility of detection (POD), false alarm ratio (FAR), possibility of false detection (POFD) and critical success index (CSI).

Table 3:8: Categorical statistics for CHIRPS when compared to rain gauge data at Spanjaardskloof

	Hits (days)	Misses (days)	False Alarm (days)	Null (days)
Mar	0	8	1	22
Apr	1	4	0	25
May	0	9	1	21
Jun	1	7	1	21
Jul	7	5	1	18
Aug	3	7	2	19
Sep	2	9	1	18
Oct	0	5	1	25
Nov	0	6	2	22
Dec	2	4	1	24
Jan	1	6	2	22
Feb	3	4	0	22
Sum	20	74	13	259
Total	366			
	CHIRPS Score	Perfect Score		
Accuracy	0.76	1		
Bias	0.35	1		
POD	0.21	1		
FAR	0.39	0		
POFD	0.05	0		
CSI	0.69	1		

Table 3.8 shows that out of 366 days, from March 2015 to February 2016, CHIRPS had 20 hits, 74 misses, 13 False Alarm and 259 Null days. The estimated accuracy statistic was 0.76. CHIRPS misses a significant number of rainy days.

Table 3.9 shows that out of 366 days, TAMSAT had 13 hits, 81 misses, 29 False Alarm and 243 null days. The accuracy statistic was 0.7. TAMSAT, like CHIRPS, misses a significant number of rainy days, which leads to underestimation of rainfall.

Table 3.9: Categorical statistics results for TAMSAT for Spanjaardskloof rain station.

	Hits (days)	**Misses (days)**	**False Alarm (days)**	**Null (days)**
Mar	0	8	1	22
Apr	1	4	1	24
May	0	9	3	19
Jun	4	4	6	16
Jul	3	9	4	15
Aug	2	8	5	16
Sep	2	9	5	14
Oct	0	5	0	26
Nov	0	6	2	22
Dec	0	6	0	25
Jan	0	7	1	23
Feb	1	6	1	21
Sum	13	81	29	243
Total	366			
	TAMSAT Score	Perfect Score		
Accuracy	0.7	1		
Bias	0.45	1		
POD	0.14	1		
FAR	0.69	0		
POFD	0.11	0		
CSI	0.66	1		

The study showed that the remotely-sensed products underestimated rainfall received. CHIRPS performed better than TAMSAT. Thus, the use of rainfall estimates derived from satellite data will lead to underestimation of water resources in the Cape Agulhas area.

3.6 Long-term rainfall variations

There is a perception among landowners in the study area that temporal variations and magnitude of rainfall have changed over time. The availability of monthly rainfall data from 1909 to 2016 (107 years) at Zeekoevlei provided an opportunity to evaluate this perception. A visual analysis of the rainfall during summer, winter and for the whole year for Zeekoevlei did not suggest any changes over time (Figure 3.6). The 1940 to 1964 period had generally above average rainfall. Severe droughts occurred in 1919 (221 mm/yr) and 1969 (244 mm/yr). Local farmers reported that the Soetendalsvlei dried up during these years.

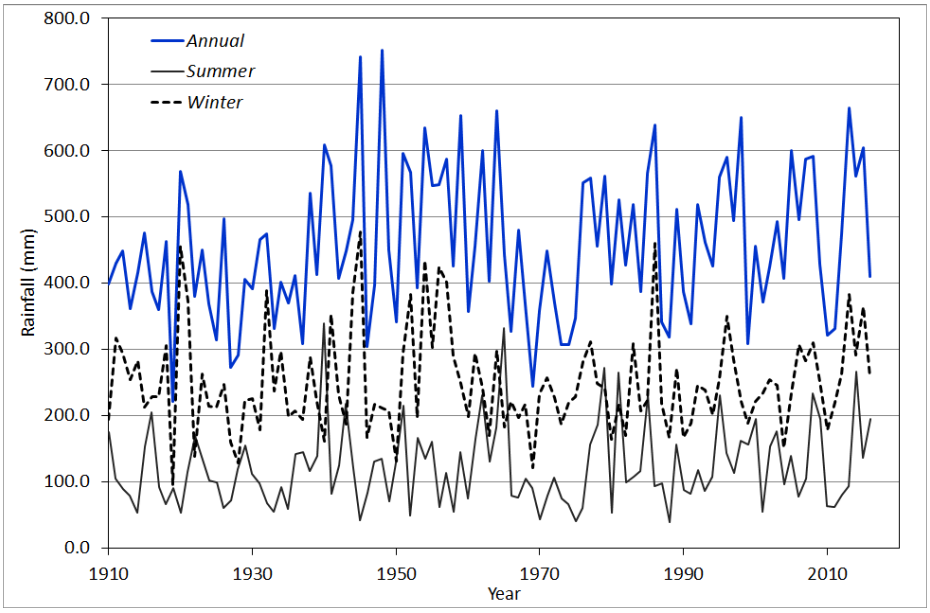


Figure 3.6: Variation over time of annual, summer and winter rainfall at Zeekoevlei, which is close to Soetendalvlei.

Several statistical tests for trend and change were undertaken on the winter, summer and annual rainfall at Zeekoevlei. The test statistics are provided in Table 3.10. Total winter rainfall was obtained as the sum of the rainfall from May to September, while the sum of rainfall from November to February was considered as the summer rainfall.

Table 3.10: Test statistics estimated for the annual, winter, and summer rainfall at Zeekoevlei. Shaded cells have values that are significant at the 5% level.

Name of the test	Winter	Summer	Annual
Mann-Kendall	0.70	1.22	1.97
Linear regression	0.15	1.30	1.99
Cusum	12.00	8.00	10.00
Worsley likelihood	2.00	1.96	3.31
Rank sum	0.54	-0.46	-0.38
Student's t	1.17	-0.81	-0.27
Median crossing	1.55	2.03	0.97
Turning point	-0.23	-1.53	0.69

All the statistical tests showed no change in the winter rainfall. A change in the median of the summer rainfall was detected. An increasing trend in annual rainfall was detected. However, the values of the test statistics are just marginally significant. The results obtained do not support the general perception that rainfall is decreasing in the Nuwejaars Catchment.

4 GROUNDWATER

4.1 Geology

The Heuningnes Catchment is largely dominated by the following main geological formations (Figure 4.1):

- Malmesbury Group
- Table Mountain Group
- Cape Granite Group
- Bokkeveld Group
- Bredasdorp Group

The Malmesbury and Cape Granite Groups are basement rocks which are overlaid by the Table Mountain and Bokkeveld Groups.

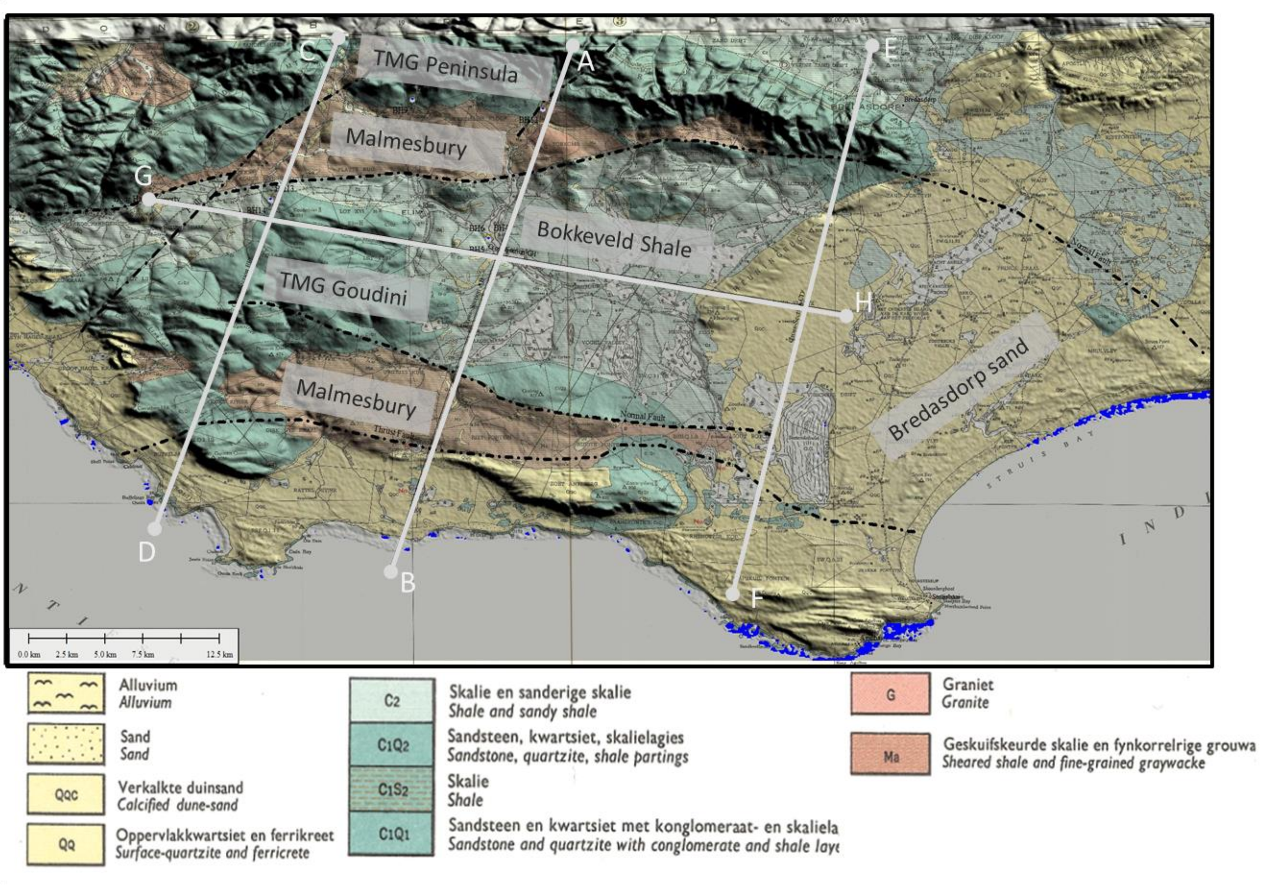


Figure 4.1: Geology of Agulhas area showing locations of cross-sectional and monitoring boreholes. Map reproduced from the 3419C. 3419D- Gansbaai 3420C – Bredasdorp 1:125 000 map published by Geological Survey, Department of Mines, 1963.

The Table Mountain Group (TMG) consists of quartzitic sandstones derived from coarse sands deposited within the Agulhas Sea, and along the coastal plane. It was deposited during the Ordivician, Silurian and earliest Devonian periods. The TMG overlies the basement formations of Malmesbury and Cape Granite Suite. Although the outcrop area is relatively small, these rocks underlie the whole of the coastal plane at varying depths of up to ~100 m.

The Bokkeveld Group constitutes the middle subdivision of the Cape Supergroup, comprising a cyclic alternation of fine-grained sandstone and mudrock units that conformably overlie the TMG in an off-lapping succession (Thamm and Johnson, 2006). Bokkeveld strata consist largely of shales and thin interbedded sandstones derived from marine continental slope muds of early to mid-Devonian. In the Heuningnes Catchment, the Bokkeveld formation lies between the TMG and the Bredasdorp Group. The Bokkeveld Group rocks occupy the largest area, comprising an alternating sequence of shales and sandstones. (Figure 4.1).

The Bredasdorp Beds are characterised by calcified dune sand, calcrete, calcarenite and basal conglomerate. In the Heuningnes Catchment, this formation occurs around Soetendalsvlei and towards the mouth of the Heuningnes River. It forms an important component of the southern part of the catchment.

A number of fairly large faults cut the TMG of the Napier-Bredasdorp Mountains, trending northeast-southwest and east-west (Figure 4.1). Bickerton (1984) reported that two fault lines are present in the catchment, running almost east-west. One fault line lies south of the Bredasdorpberge and the other is further south wards.

The upper catchment of the Kars River is dominated by TMG sandstone, quartzite as well as shales of the Heuningberg Mountain. Further downstream, east of Bredasdorp, the river transverses calcified dune sand and coastal limestone of the Bredasdorp Beds. The upper part of the catchment of the Nuwejaars River is dominated by the sandstone, quartzite and shales of the TMG. Further downstream, near Elim, the Nuwejaars River transverses the shale and sandy shale of the Bokkeveld Group.

Cross-sections, perpendicular to the main fault strike direction (Figure 4.2, Figure 4.3 and Figure 4.4), show the positively weathered quartzite mountains towards the north of the catchment, with graben structures causing abrupt changes in geology and age of deposits. These changes in geology are likely to influence the hydrogeology of the system, with the main flow rather expected along the faults than across these geological boundaries along the cross-section profile.

The cross-section along the main fault strike direction (Figure 4.5) shows a continuous geological layering, which, in combination with the main faults, would contribute to the principal groundwater flow direction in an ESE direction.

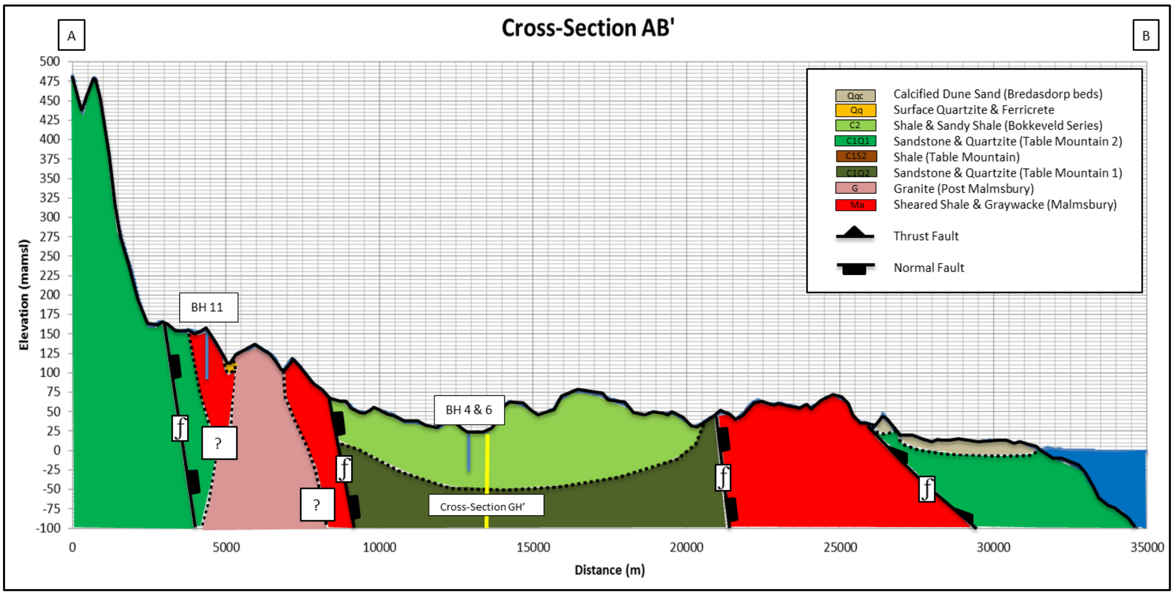


Figure 4.2: NNE-SSW trending cross-section traversing the "spine" of the catchment, covering BH11-12 and BH4-8

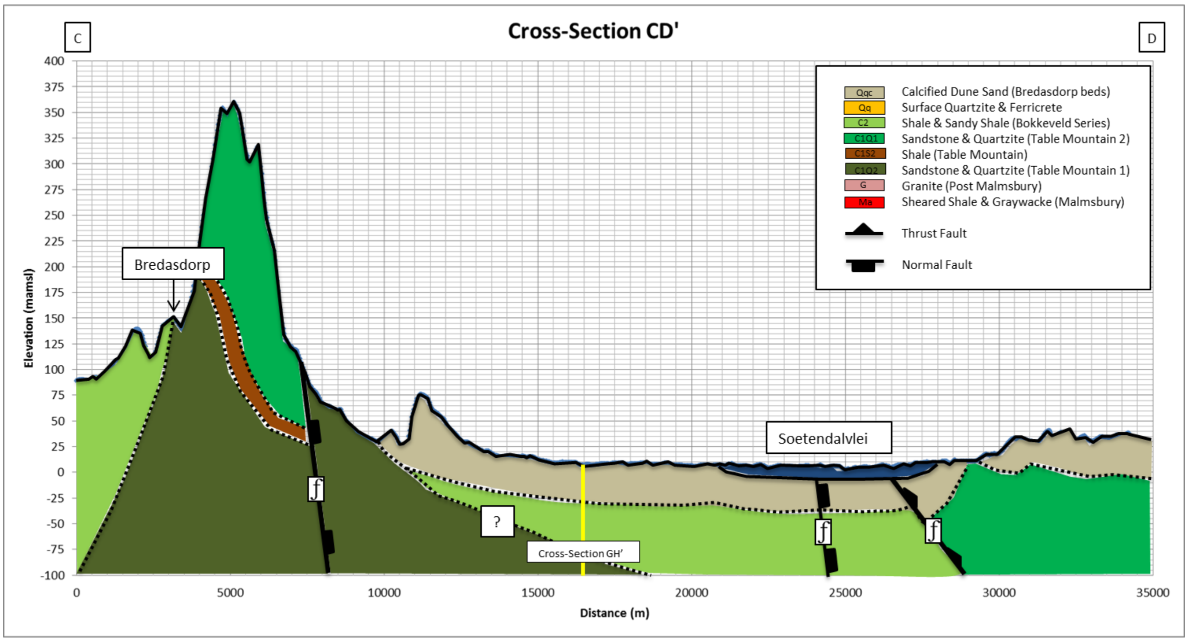


Figure 4.3: NNE-SSW trending cross-section traversing to the east of Line AB', covering low-lying floodplain areas

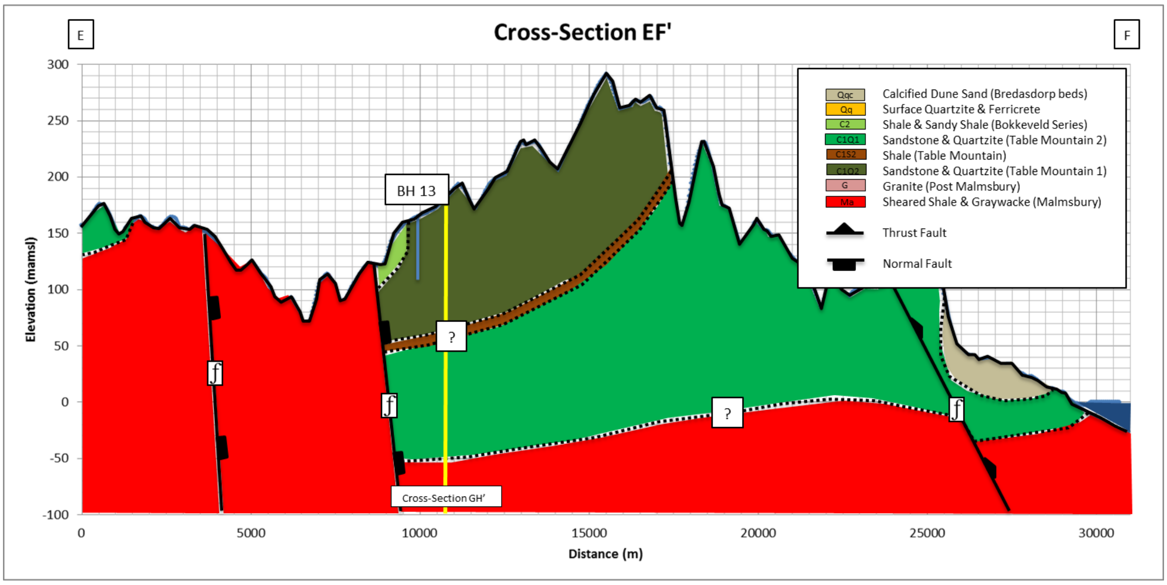


Figure .4.4: NNE-SSW trending cross-section traversing to the west of Line AB', covering more sandstone hill areas. BH13-14 are also shown.

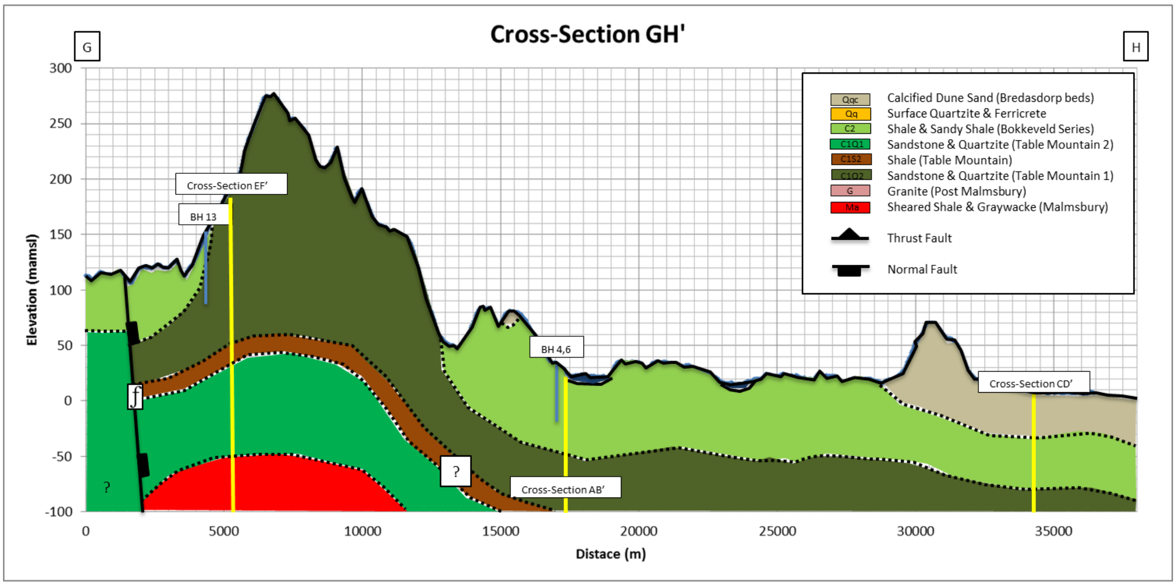


Figure 4.5: W-E trending cross-section traversing all three line cross sections, covering BH13-14 as well as BH4-8.

Both primary and secondary aquifers occur within the catchment. Primary aquifers occur in unconsolidated sediments deposited as alluvium in floodplains of major river systems and ocean deposition during sea level changes.

A primary aquifer, with a depth of 8 and 30 m deep, was identified from the electrical resistivity survey and drilling done at the Zoetendal site, within the Moddervlei floodplain of the Nuwejaars River. Fresh water is associated with sand channels, while more saline water is associated with clay layers. The aquifer thins towards the edges of the river valley.

Fractured bedrock aquifers are expected to be semi-confined, anisotropic and secondary in nature. The movement of groundwater is predominantly associated with secondary structures such as fractures, joints and faults. This seems to be true for most of the drilling data obtained at the Agulhas site.

The geophysical survey across the shale hills to the west of the Zoetendals site suggested unsaturated weathered material to depths varying between 10 and 15 m, underlain by conductive saline aquifer. Drilling into the shale below the primary aquifer associated with the river channel indicated some fractures with yields of above 1 litre/sec.

Drilling results at the Spanjaardskloof and Boskloof sites showed the existence of weathered rock to depths of 40 m with water strikes associated with the contact between the weathered and fresher rock.

The regional groundwater flow is expected to be controlled by the TMG recharge areas and fault systems. Most springs in the study area are associated with TMG formations and closely linked to faults.

Some local temporary groundwater flow can be expected in the shallow weathered aquifers across the study area, contributing to the local streams. The salinity of the units not associated with the TMG suggests low-yielding and low-recharge characteristics.

4.2 Development of monitoring boreholes and piezometers

Prior to the study presented in this report, the Nuwejaars Catchment did not have a groundwater monitoring system. A groundwater monitoring system was therefore developed to achieve the following objectives:

- Determine the occurrence of groundwater in the upland areas and lowlands.
- Establish the influence of major faults on groundwater occurrence.
- Determine the possible interactions between surface water and groundwater in the Moddervlei floodplain wetland of the Nuwejaars River, and around the Soetendalsvlei and Voëlvlei.
- Determine relationships between water use by invasive alien trees and groundwater.

The development of this monitoring system was done in two stages. During the first stage, the following 3 boreholes and 23 piezometers were developed on the lower part of the Nuwejaars Catchment (Quarternary Catchment G50C) (Figure 4.6);

- 3 boreholes and 9 piezometers along the shoreline of Soetendalsvlei
- 6 piezometers around Voëlvlei
- 8 piezometers in the Nuwejaars River floodplain between Elandsdrift and Weisdrif

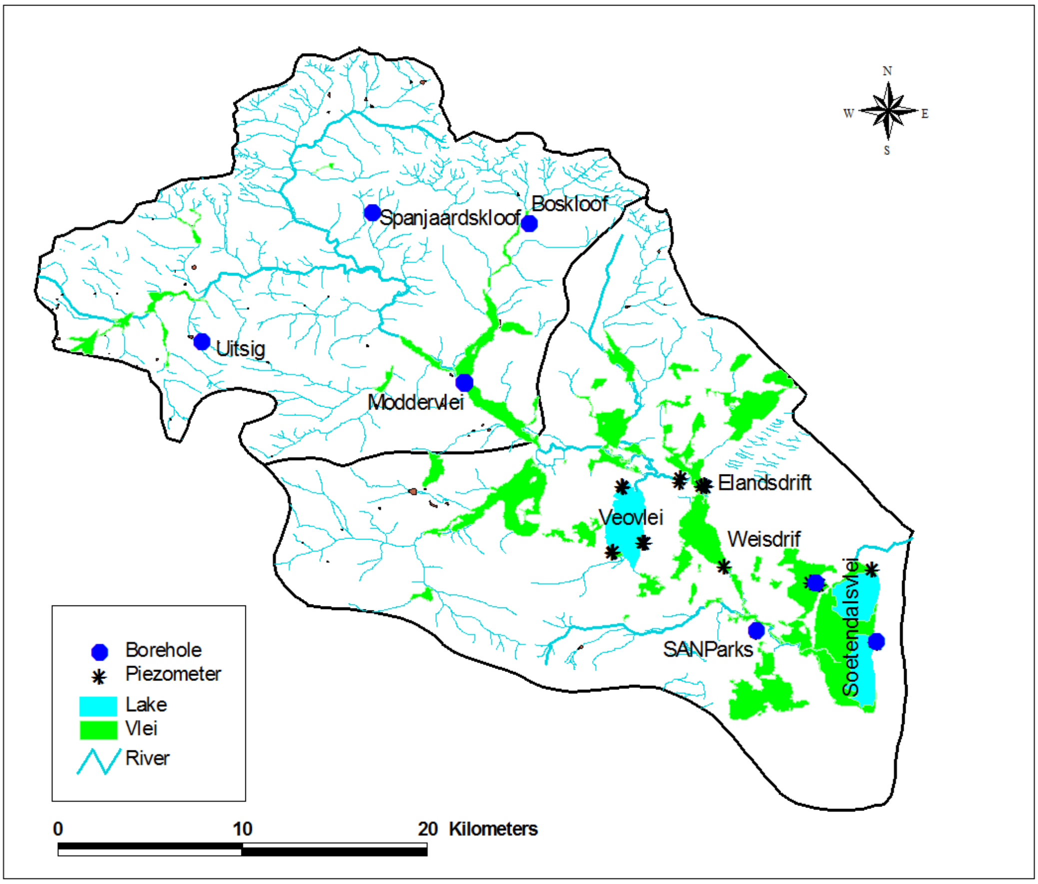


Figure 4.6: Locations of monitoring boreholes and piezometers developed in the Nuwejaars Catchment

Fine sand was encountered during the drilling of boreholes and piezometers around Soetendalsvlei (Figure 4.7). Sandy clay was dominant up to 10 m for borehole and piezometer drilling to the west of Soetendalsvlei at the SANParks Bosheuwel Training Centre. Clay sand and sandy clay were encountered in the Nuwejaars River floodplain between Elandsdrift and Weisdrif.

The depth to the water table for piezometers and boreholes around Soetendalsvlei was 2.2–3.8 m. The water table depth was at 0.5 to 4.4 m around Voëlvlei. For piezometers in the Nuwejaars River floodplain between Elandsdrift and Weisdri, the depth to the water table was 0.9 to 2.4 m. This part of the Nuwejaars Catchment is therefore characterised by shallow water tables, as is expected within wetlands.

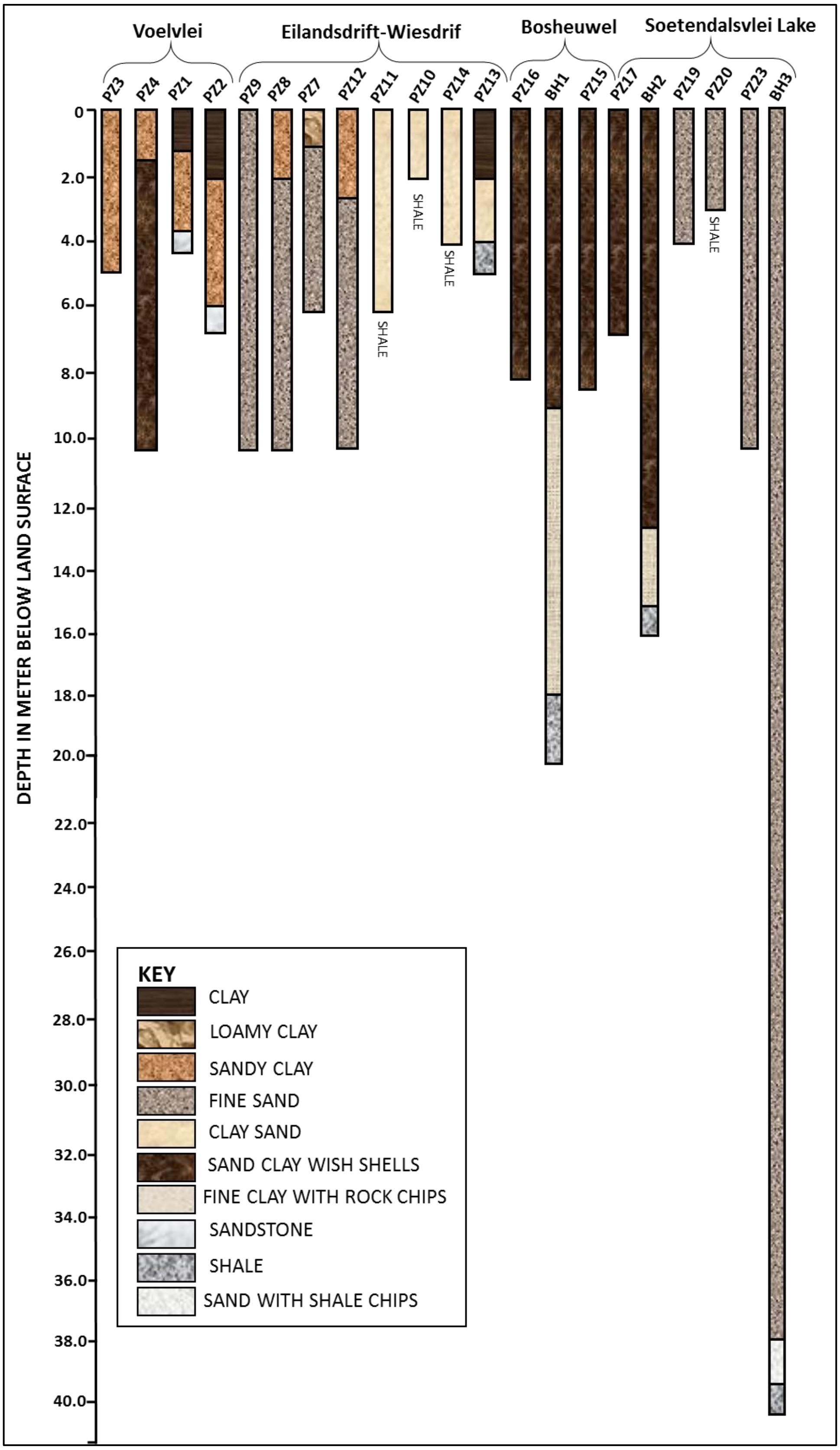


Figure 4.7: Materials encountered during drilling of boreholes and piezometers in the lower part of the Nuwejaars Catchment

The second stage of developing a groundwater monitoring system took place in 2017. Eleven monitoring boreholes were developed in the upper part (G50B) of the Nuwejaars Catchment, at the following locations:

- 2 boreholes at Spanjaardskloof
- 2 boreholes in the Bloskloof plantation
- 2 boreholes at Uitsig Farm
- 5 boreholes and 3 piezometers in the Nuwejaars River floodplain at Zoetendals, also referred to as Moddervlei.

The typical construction of monitoring boreholes is illustrated in Figure 4.8.

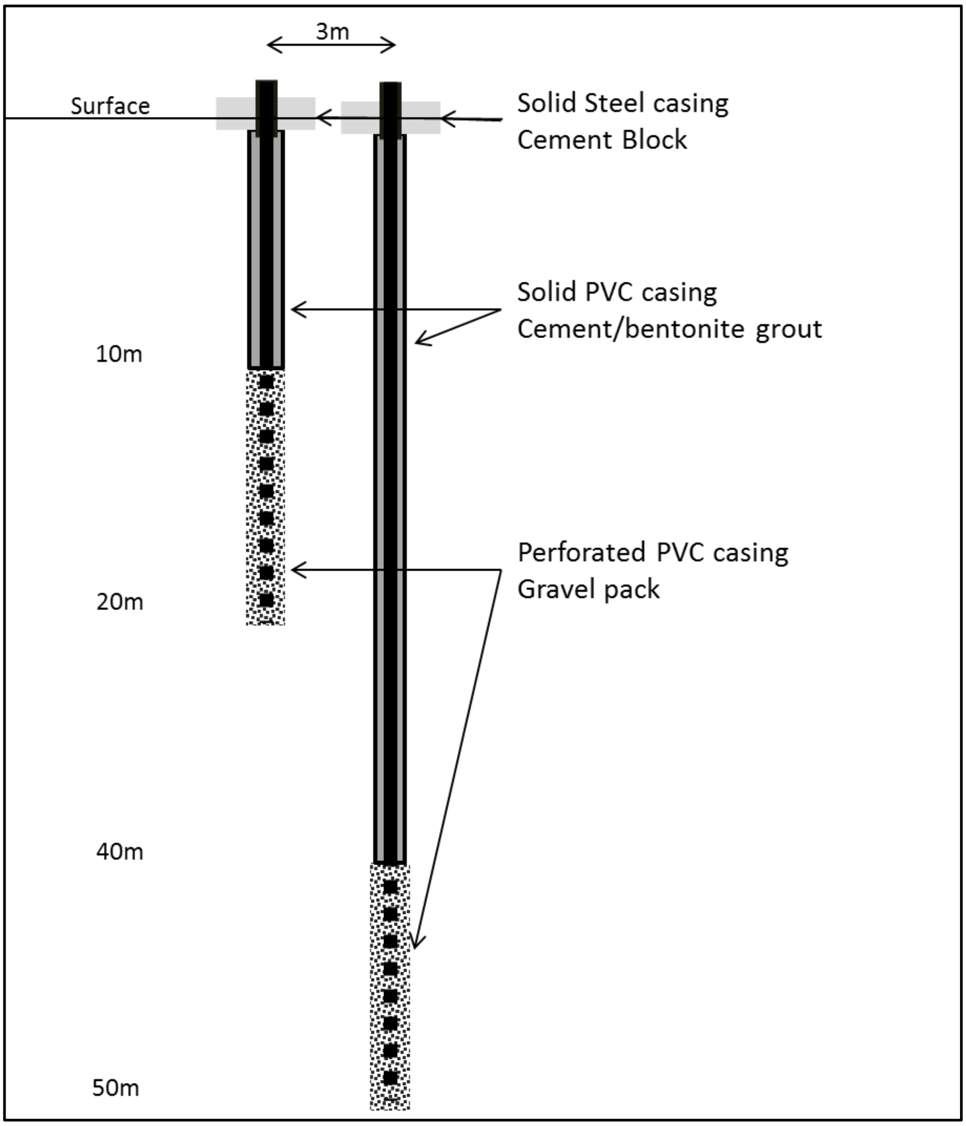


Figure 4.8: Typical borehole construction to characterise both shallow and deeper aquifer characteristics

For the boreholes located in the Nuwejaars River floodplain at Zoetendal, sand was generally encountered from about 1 to 10 m (Figure 4.9). Sand, sandstone pebbles, and sandstone and shale were encountered in two boreholes, from about 7 to 12 m. Shale occurred at all the boreholes from 15 to 60 m. The depth to the water table was 2.4–2.9 m for all boreholes, with the exception of the 8 m borehole for which this was 5.16 m.

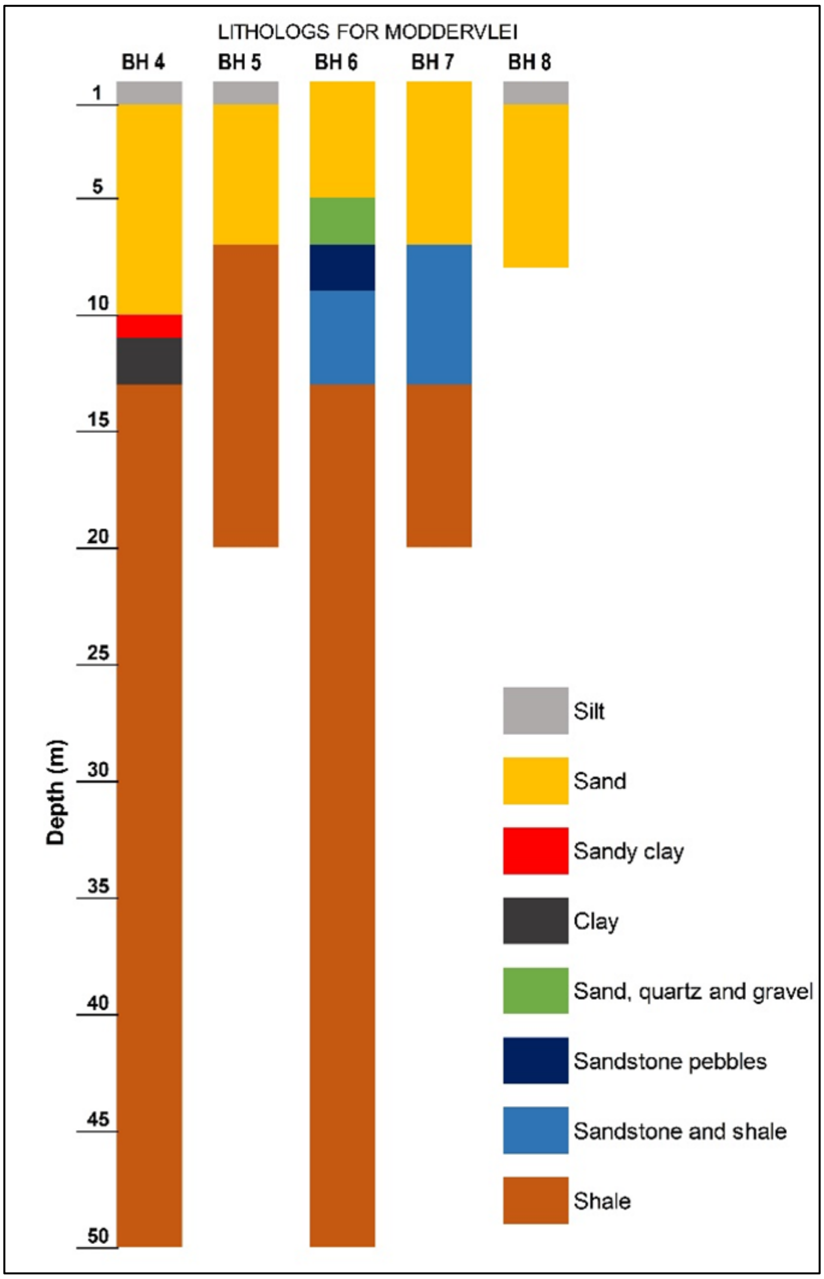


Figure 4.9: The different lithology encountered during the drilling of boreholes and piezometers within the Nuwejaars River floodplain at Zoetendal

Table 4.1 provides additional details about the locations, drilling and casing depths of the monitoring boreholes developed in 2017.

Table 4.1: Locations, drilling and casing depths of groundwater monitoring boreholes developed on the upper part of the Nuwejaars Catchment on 2017.11.03

Site name	Latitude, S	Longitude, E	Elevation (m)	Borehole depth (m)	Collar height (m)	Screen length (m)	Length of metal casing (m)	Water level (m)
BH 4	34.60535	19.79761	21	50	0,9	11.2	9.5	2.9
BH 5	34.60535	19.79758	22	20	0,95	11.2	8	5.16
BH 6	34.60561	19.79758	21	50	1,01	11.2	8	2.45
BH 7	34.60561	19.79753	21	20	0,97	8.4	8	2.42
BH 8	34.60531	19.79741	21	8	1,02	5.6	8	2.61
BH 9	34.52958	19.75255	149	60	1	11.2	0.3	5.53
BH 10	34.52961	19.75252	149	20	1	11.2	1	6.38
BH 11	34.53489	19.82909	135	60	1	14	5.7	10.64
BH12	34.53485	19.82910	134	20	1	11.2	5.6	10.49
BH 13	34.58694	19.66944	157	55	1	16.8	8m for 10" and 31m for 6½"	3.12
BH 14	34.58694	19.66944	157	20	1	11.2	4	3.16

4.3 Groundwater response to rainfall events in 2017

Water levels for the different piezometer nests through the catchment show different responses to rainfall (Figure 4.10).

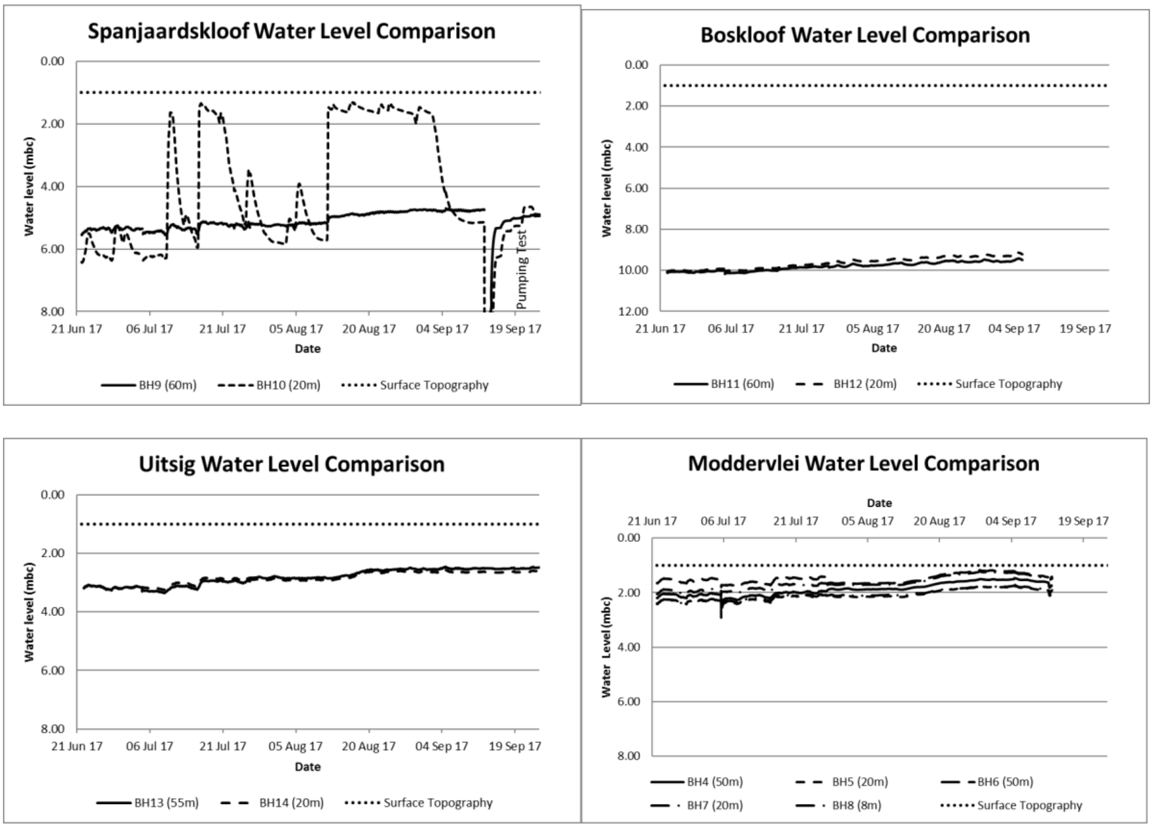


Figure 4.10: Changes in water table depths during the June to September 2017 period for boreholes developed on the upper part of the Nuwejaars River

At the Spanjaardskloof site, which is on a hillslope in the upper catchment (Figure 4.6), there was active recharge of the shallow aquifer after the occurrence of rainfall (Figure 4.10). This water is available to shallow plant root systems, draining from the shallow aquifer over a period of a few days. The deep aquifer had a slower response to rainfall, showing an increase in water level probably due to leakage from the shallow aquifer into the deeper aquifer (Figure 4.10).

The Boskloof boreholes (Figure 4.6) were drilled close to a fault. About 25 m of weathering was encountered during drilling. There was a slightly higher water level in the upper aquifer (Figure 4.10) which suggests the occurrence of local recharge processes and a downward recharge flux into the deeper aquifer system.

The boreholes at Uitsig (Figure 4.6) are in an area with springs. The water table is higher in the deeper borehole (Figure 4.10) which suggests the existence of a regional groundwater flow system, with the deep aquifer feeding the shallow aquifer from below.

The Moddervlei boreholes (Figure 4.6) were drilled close to the Nuwejaars River. Groundwater had a delayed response to rainfall and a significant slow response to rainfall late in the season

(Figure 4.10). The shallow and deep boreholes have slight differences in depth to the water table but similar response to rainfall. The water table was within 1 m from the surface under dry conditions, and rose close to the surface during wet periods.

4.4 Groundwater specific conductance

The specific conductance (SC) of groundwater generally increases from the upper catchment to the middle and lower catchment (Figure 4.11). The SC in the upper catchment (Spanjaardskloof, Boskloof, Uitsig) is very low and corresponds to the expected water quality for the TMG aquifers in the upper catchment. The low SC also suggests efficient rainfall infiltration and groundwater recharge mechanisms.

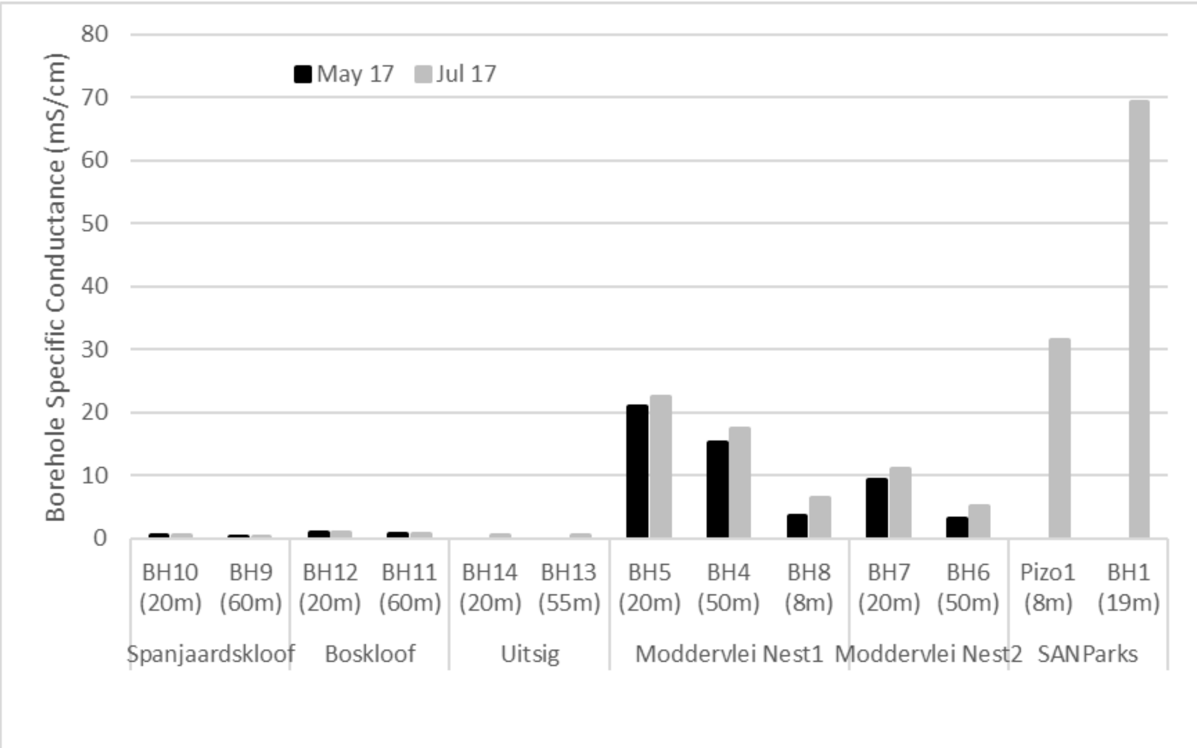


Figure 4.11: Spatial variation of specific conductance in monitoring boreholes within the Nuwejaars Catchment

Groundwater at the Moddervlei site has significantly more salts in the water than in the upper part of the catchment at Spanjaardskoof, Boskloof, and Uitsig (Figure 4.11). The differences in specific conductance observed in different boreholes at the Moddervlei site indicate that these boreholes are intersecting different parts of the layered sand, clay and bedrock system. The shallow 20 m bedrock boreholes have more salts than their associated 50 m piezometers (Figure 4.11). This can be a result of salts being released from the weathered shale aquifer (Figure 4.9), but very few salts from the deeper fractured aquifer. The thick clay layer intersected in borehole BH4 (Figure 4.9) is likely to limit any rainfall recharge. Recharge from rainfall is likely to occur in a sandy area that is a few hundred metres away, and from the river bed. Rainfall recharge is possible on the margins of the floodplain that are in contact with the shale hills. The relatively high salt content at the Moddervlei site is therefore a product of the geology, weathering of the rock and reduced rainfall infiltration.

Very high salinity was observed in boreholes at the SANParks Bosheuwel Training Centre (Figure 4.11). These boreholes are located 1 km from Soutpan which is to the south-west, and 0.5 km from the Nuwejaars River occurring on both the northern and eastern parts. Groundwater quality in this area is expected to be influenced by evaporative processes from the nearby wetlands with almost no groundwater through-flow. The shallow aquifer had a lower salinity than the deep aquifer (Figure 4.11). Some periodic freshening of the shallow aquifer can be expected from surface water inflow from the upper catchment.

4.5 Groundwater temperature

The variation of groundwater temperature with depth provides an indication of how regional and local flow processes and recharge influence different parts of the aquifer. Local surface recharge of cold winter rain is expected to cause cooling of groundwater. Deep regional flow on the other hand can cause an increase in temperature. The flow of water through the aquifer due to hydraulic pressure differences can cause local cooling due to the increased flow rate.

In general, an increase in temperature from the upper catchment to the lowland areas was observed (Figure 4.12). This corresponds to possible higher recharge rates and cooling of the groundwater in the upper catchment, and higher temperatures in the lowlands due to reduced recharge resulting in the higher salinities.

There were minor temperature differences between shallow and deep piezometer nests in the upland areas, i.e. Spanjaardskloof, Boskloof, and Uitsig (Figure 4.12). This can be interpreted as being due to downward flow in the aquifer due to infiltration and recharge processes leading to a reducing temperature gradient.

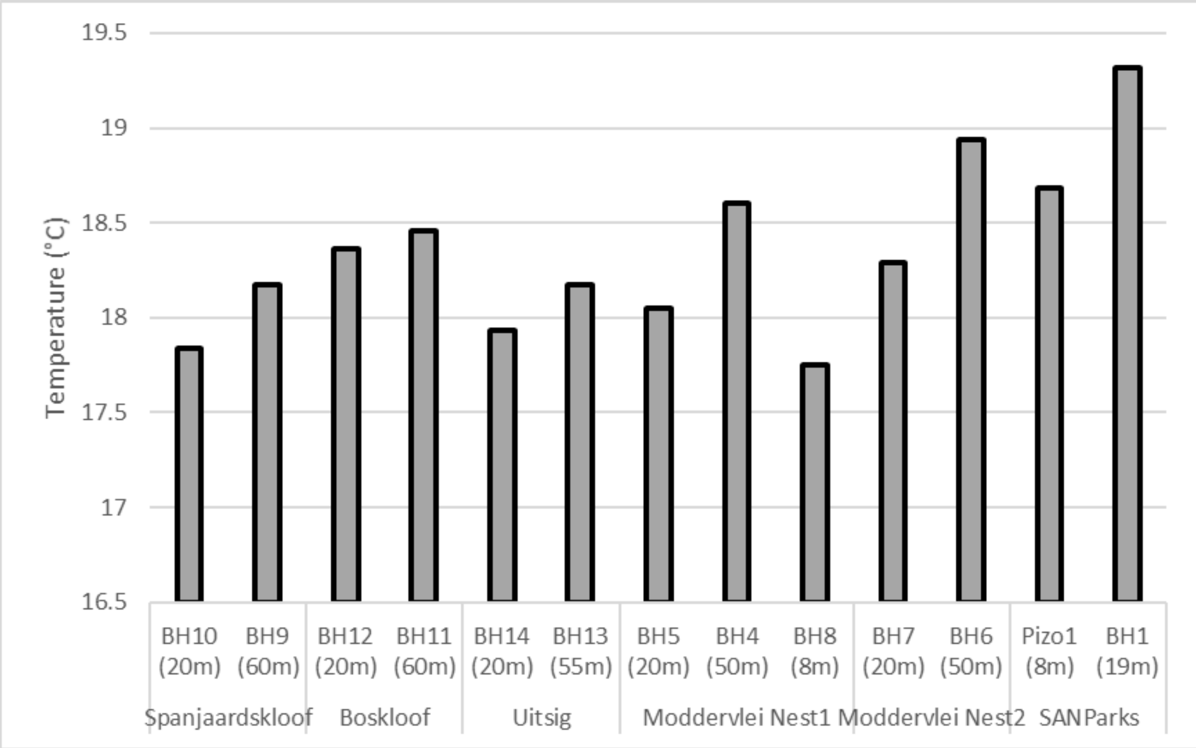


Figure 4.12: Groundwater temperature variations across the catchment, and with depth, at sites with monitoring boreholes.

4.6 Groundwater flow in catchment

Water tables were between 1 and 2 m below the surface in monitoring boreholes located in the upper catchment, with the exception of Boskloof where the depth was 8 m. Groundwater in the uplands contributes to spring flow throughout the year. Interflow causes the water table to rise close to the surface resulting in groundwater discharge to the surface water flow systems.

The shallow water tables are believed to be well within reach of root systems. Even at Boskloof, with an 8 m deep water table, the Eucalyptus trees occurring at this site should have easy access to the groundwater. The dense invasive trees in the upper catchment have access to groundwater and cause a significant reduction of spring flow and interflow. This decreases water flowing downstream to the rest of the catchment.

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 are in hydraulic connection with the rivers and therefore water tables will respond to changes in river flows. Groundwater flow direction between the aquifer and the river will change throughout the season depending on the hydraulic gradient at the time. The valley fill primary aquifer storage and releases will influence surface water flow systems due to the temporary storage and releases during and after rainfall events.

The dense invasive trees seem to occur along the sandy sections of the valley fill aquifers. The groundwater levels are within reach of their root systems at about 2 m below surface. These sandy areas seem to be associated with lower salinity groundwater, with the clay areas containing significantly higher salinity. The invasive trees do not seem to grow to the same extent and density in the clay and saline sections of the valley fill primary aquifer. The trees occurring on part of the aquifer with low salinity will reduce fresh water and also indirectly cause salinisation of the downstream flow in the river.

The regional faults seem to influence the main flow paths and direction in the catchment. Lithological changes are associated with most of these faults, providing some preferential flow along the faults. Very low hydraulic conductivity in the Malmesbury and Bokkeveld shale, and low flow gradients near sea level prevent any significant flow through the blocks between faults.

5. THE CONTRIBUTION OF SUB-CATCHMENTS TO RIVER FLOWS

5.1 Development of a river flow monitoring system

This chapter describes the development of a river flow monitoring system for a previously ungauged Nuwejaars Catchment. Information about river flows is required for the achievement of all the research aims. The chapter also examines the contribution of sub-catchments to river flows and effects of floodplain wetlands on these flows, which are the first and third aims of the study.

The main tributaries of the Nuwejaars River are the Koue River, which drains uplands located on the Koue Mountains, and the Jan Swartskraal and Pieterseiskloof rivers with headwaters in the Bredasdorp Mountains. These tributaries have their confluences with the Nuwejaars River in the transition zone from the uplands to the lowland. Flow measuring stations in this transition zone enable an assessment of the contribution of the uplands to the Nuwejaars River flows. The Bloomkraal and Voëlvlei rivers drain the middle and western part of the Nuwejaars Catchment.

The following World Meteorological Organization guidelines for selecting sites for river flow measuring stations were used (WMO, 2010):

- A channel cross-section with regular profile, stable bed and banks to enable derivation of an accurate and reliable stage–discharge relationship.
- Straight channel without curvilinear streamlines.
- Free of aquatic weeds that interfere with velocity measurements using a current meter.
- All the flowing water should be contained in a single channel at all stages.
- Land owner willing to allow regular access to the site.

The heavy infestation of invasive alien woody plants along channels, particularly in the transition zone from uplands to lowlands, presented a problem in selecting sites for river flow measurement. The lowlands have very low gradient with meandering channels, splitting of the main channel, and numerous off-channel pools along floodplains. Due to these constraints, the selection of sites was restricted to bridges that provided artificial control sections.

The study established the following 17 river flow and lake level measuring stations (Figure 5.1; Table 5.1):

- 10 sites on the Nuwejaars River and its tributaries
- 3 sites on the Kars River and its tributary
- 2 sites on the Heuningnes River downstream of Soetendalsvlei
- 2 lake level sites in Soetendalsvlei

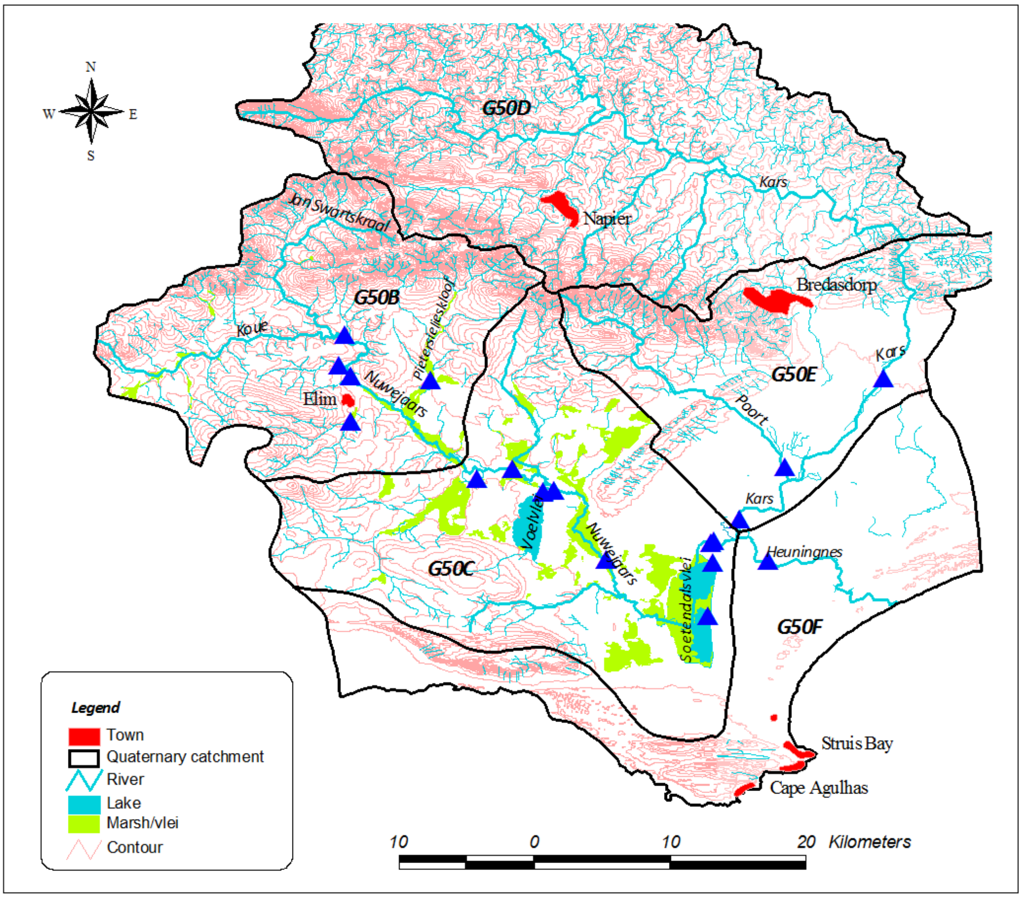


Figure 5.1: Locations of river flow and lake level monitoring stations established in the Heuningnes Catchment, shown as triangles

Most of the stations have been equipped with HOBO and OTT water level data loggers (Table 5.1). The data loggers are recording water levels at an hourly interval. The Department of Water and Sanitation in the Western Cape Province assisted by installing gauge plates on nine stations. Water level data loggers have been installed in stilling wells made of a PVC pipe with a 75 mm diameter and fixed to a bridge pier. The PVC pipe is closed at the top by a cap which is kept in place by a 14 mm bolt and nut.

(a) Stilling well (blue PVC) with data logger in the Voëlvlei River at the Elim-Struis Bay road bridge

(b) Nuwejaars River at Elandsdrift flow measuring station, and, on the right, Daniel Mehl (MSc student) retrieving a data logger from the blue PVC which acts as a stilling well.

Figure 5.2: Typical flow measuring stations established in the Nuwejaars Catchment

Table 5.1: Locations and details of river flow monitoring stations established by the project

River	Location	GPS Coordinates	Altitude (m)	Data Logger	Gauge Plate	Start Date
Jan Swartskraal River	Elim-Spanjaardskloof Road Bridge	34.554017° S, 19.753187° E	48	HOBO Water Level Data Logger	No	5/5/2016
Upper Nuwejaars Tributary	Elim Waste Water Treatment	34.572228° S, 19.749723° E	41	OTT Orpheus Mini Water Level Logger	No	27/4/2016
Nuwejaars River	Bridge at the Elim Melkery	34.578672° S, 19.757813° E	34	HOBO Water Level Data Logger	Yes	13/5/2016
Nuwejaars Tributary at Elim	Elim Flow Diversion Point	34.605981° S, 19.757341° E	49	HOBO Water Level Data Logger	Yes	27/4/2016
Pietersielieskloof River	Farm 299	34.581193° S, 19.810442° E	43	OTT Orpheus Mini Water Level Logger	No	27/4/2016
Blomkraals	Elim-Bredasdorp R43 Road Bridge	34.639819° S, 19.841316° E	15	HOBO Water Level Data Logger	No	27/4/2016
Nuwejaars	Elim-Bredasdorp R43 Road Bridge	34.633695° S 19.864833° E	16	Staff Gauge	Yes	

River	Location	GPS Coordinates	Altitude (m)	Data Logger	Gauge Plate	Start Date
Voëlvlei	Elim-Struis Bay Road Bridge	34.647549° S, 19.885179° E	10	HOBO Water Level Data Logger	Yes	27/4/2016
Nuwejaars River	Elandsdrift	34.646425° S, 19.891785° E	10	HOBO Water Level Data Logger	Yes	17/10/2014
Nuwejaars River	Wiesdrif	34.687441° S, 19.926537° E	9	HOBO Water Level Data Logger	No	24/10/2014
Heuningnes River	Vissersdrift	34.677811° S, 19.995915° E	7	Solinst Water Level Data Logger	Yes	17/10/2014
Heuningnes River	Elim-Struis Bay R319 Road Bridge	34.688656° E20.033207° S	7	Staff Gauge	Yes	
Kars	Nacht Wacht Farm Weir	34.538257° S, 20.126575° E	30	OTT Orpheus Mini Water Level Logger	Yes	28/8/2016
Poort	Klein Heuwels Farm	34.638040° S, 20.046893° E	9	OTT Orpheus Mini Water Level Logger	No	5/5/2016
Kars	Zeekoevlei Farm	34.664033° S, 20.014726° E	8	OTT Orpheus Mini Water Level Logger	None	27/4/2016
Soetendalvlei	Langrug Lodge in Vissersdrift Farm	34.719452° E19.996328° S	6	OTT Orpheus Mini Water Level Logger	Yes	3 March 2015

River	Location	GPS Coordinates	Altitude (m)	Data Logger	Gauge Plate	Start Date
Soetendalvlei	Vissersdrift Farm Homestead	34.689839° E19.997228° S	6	OTT Orpheus Mini Water Level logger	Yes	9 May 2015

5.2 Development of stage-discharge relationships

Between 2014 and 2016, 95 discharge measurements have been taken at the gauging stations established in the Heuningnes Catchment (Table 5.2).

Table 5.2: Number of current meter river discharge measurements made in the Heuningnes Catchment during the 2014 to 2016 period

River	Location	No. of Discharge Measurements
Jan Swartskraal	Elim-Spanjaardskloof road bridge	4
Koue Tributary	Waste water treatment plant	4
Nuwejaars	Melkery Bridge	7
Pietersielieskloof	Pietersielieskloof	5
Right Tributary of Nuwejaars at Elim	Elim flow diversion	8
Bloomkraal	Elim-Bredasdorp R43 road bridge	4
Voëlvlei	Elim-Struis Bay road bridge	13
Nuweajaars	Elandsdrift	16
Nuwejaars	Wiesdrif	16
Heuningnes	Vissersdrift	10
Poort		5
Kars	Zeekoevlei	3
Total		95

Figure 5.3: One of the MSc students, Daniel Mehl, doing discharge measurements using an OTT MF pro electromagnetic current meter in the Pietersielieskloof River in 2016.

The Voëlvlei station (Figure 5.2a) is problematic because the direction of flow reverses, depending on the difference in water level between the Voëlvlei River and the downstream

Nuwejaars River. The station of the Nuwejaars River at Elandsdrift is located on a bridge with two rectangular channels, each 2.45 m wide and about 2.0 m high (Figure 5.2b). The base is lined in concrete and therefore a stable stage-discharge relationship can be established (Figure 5.5). The station at Weisdrif is located at a bridge with ten rectangular culverts, each being 1.20 m wide. However, some of the culverts on the right bank are prone to being blocked by the deposition of sediment and subsequent growth of grass. The tentative stage–discharge (Q-H) relationships presented in Figure 5.4 should not be extrapolated beyond stages that were measured, especially when an exponential relationship has been used. Beyond the stage values used to derive the Q-H relationship, an exponential equation rapidly gives unrealistic discharge values.

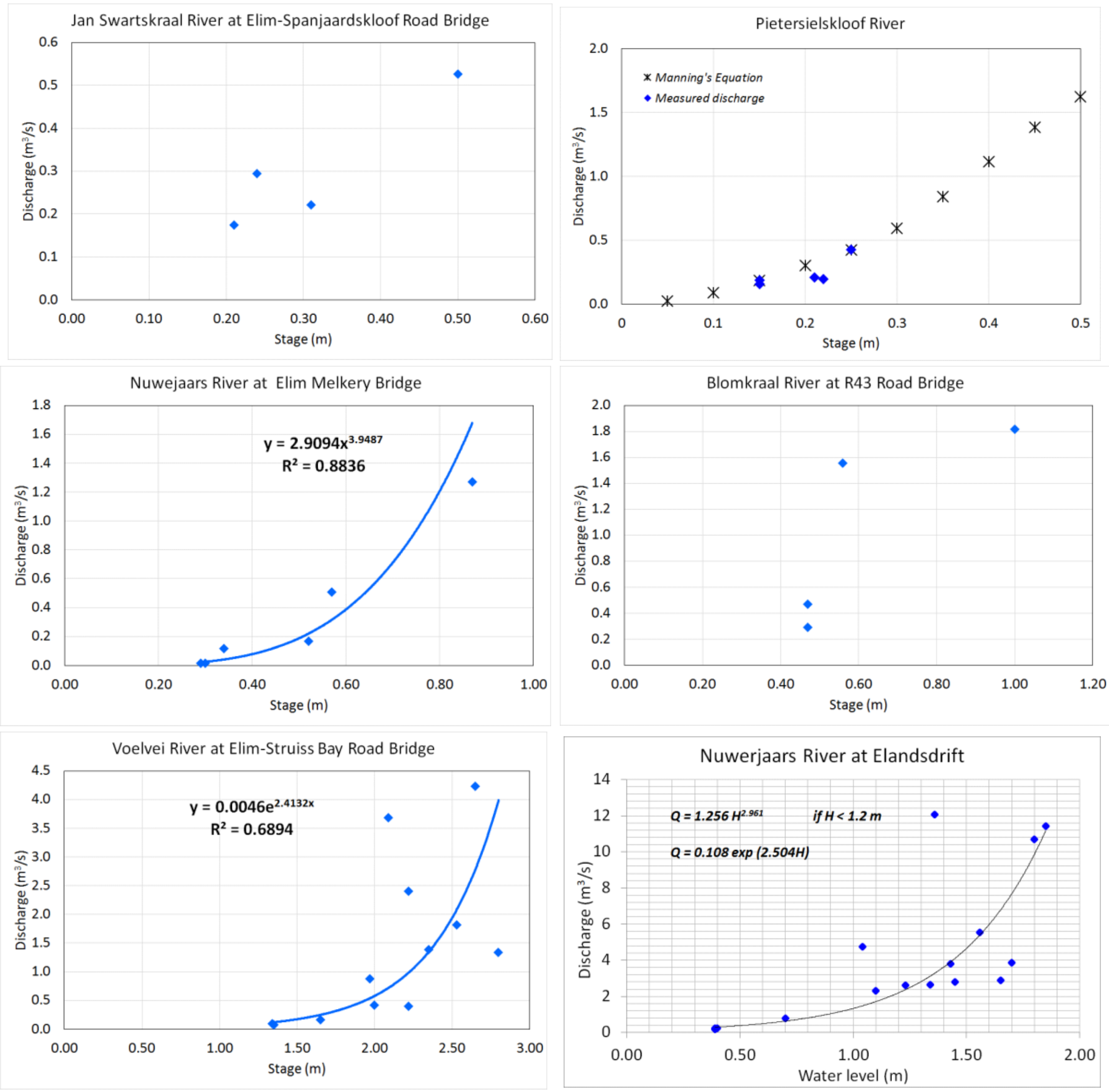


Figure 5.4: The relationship between stage and discharge established from flow measurements taken during 2015 and 2016 in the Nuwejaars Catchment

The are few discharge measurements made on the Jan Swartskraal River (Figure 5.4). The following rating equation with a low level of confidence in its accuracy was derived using these measurements:

$$Q = 1.096H \quad (5.1)$$

where Q = discharge in m^3/s, and H is the stage in metres. The rating curve for Pietersielieskoof was derived using the Manning's equation. The channel cross-section was surveyed. The Manning roughness coefficient which gave discharges that fitted the measured discharges was n = 0.025. The following rating curve for Pietersielskloof which best fitted flows estimated by the Manning's equation was derived

$$Q = 6.900H^{1.924} \quad (5.2)$$

The followiing rating equation was derived for the Bloomkraal River station:

$$Q = 0.16H + 1.86H^2 \quad (5.3)$$

The station on the Kars River at Nacht Wacht Farm comprises a weir which is 40 m long with a crest width of 0.25 m. It has been assumed that the relationship between stage and discharge for this weir can be approximated by the following broad-crested weir equation (Bos, 1976):

$$Q = C_d C_v \frac{2}{3}\left(\frac{2}{3}g\right)^{0.5} bH^{1.5} \quad (5.4)$$

where Q = discharge in m^3/s, C_d = 1.1 is the correction coefficient, C_d = 0.848 discharge coefficient, g = acceleration due to gravity, b = 40 m, breadth of the weir with a crest thickness of 0.25 m, H = stage in metres.

The rating curves derived for stations on the Poort River and Kars River are given in Figure 5.5.

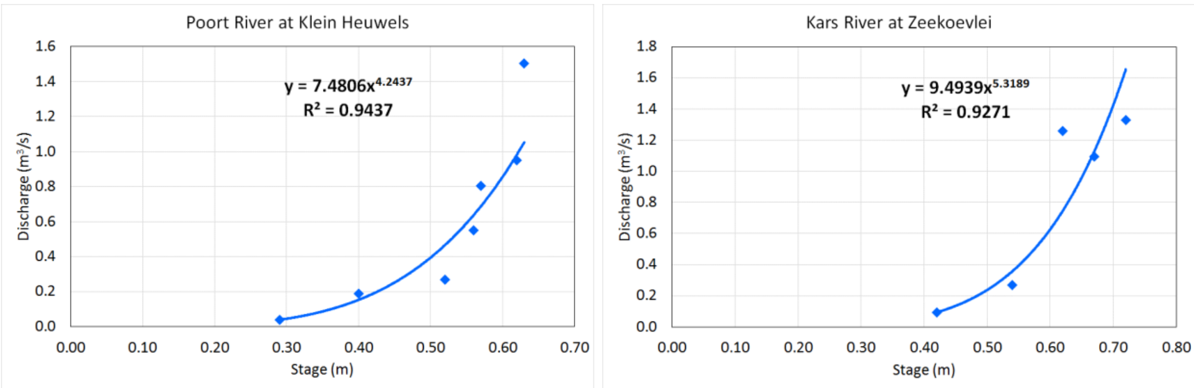


Figure 5.5: Relationship between stage and discharge based on discharge measurements at stations in the Kars River Catchment

5.3 Measured water levels

Water level data has been collected at most stations for periods of about 1.5 to 2.5 years (Table 5.3). Stations for Soetendalsvlei lake levels have the longest data.

Table 5.3: Record length of water levels recorded at one hourly intervals at the river gauging stations in the Heuningnes Catchment

Station	Record Length (days)
Nuwejaars @ Elandsdrift	684
Voëlvlei	411
Bloomkraal	410
Jan Swartskraal	418
Nuwejaars @ Elim Melkery	365
Elim flow diversion	406
Pieterseilieskloof	192
Kars @ Nacht Wacht	496
Poort River	489
Kars River @ Zeekoevlei	244
Soetendalsvlei @ Langrug Lodge	909
Soetendalsvlei @ Vissersdrift	851
Total	5875

The Elandsdrift station on the Nuwejaars River has the longest recorded water level data, starting in August 2014. Most of the stations on the tributaries of the Nuwejaars River have data starting in April 2016 (Figure 5.6). On almost all the stations, data loggers had to be removed in December in order to prevent them being vandalised as they would be visible when rivers dried up.

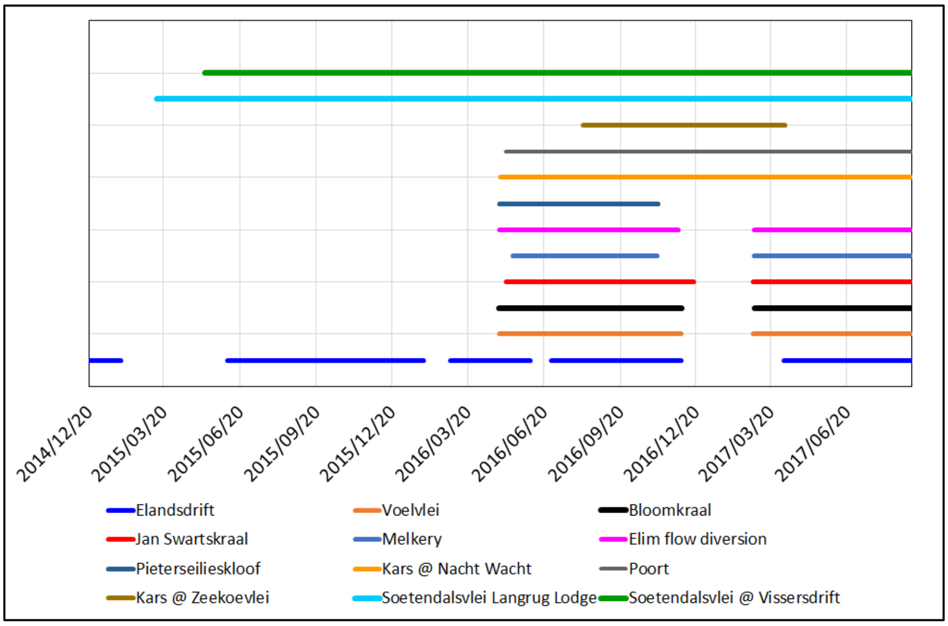


Figure 5.6: Period with water level data at stations in the Heuningnes River Catchment

5.4 Catchment response to rainfall events

A comparison of the responses of the main tributaries to rainfall events is possible in 2016 when flow data are available for all these rivers. During the start of the wet season, from May to July 2016, when soils and channels were dry, none of the tributaries had a significant response to rainfall events until cumulative rainfall was greater than 50 mm, in July 2016 (Figure 5.7 and 5.8). Significant increases in flows occurred when cumulative rainfall had increased from 52 to 130 mm during the 24–25 July 2016 period. All the tributaries draining the upland area with relatively steep slopes had similar shapes of the rising and falling limbs of the hydrographs as a response to this rainfall event. Temporal variations of flows draining from the Voelvlei Lake were similar to those of flows of the Nuwejaars River floodplain upstream of Elandsdrift.

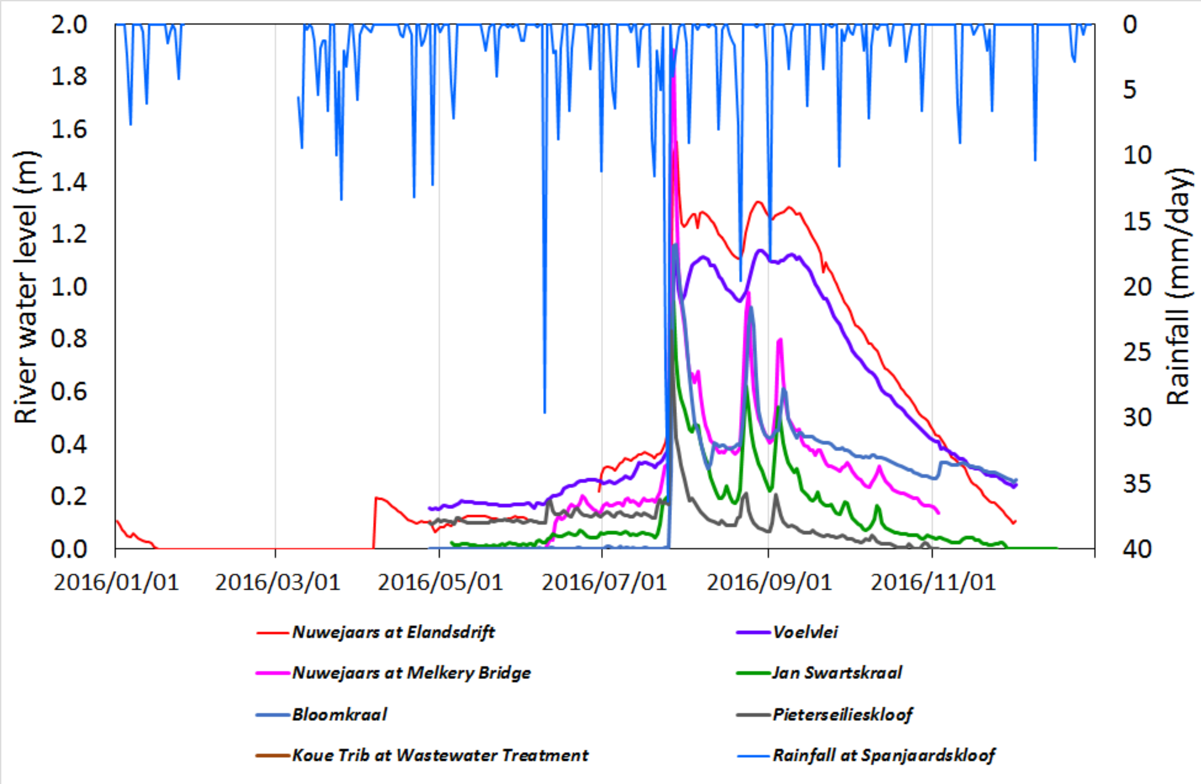


Figure 5.7: Daily water levels of the Nuwejaars Rivers and its tributaries during 2016. The red line is the daily rainfall at Spanjaardskloof.

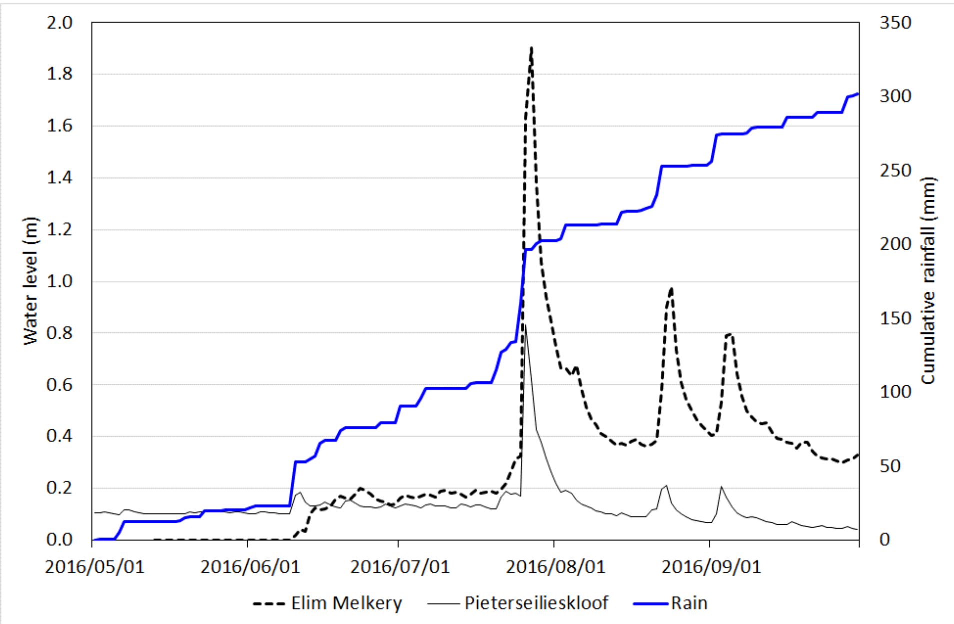


Figure 5.8 Comparison of cumulative daily rainfall at Spanjaardskloof and river water levels of the Nuwejaars River at Elim Melkery and Pietersieliekloof during the 1 May–30 September 2016 period

The 2015–2016 flows of the Nuwejaars River at Elandsdrift do again show that no major changes in river flow occur when rainfall of less than 15 mm/day is received (Figure 5.9). Rainfall events greater than 20 mm/day do cause significant increases in peak flows. Such rainfall events only occurred two to five times during the wet season. River flows started to decline in September, and by December, in both 2015 and 2016, the Nuwejaars River had dried up. This proves that the Nuwejaars River is non-perennial.

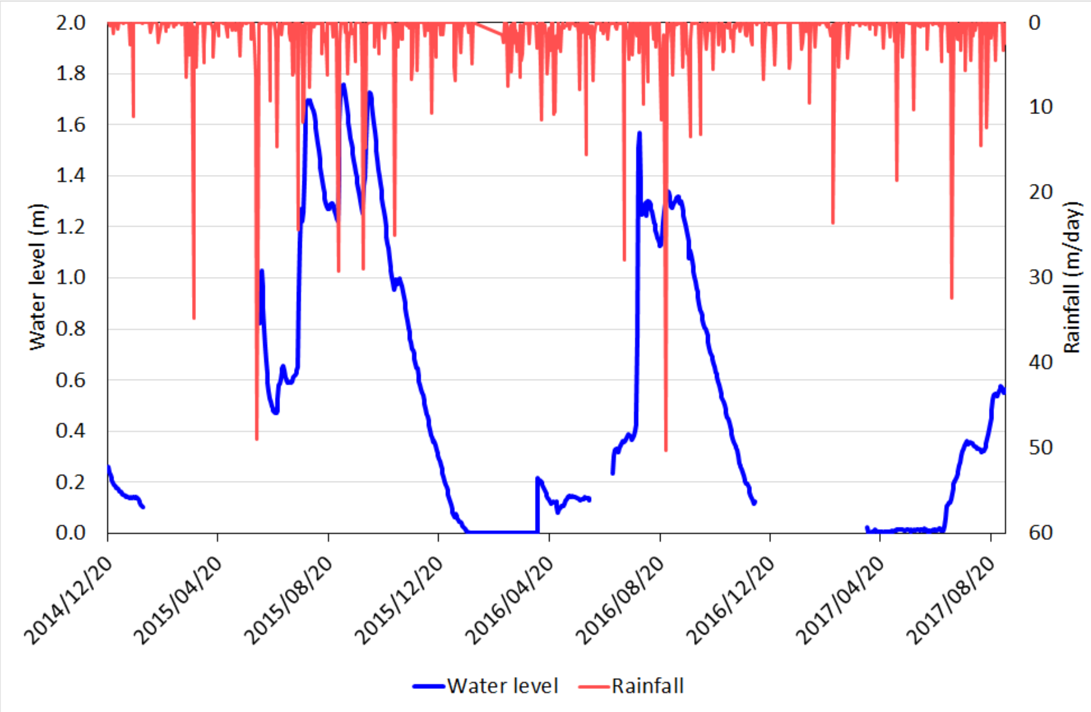


Figure 5.9: Temporal variations of water levels of the Nuwejaars River at Elandsdrift. The blue line shows water levels, while the red line represents the catchment rainfall. The gap in the record from the end of 2016 to early 2017 was due to the logger being removed as the river was dry.

5.5 The influence of the floodplain wetland on the flow of the Nuwejaars River

Floodplain wetlands occur along the Nuwejaars River and its tributaries located in the lowland region. Such wetlands are generally assumed to reduce peak flows, increase flow travel times, and sustain dry season flows. Since the Nuwejaars Catchment has been ungauged, the specific effects of the floodplain wetlands on river flows are not well understood. One of the major floodplain wetlands, which occurs along the Nuwejaars River from Elim up to the Soetendalsvlei, is commonly referred to as the Moddervlei. This floodplain attains widths of up to 600 m. The main channel meanders through this wetland with some pools that are not connected to the main channel. At some locations the main channel splits into distributaries. The top soil comprises loamy sand to sandy loam, and is underlain by sandy loam and silty loam. The depth to the water table was generally less than 5.0 m. During the wet season, the water table reaches the surface. Palmiet occurs along the main channel at some locations. The floodplain wetland has sedges and reeds.

The Moddervlei floodplain wetland is 12 km long. Inflows into the wetland, as measured on the Nuwejaars River at Elim Melkery Bridge, and outflows of the Nuwejaars River at Elandsdrift, over the period 1 May–30 November 2016, were compared. This period was selected as flow data are available for the major tributaries. The response of the wetland to the rainfall which occurred during the 25–29 July 2016 period is illustrated in Figure 5.10. This rainfall event occurred when previously there had not been any significant rainfall, and therefore the channels and pools had low water levels. Peak rainfall (12 mm/hr) at Spanjaarsdskoof occurred on 26 July 2017 at 01.00 hr. The peak water level (2.04 m) on the Nuwejaars River upstream of Elim Melkery occurred at 15.00 on 26 July 2016 (Figures 5.10 and 5.11). The highest flow (1.79 m) at the downstream Elandsdrift location on the Nuwejaars River occurred at 16.00 on 27 July 2016. This means that peak flows took 25 hours to travel the 12 km through the floodplain wetland. This shows that when the channels and pools have low water levels, if high inflows occur, there is considerable delay in the movement of the water through the floodplain wetland as is expected. The time delay is expected to reduce as the channels and pools are filled with water. Inundation of parts of the wetland not connected to the main channel is frequently observed. Water depths reach up to about 0.5 m on some parts. This inundation is caused by ponding of rain falling over the wetland, and not flow spilling from the main channel.

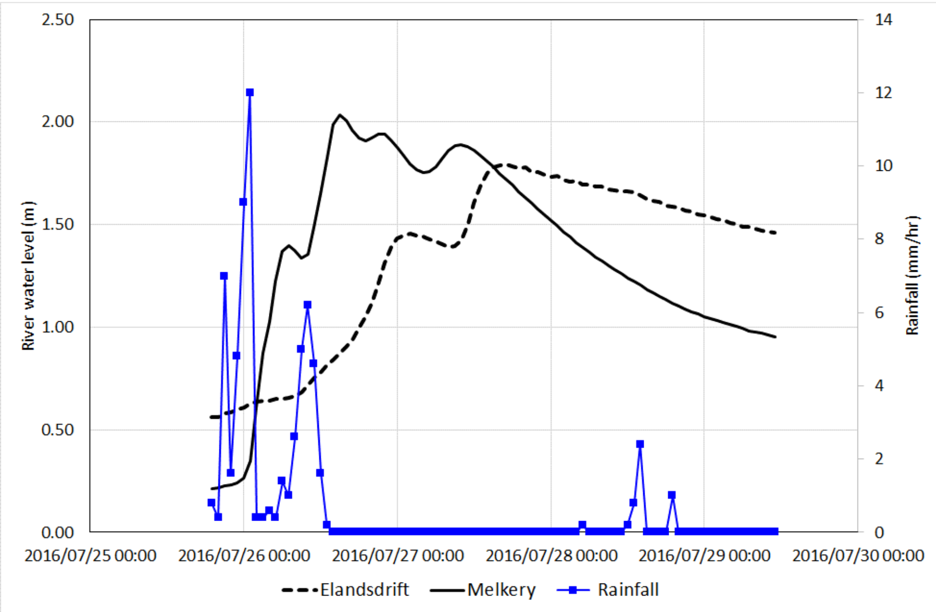


Figure 5.10: Response of the Nuwejaars River at Elim Melkery and Elandsdrift to a 25–26 July 2016 rainfall event

Figure 5.11: High water levels on the Nuwejaars River upstream, at the bridge immediately upstream of Elim

The inflows from tributaries ranged from 12–35 m^3/s, while downstream flows of the Nuwejaars River at Elandsdrift reached a peak of about 5 m^3/s. The floodplain wetland reduces peak flows as expected. A comparison of total daily inflows and outflows of the Moddervlei shows that during the 25–27 July 2016 period, about 5.8 Mm^3 were stored along the channels and pools in this wetland. Water stored in the wetland gradually drained resulting in outflows from the wetlands being generally greater than inflows from 1 August to 27 October 2016 (Figure 5.12).

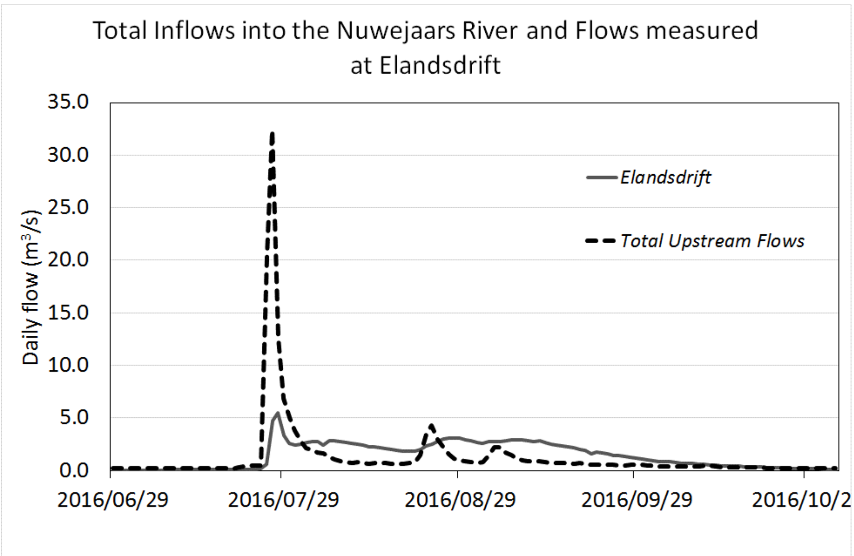


Figure 5.12: Daily flows of the tributaries of the Nuwejaars Rivers and flows of the same river measured at the downstream Elandsdrift station

5.6 Contributions of sub-catchments to the flow of the Nuwejaars River

The Nuwejaars River at Elandsdrift had the highest flow, being 8.8 m^3/s, in September 2015 (Figure 5.13). River flows started to decrease to less than 1.0 m^3/s by mid-November 2015. During 2016, daily flows reached a peak of 5.5 m^3/s in late July 2016 and decreased to less than 1.0 m^3/s by early October 2016.

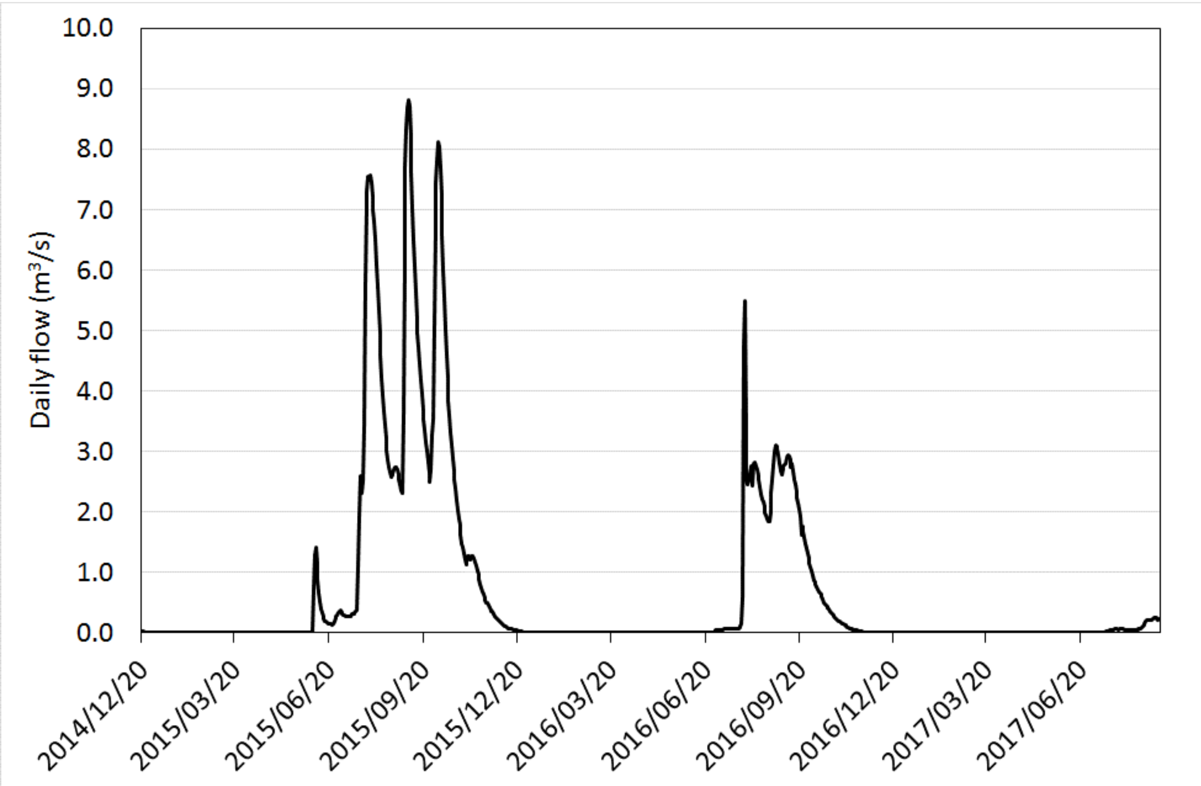


Figure 5.13: Daily flows of the Nuwejaars River at Elandsdrift

Catchments of the Koue (91 km^2), Jan Swartskraal (69 km^2), and Pietersielieskloof (73 km^2) rivers each contributed about 15–17% of the 2016 flow of the Nuwejaars River (Figure 5.14). The Bloomkraal Catchment, with an area of 104 km^2, contributed about 27% of the flow of the Nuwejaars River. Very little runoff is expected from the Moddervlei catchment due to the dominance of floodplain wetlands. Similarly, a considerable amount of flow from the Voëlvlei catchment (27 km^2) is stored in the Voëlvlei Lake which has a storage capacity of about 7 Mm^3 (Seaton, 2016).

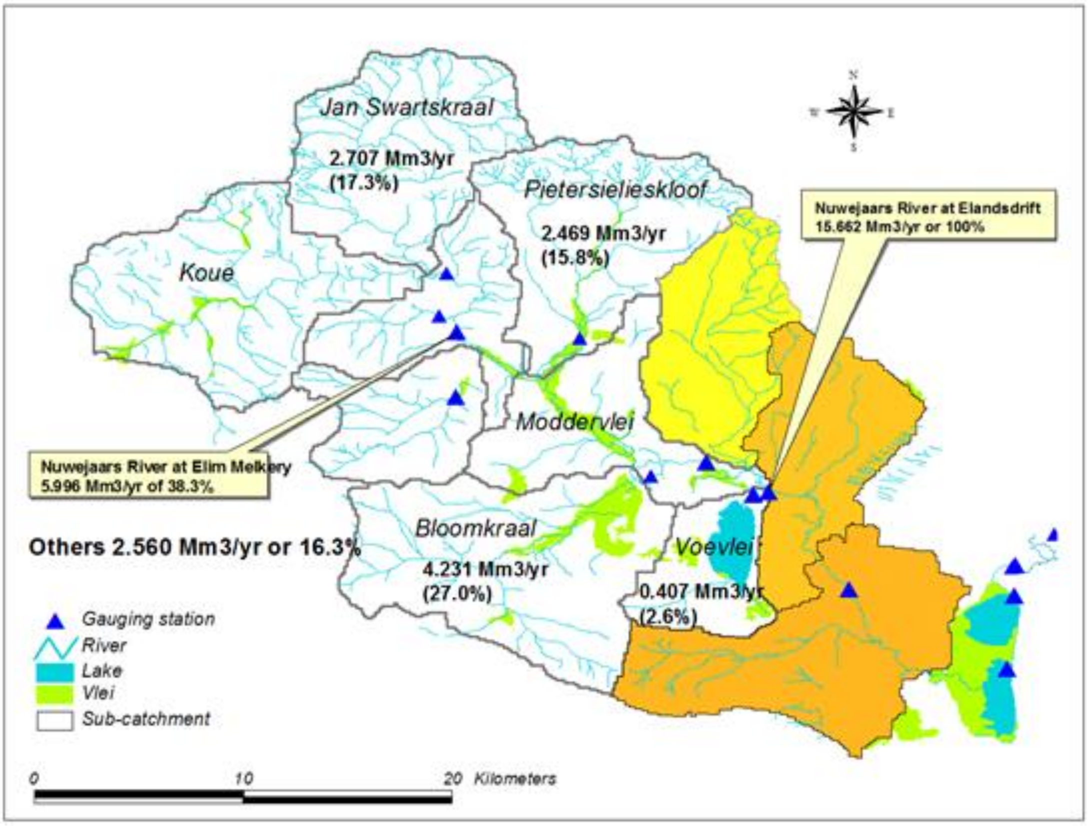


Figure 5.14: Contributions of the sub-catchments to the 2016 annual flow (15.662 Mm^3/yr) of the Nuwejaars River at Elandsdrift. Shaded sub-catchments drain downstream of this location. The Koue sub-catchment is not gauged and contributed about 3.0 Mm^3/yr. 'Others' refers to ungauged parts, such as the sub-catchment with the Elim flow diversion point, and Moddervlei.

During the July to November 2015 period, the total monthly flows were over two million cubic metres per month, with a peak of 12 million cubic metres per month in September 2015 (Figure 5.15). In contrast, during 2016, the highest monthly flow was about 6 million cubic metres.

The 2015 total annual flow was 43.885 Mm^3/yr, while the 2016 total annual flow was 15.662 Mm^3/yr (Table 5.4). The 2016 annual flow is almost of the same order of magnitude as the long-term mean annual runoff estimated by the WR2012 water resources assessment.

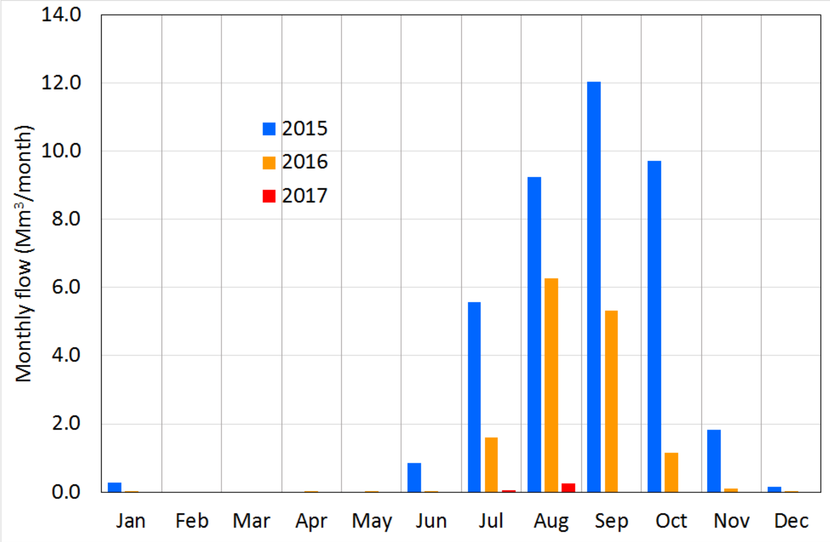


Figure 5.15: Monthly flows of the Nuwejaars River at Elandsdrift during 2015, 2016 and up to August 2017

Table 5.4: Annual runoff of the Nuwejaars River at Elandsdrift during 2015 and 2016

	Rainfall (mm/yr)	**Runoff (Mm^3/yr)**	**Runoff (mm/yr)**	**Runoff coefficient (%)**
2015	562	43.885	81	14
2016	499	15.662	29	6
WR2012 (G50B & G50C)	427	18.780	25	6

The runoff coefficient for 2015 was estimated to be 13% while this was 5% for 2016. The 2016 runoff coefficient is very similar to that obtained based on the WR2012 water resources assessment. The 1910–2016 rainfall data for Zeekoevlei, 5 km north-east of Soetendalsvlei, shows that 2015 received 130% of the long-term average rainfall, while 2016 received 90%. Since 2016 received rainfall just slightly below the long-term average, the runoff coefficient is also very close to that of WR2012, based on long-term simulated runoff. This study has confirmed that the mean annual runoff (MAR) estimated during the WR2012 assessment, using the Pitman model with regionalised model parameters, is realistic.

6 WATER QUALITY

6.1 Water quality monitoring system

One of the aims of this study was to establish the effects of land use on river flows and consequently inflows into the Soetendalsvlei. A water quality monitoring system was therefore developed to achieve this aim. This system involved *in situ* measurements of electrical conductivity (EC), dissolved oxygen (DO) and pH. Initially, 13 sites along the Nuwejaars River were visited on 12 occasions between August 2014 and November 2015 (Table 6.1, Figure 6.1). The sampling network was expanded in 2017 to incorporate more sites, on tributaries and in the surrounding wetlands. Preliminary data from the 2017 sampling regime are presented in order to provide further explanation of the trends observed.

Table 6.1: Locations of the initial water quality monitoring sites along the Nuwejaars River and its tributaries.

River	Site Name	Latitude (°S)	Longitude (°S)
Jan Swartskraal	Tussenberge	-34.47425	19.76982
Jan Swartskraal	Napier-Elim Bridge	-34.48661	19.74805
Jan Swartskraal	Elim-Spanjaards Bridge	-34.55361	19.75336
Koue	Tierfontein	-34.56608	19.60256
Boskloof	Kersgat	-34.54731	19.80727
Koue	Elim-Kersgat Bridge	-34.57613	19.75774
Waskraalvlei outflow	Blomkraals River Bridge	-34.63971	19.84104
Nuwejaars	Nuwejaars R43 Bridge	-34.63372	19.86450
Voëlvlei outlet	Voëlvlei Bridge	-34.64757	19.88525
Nuwejaars	Elandsdrift	-34.64646	19.92511
Nuwejaars	Wiesdrift	-34.68748	19.92656
Heuningnes	Vissersdrift	-34.67796	19.99604
Heuningnes	Heuningnes River Bridge	-34.68867	20.03313

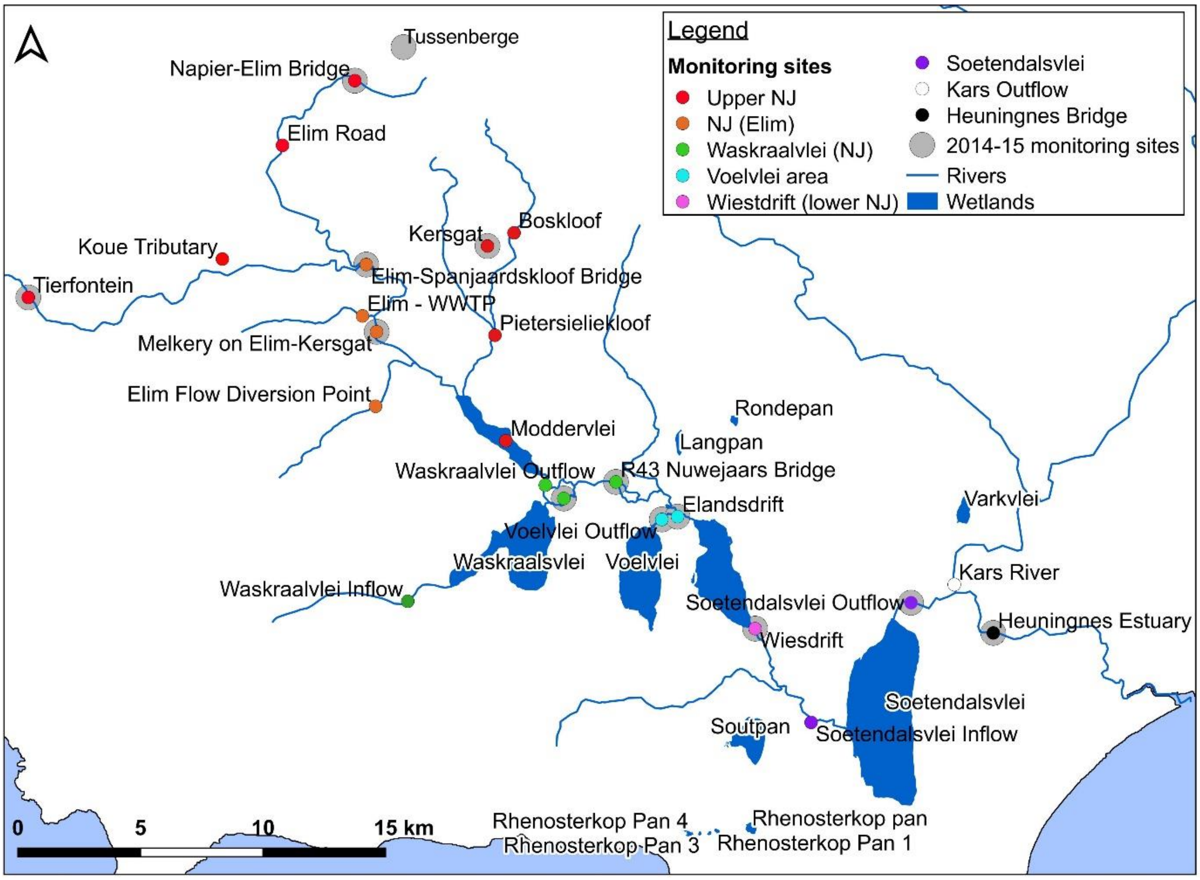


Figure 6.1: Spatial distribution of water quality monitoring sites on the Nuwejaars River between 2014 and 2015 (grey dots), and the expanded network (2017 onwards). Colours indicate groupings along the Nuwejaars (NJ) River.

Sampling protocol

Sampling sites (Figure 6.1) were selected to allow identification of the effects of water from different rivers and wetlands, as well as the effects of land use on water quality. The following variables were measured *in situ* using a YSI multimeter 12 times between August 2014 and November 2015:

- water temperature (°C)
- pH
- dissolved oxygen (mg/L)
- electrical conductivity (mS/cm)

From 2017, samples were taken twice per season. When comparing the averages of 2014–15 data and 2017 data, only the sites that were sampled over both study periods are used (section 6.3). Seasonal data are also given for a selection of the expanded network of sites to illustrate physico-chemical variability within the catchment and across seasons.

Austral seasons were defined as follows:

Summer → December–February	Autumn → March–May
Winter → June–August	Spring → September–November

6.2 Spatial and temporal variations in water quality (2014–2015)

There was a tendency for the pH of the water in the Nuwejaars River to increase from the upper tributaries to the lower reaches (One-way ANOVA $F_{6,68} = 2.453$, $p = 0.033$). The Jan Swartskraal and Pietersielieskloof rivers, which flow from the Bredasdorp Mountains, were slightly acidic for most sampling periods (Figure 6.2). This acidic water is most likely due to the natural fynbos vegetation in the upper reaches of the catchment (2012 National Vegetation Map for South Africa at www.sanbi.org). In general, the pH is circum-neutral along the main Nuwejaars River, as well as after Soetendalsvlei. The underlying geology along the main Nuwejaars River is Bokkeveld shales, which are likely to contribute towards slightly increased pH values downstream. Agricultural runoff could also be increasing the nutrient load in the water, which would increase photosynthetic rates and, consequently, pH values. There do not appear to be further changes in the lower reaches of the Nuwejaars River between Elandsdrift and Visserdrift, even though it passes through a large wetland, Soetendalsvlei. These data do not indicate a significant influence of the Voëlvlei wetland (bridge) on pH values in the river (Nuwejaars R43 Bridge) over this period (TUKEY HSD, $p = 0.899$).

Dissolved oxygen (DO) values varied throughout the catchment and over the months, there was a significant difference in mean DO between sites (ANOVA $F_{8,91} = 8.054$, $p < 0.001$) (Figure 6.3). DO was higher in the upper tributaries (Jan Swartskraal and Pietersielieskloof) than further downstream. The decrease in flow velocity on the relatively flat profile of the main Nuwejaars River could contribute towards this reduction. The increase in DO after Soetendalsvlei could partially be a result of the channel morphology at the sample site that results in an increase in flow and, therefore, oxygen levels. More likely, higher decomposition rates occurring in the wetland affect the DO levels at the outflow. In addition, there are simultaneous spikes in pH and DO (e.g. see Pietersielieskloof and Voëlvlei in Figures 6.2 and 6.3), which are likely a result of eutrophication, especially when DO is much greater than 100%.

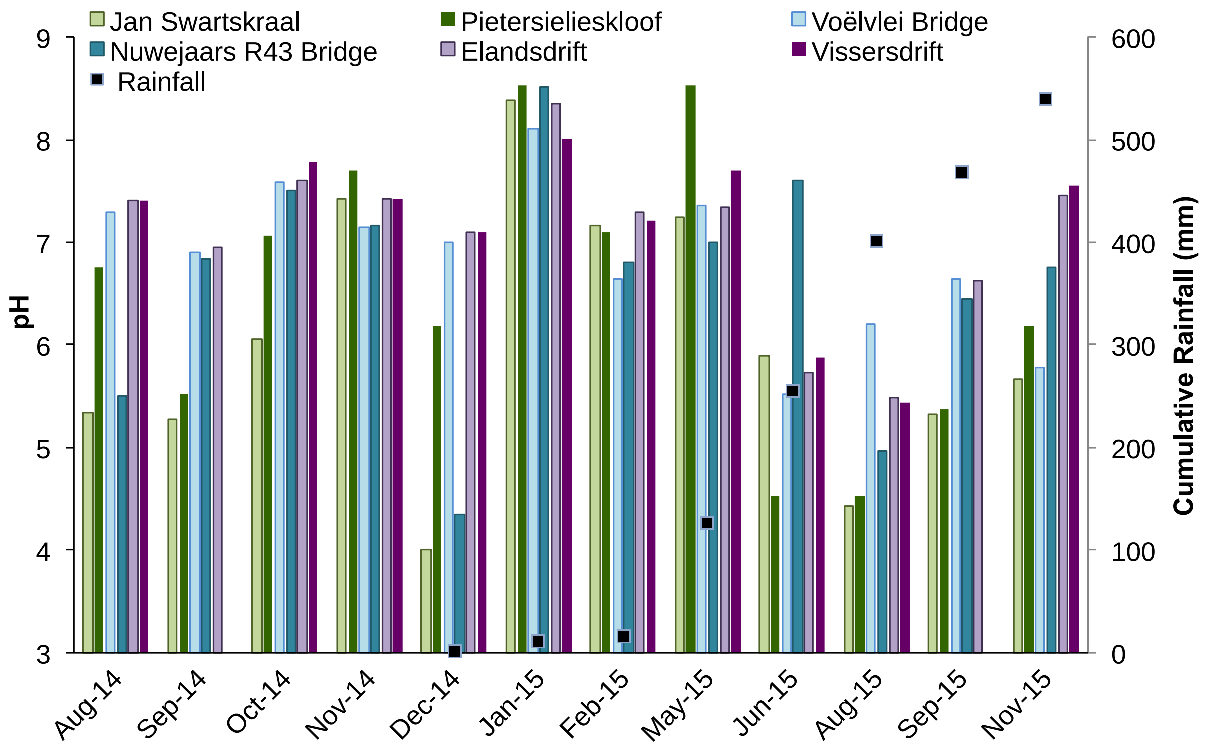


Figure 6.2: Spatial and temporal variations in pH from upstream to downstream: the upper tributaries (Jan Swartskraal, Pietersielieskloof), along the Nuwejaars River (Nuwejaars R43 Bridge, Voëlvlei Bridge, Elandsdrift), and after Soetendalsvlei (Vissersdrift). Cumulative monthly rainfall from the Vissersdrift Weather station is also given (data available from December 2014).

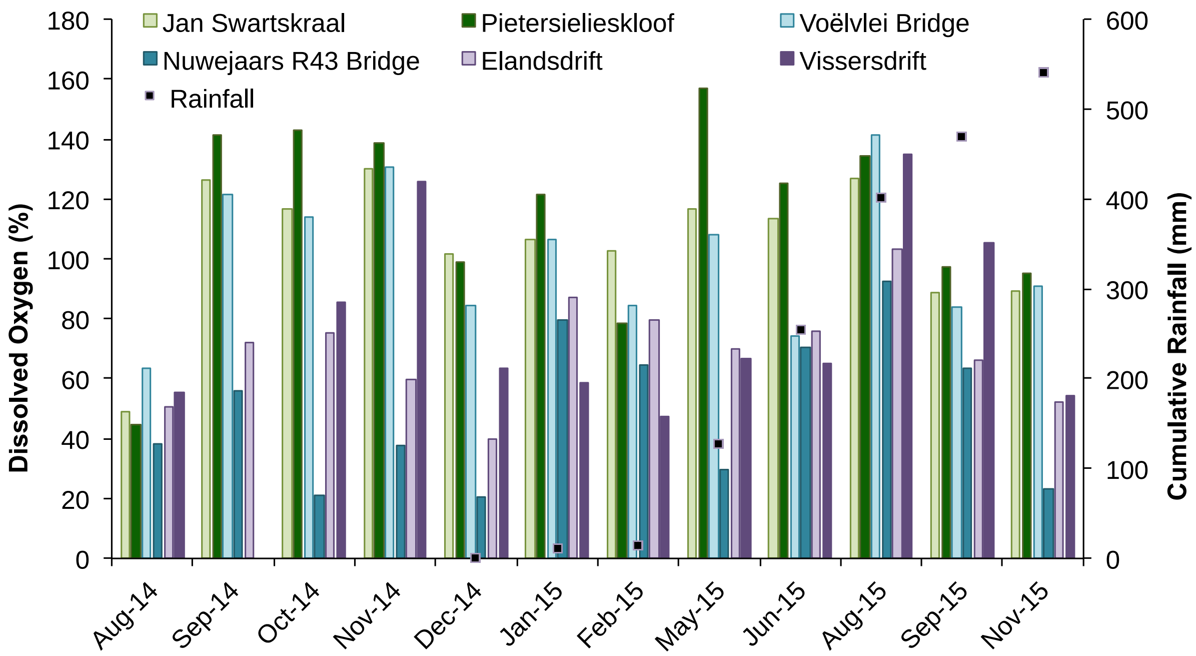


Figure 6.3: Spatial and temporal variations of dissolved oxygen (%) from upstream to downstream

Lower salinity values were recorded in the upper tributaries than in the main channel of the Nuwejaars River (ANOVA $F_{4,55} = 13.121$, $p < 0.001$) (Figure 6.4). EC naturally increases down the length of a stream as a result of weathering of rocks and leaching from sandy substrata. Human activities, such as cultivation of fields (seen further downstream), also contribute to increased EC values, often as a result of evaporation from irrigated surfaces. Many wetlands on the Agulhas Plain are relatively saline. One of these, Voëlvlei, probably contributes the majority of salts to the river. Outflows from Soetendalsvlei were more saline than inflows because the Heuningnes River downstream of Soetendalsvlei is affected by tidal movements.

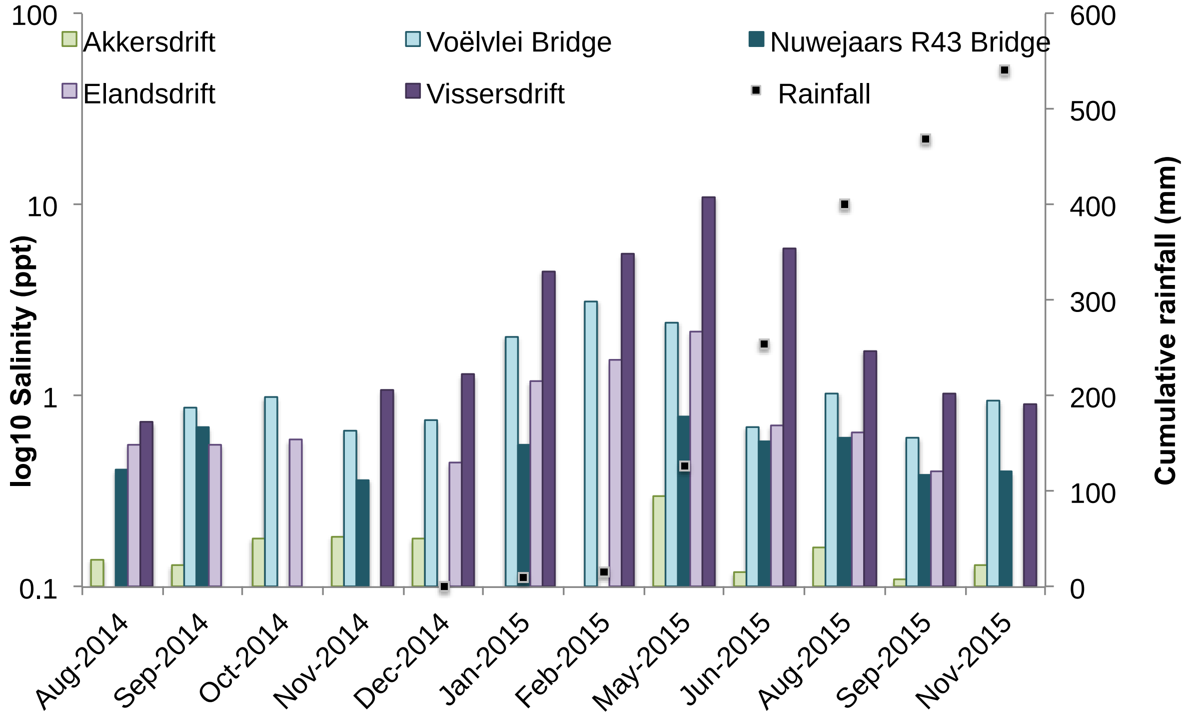


Figure 6.4: Spatial and temporal variations of Log_{10} salinity from upstream to downstream

Salinity (measured as EC) also varied significantly along the Nuwejaars River (ANOVA $F_{3,36} = 8.284$, $p < 0.001$). Water in the upper tributary (Akkersdrift) was significantly less saline than at Voëlvlei Bridge (TUKEY HSD, p = 0.01) and Elandsdrift (TUKEY HSD, p = 0.05). Salinities also differed between Voëlvlei and the R43 Bridge (TUKEY HSD, p = 0.05), even though these sites are in close proximity to each other. Voëlvlei therefore appears to be a large contributor to salinity in the river. As mentioned previously, the underlying Bokkeveld shales are another source of salinity in the catchment.

The lack of rainfall data from the beginning of data collection, as well as the short period of collection (15 months), makes it difficult to fully understand the link between rainfall and water quality. However, it is possible that there is some lag effect with changes in water quality occurring after rainfall. For example, there was a large amount of rainfall between February and August 2015, which could be linked to the drop in pH in August and September (Figure 6.3), and the drop in total dissolved solids from June to November 2015 (Figure 6.5).

6.3 Spatial and temporal variations in water quality (2014–2017)

The 2017 data (Figures 6.5 and 6.6) illustrate the spatial and temporal variability in a number of physico-chemical properties of the waters of the Nuwejaars River in 2017. The pH values varied throughout the catchment, and sometimes within a small spatial area (Figure 6.5). For example, Waskraalvlei, the outflow and the nearby river (R43 bridge) had different pH ranges. The same was observed in Voëlvlei and at its outflow. This variation is likely to have been caused by the mobilisation of humic substances during the wet season. Although more data need to be collected to perform statistical comparisons, it appears that the pH of the inflow to Soetendalsvlei differs more from the pH of the outflow during autumn and winter, than in spring.

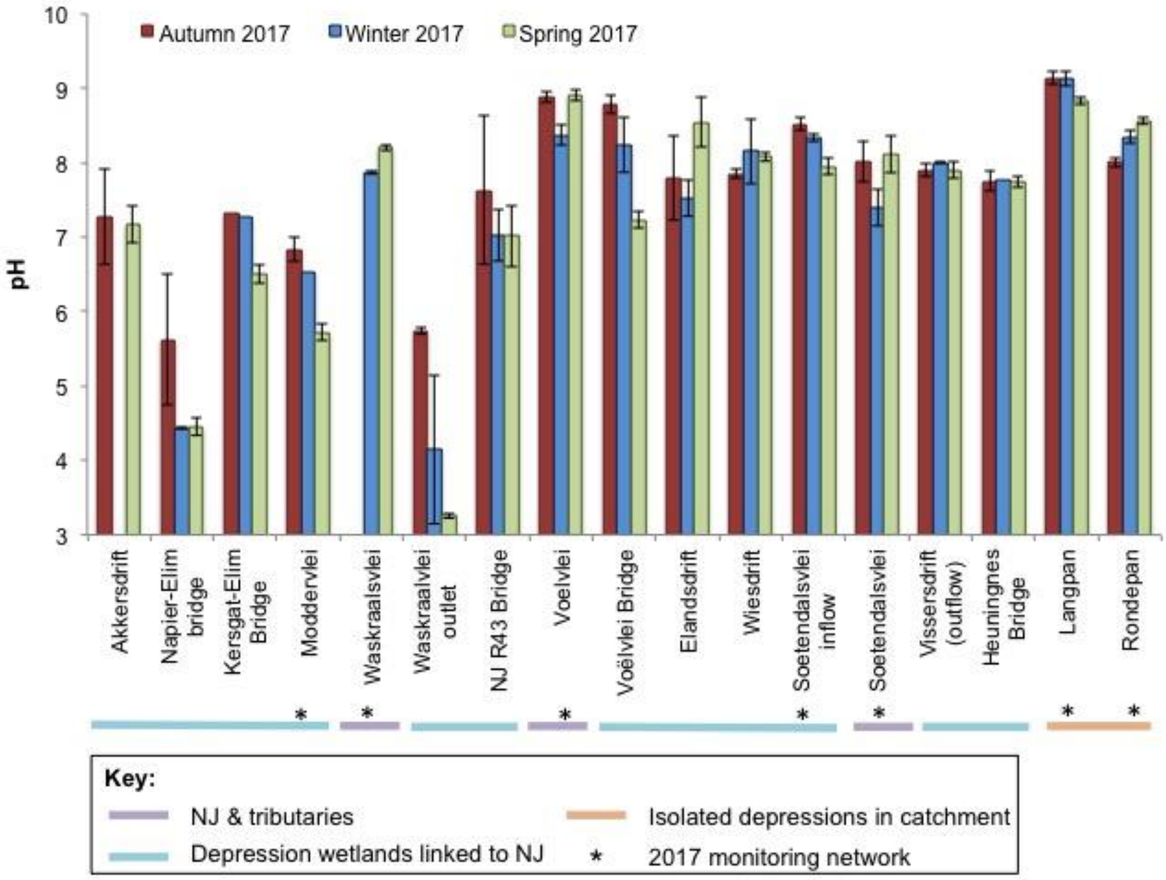


Figure 6.5: Spatial and temporal variability in pH (± standard error) in the Heuningnes Catchment in 2017. See Figure 6.2 for position in catchment. Sites are ordered upstream to downstream, with the new sites highlighted by an asterisk. Coloured bars indicate whether the sites are riverine or wetland sites.

Electrical conductivity was also variable in the catchment, with depression wetlands becoming more saline as they dried up towards the end of 2017 due to lack of rainfall (Figure 6.6). This phenomenon is more distinct in the wetlands than in the river itself, which continued to receive water from upstream, albeit in smaller quantities than in the winter.

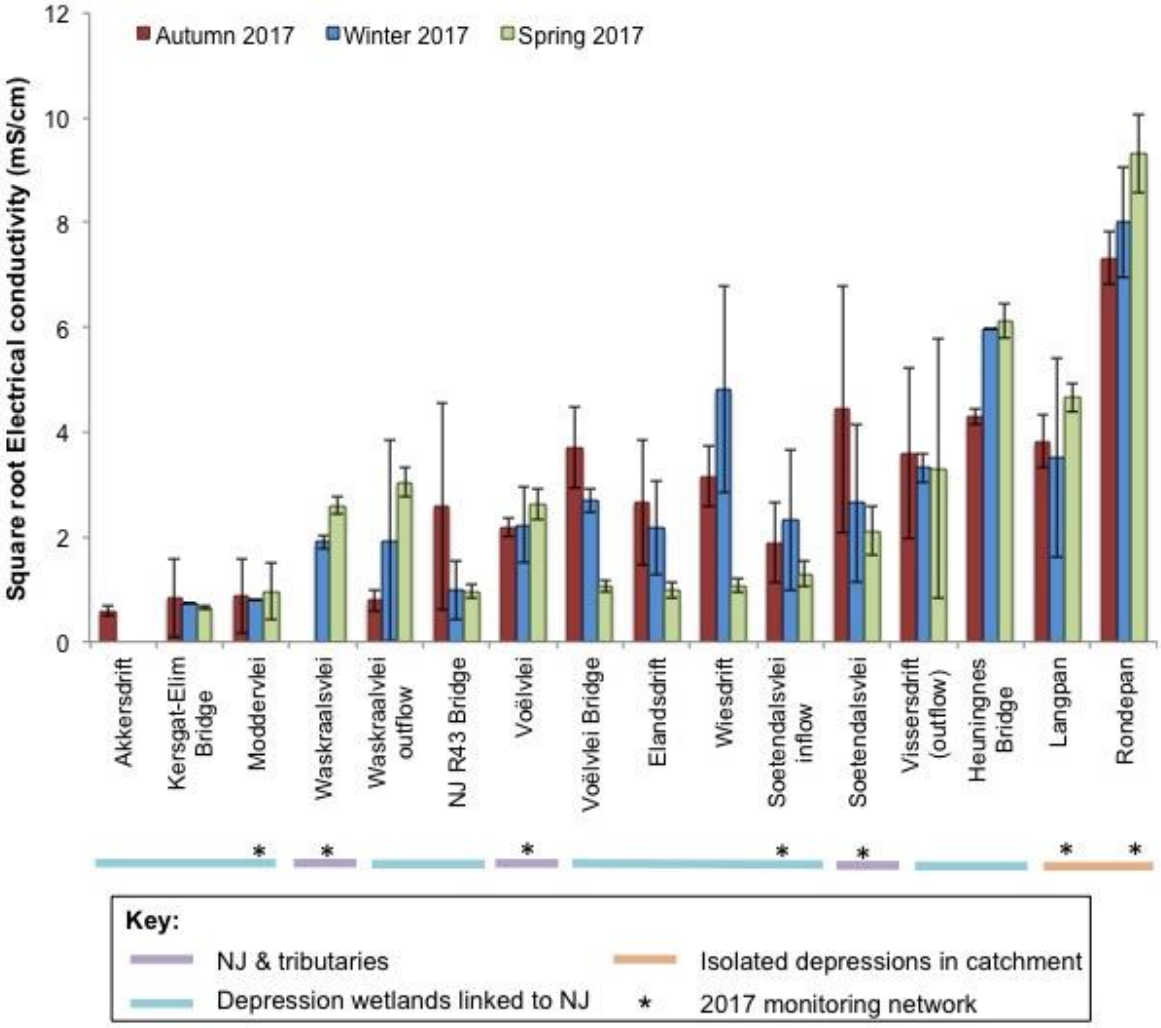


Figure 6.6: Spatial and temporal variability in electrical conductivity (± standard error) in the Heuningnes catchment in 2017. Data square-root transformed. See Figure 6.2 for position in catchment and Figure 6.5 for further details.

6.4 Comparison of 2014–15 and 2017 data

A wide range of pH readings (3.3 to 8.4) were measured in the catchment during 2014–15 and 2017, for reasons mentioned above (Figure 6.7). Generally, it appears that the readings have remained relatively stable over the last few years, apart from seasonal fluctuations (Figure 6.7). Average winter and spring pH values for 2014 appear to be more similar to data collected in 2017 than in 2016. The low average pH measurements during winter 2015 should be explored further. We hypothesise that these low values are related to increased concentrations of humic substances being mobilised from ground water in fynbos-vegetated areas. Contrastingly, autumn pH levels tend to be higher overall.

EC fluctuated across seasons and years, with no clear seasonal patterns emerging, other than those related to proximity to the sea and estuary (e.g. Visserdrift and Heuningnes Bridge), and to seasonal rainfall patterns (Figure 6.7 and 6.8). A more detailed analysis of the relationships between rainfall and salinity patterns, over both the short and the long term, is required but will not be possible without additional data.

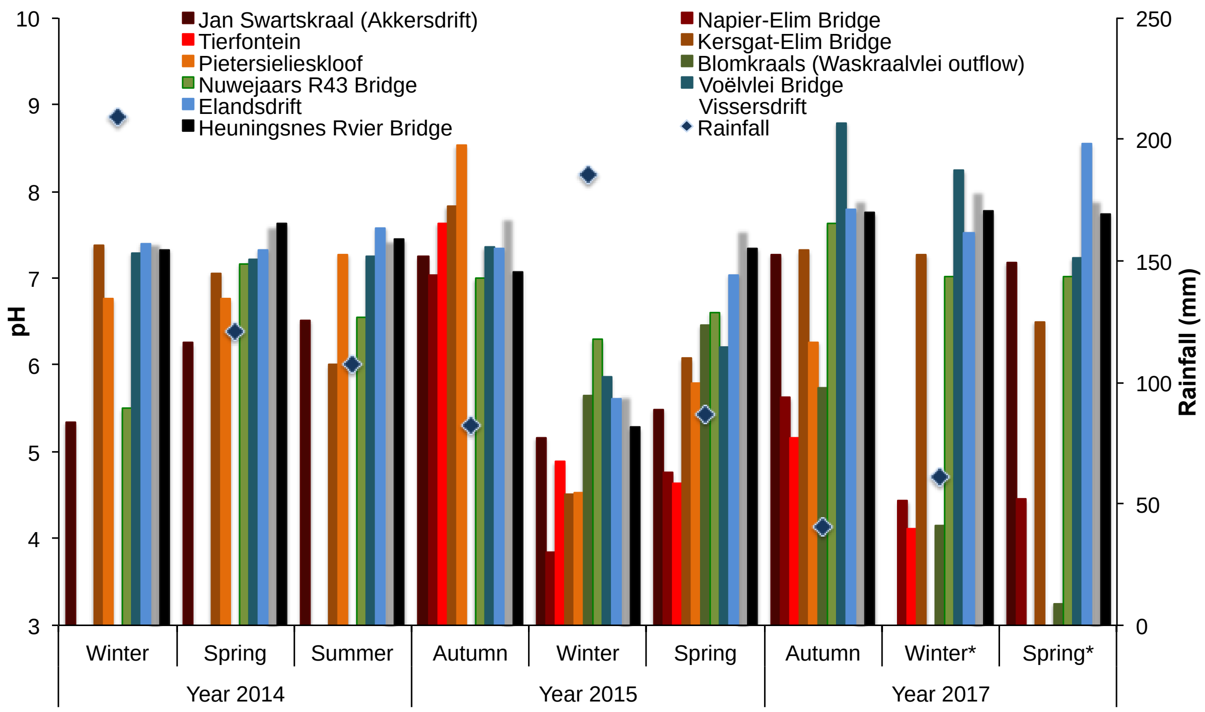


Figure 6.7: Seasonal patterns in pH at various sites along the Nuwejaars River, between 2014 and 2017. Total rainfall within each season also given (data from UWC Napier weather station). * denotes missing/incomplete rainfall data.

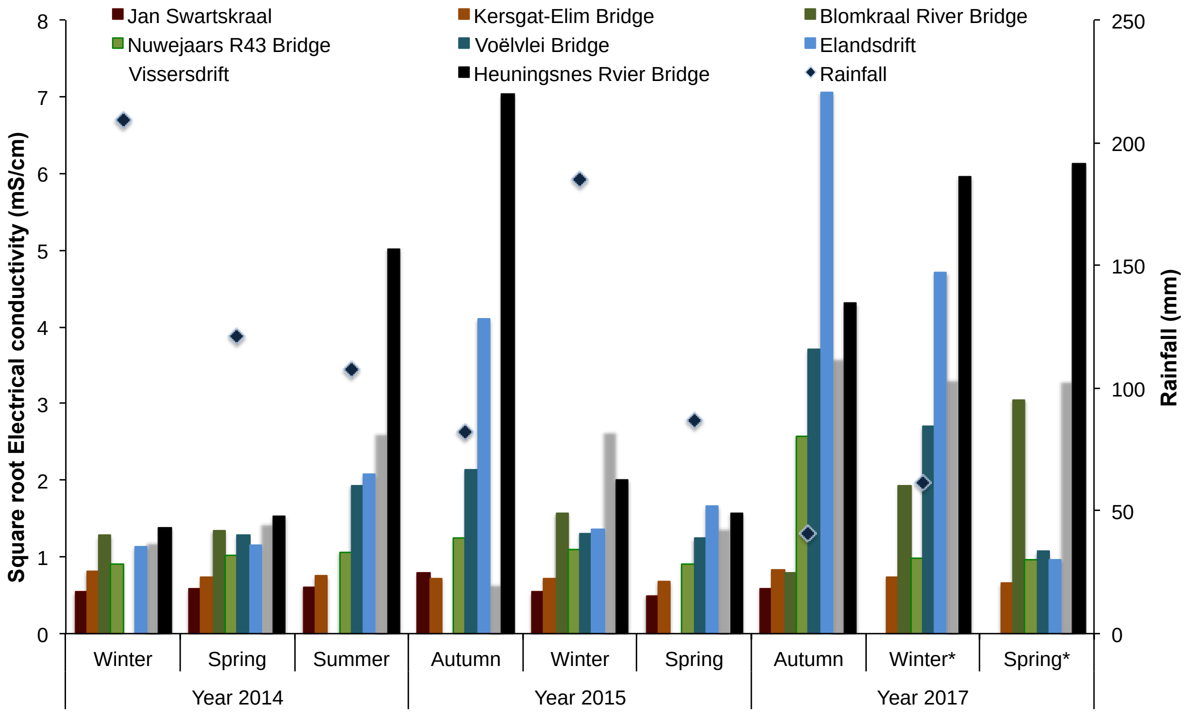


Figure 6.8: Seasonal patterns in electrical conductivity (mS/cm) at various sites along the Nuwejaars River, between 2014 and 2017. Total rainfall within each season also given (data from UWC Napier weather station). * denotes missing/incomplete rainfall data.

6.5 General findings and conclusions

Rainfall measurements, flow velocity and water level data should be used to further understand the timing and extent of fluctuations in water chemistry. Chemical data, which are currently being collected, should provide a better understanding of the water chemistry dynamics in the Nuwejaars and Heuningnes rivers. Interactions between the underlying lithology and ground water influence the quality of the surface water in the rivers, and these interactions also need to be better understood.

The timing and intensity of rainfall in this catchment is likely to induce different responses, depending on the amount of water that is present in the system. Certain responses may have a ripple effect, resulting in ecosystem shifts if the ecosystem reaches some threshold level. Changes in climate patterns, such as changes in intensity and timing of rainfall, may exacerbate these ecosystem shifts if the system is already under stress. Effective management of water quantity and quality issues thus requires an integrated understanding of these surface water–groundwater interactions at different spatial and temporal scales.

This chapter has highlighted the complexity and dynamic nature of the Nuwejaars and Heuningnes river system. Although more detailed data are needed to understand the drivers of fluxes in water quality and quantity in the catchment, the data presented here partly address both Aims 1 and 2 of this project. The results indicate that there are variations over the catchment in pH and EC which have been attributed to rainfall, groundwater input and underlying geology. These interactions, and their influence on the waters of Soetendalsvlei and the Heuningnes Estuary, are being further explored in current research.

7 WATER BALANCE ANALYSIS OF THE SOETENDALSVLEI

7.1 Occurrence of permanent ponds/lakes

This chapter deals with the last aim of the study which is to determine how river inflows and interactions between surface water and groundwater affect the water balance of the Soetendalsvlei. The Soetendalsvlei is about 3 km wide and 8 km long and is a dominant hydrological feature of the Nuwejaars Catchment. Other lakes occurring in this catchment are the Voelvlei (4 km by 1.7 km), Soutpan (1.3 km by 1.9 km), Longpan (1 km by 0.5 km), and Roundepan (0.6 km by 0.4 km) (Figure 7.1). A bathymetric survey was carried out to establish the relationships between water depth, surface area and volume of water in the Soetendalsvlei. These relationships are required to predict changes in water storage in the lake as a response to rainfall, evaporation, inflows and outflows. The water balance was analysed using a lake model.

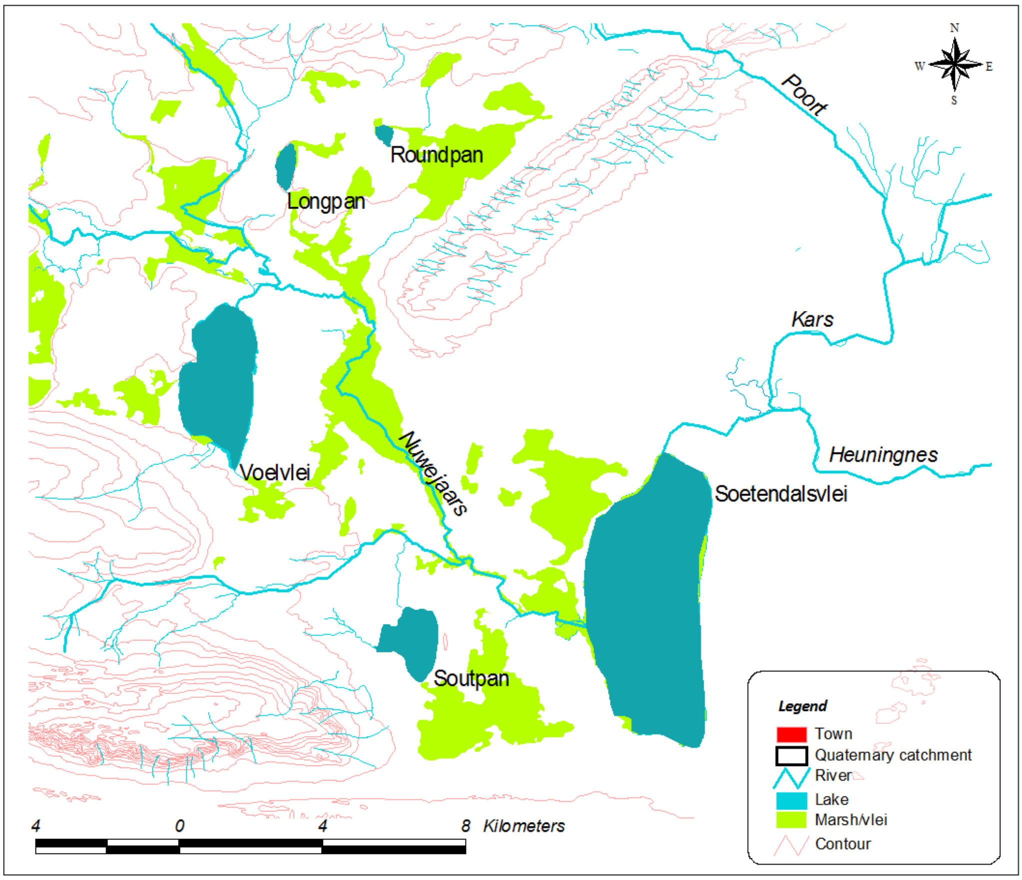


Figure 7.1: Distribution of permanent lakes/pans in the lower part of the Nuwejaars River Catchment

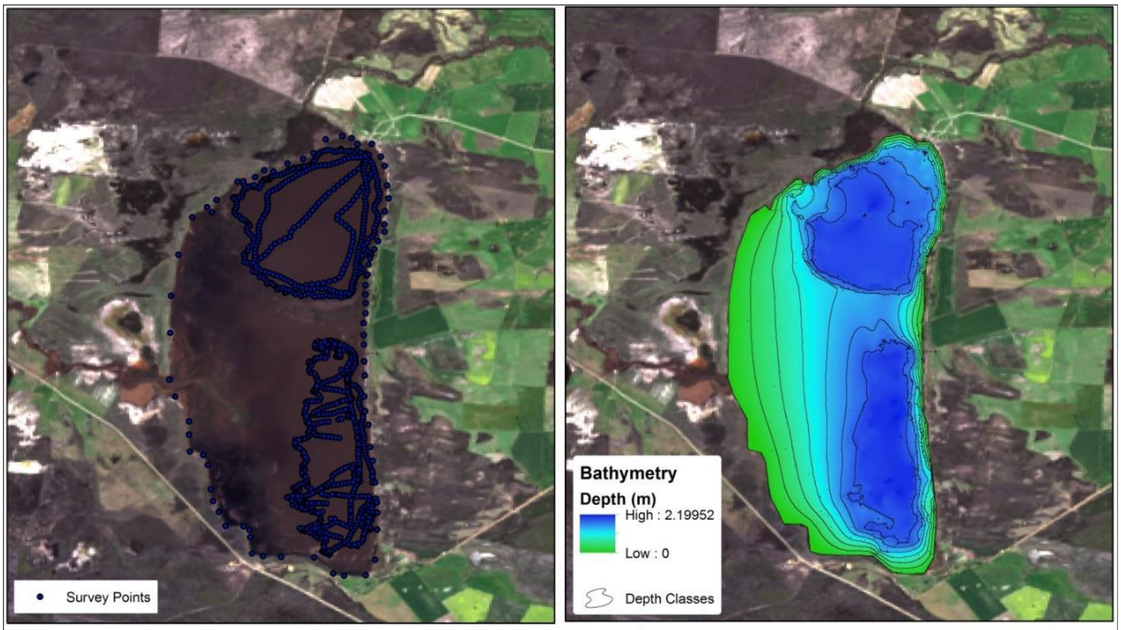
7.2 Bathymetric survey

A full report on the bathymetric survey was presented as Deliverable No. 2, in November 2014. The bathymetric survey was carried out using a GARMIN Fishfinder 250C fathometer installed on a boat. A total of 1038 water level measurements were taken, in both the north and south pools. Some western parts of the lake could not be accessed due to the presence of reeds. The depth ranged from 0.7 to 2.2 metres with 1.76 to 2.00 m being the most frequent (Table 7.1)

Table 7.1: Frequency distribution of the water depths measured during the survey of the Soetendalsvlei.

Depth Range (m)	Frequency (%)
0.7	0.7
0.80–1.00	5.9
1.1–1.25	2.6
1.26–1.50	15.1
1.51–1.75	18.3
1.76–2.00	46.5
2.01–2.20	10.9

The ‘Natural Neighbour’ interpolation algorithm in ArcGIS 10.0 was used to derive a generalised bathymetric surface based. The variation of the water level throughout the Soetendalsvlei, derived from interpolation, is shown in Figure 7.2.



Depth Class	Depth Range (m)	Total Area (m^2)	Total Area (ha)	Total Volume (m^3)
1	0 - 0.29	1940248.103	194.0248103	273212.3124
2	0.29 - 0.61	1817817.891	181.7817891	854710.648
3	0.61 - 0.94	1801932.423	180.1932423	1452122.278
4	0.94 - 1.28	1851492.545	185.1492545	2113393.267
5	1.28 - 1.59	2159789.078	215.9789078	3169065.273
6	1.59 - 1.85	2174722.687	217.4722687	3806016.927
7	1.85 - 2.19	3800688.122	380.0688122	7540687.458
All		15546690.85	1554.669085	19209208.16

Figure 7.2: Variation of water depth within the Soetendalsvlei

The variation of a) surface area and b) storage of water is given in Table 7.2 and Figure 7.3.

Table 7.2: Variation of surface area and storage with water level in the Soetendalsvlei

Water Level (m)	Area (ha)	Volume ($10^6 m^3$)
0.29	194.025	0.273
0.61	375.807	1.128
0.94	556.000	2.580
1.28	741.149	4.693
1.59	957.128	7.863
1.85	1174.600	11.669
2.19	1554.669	19.209

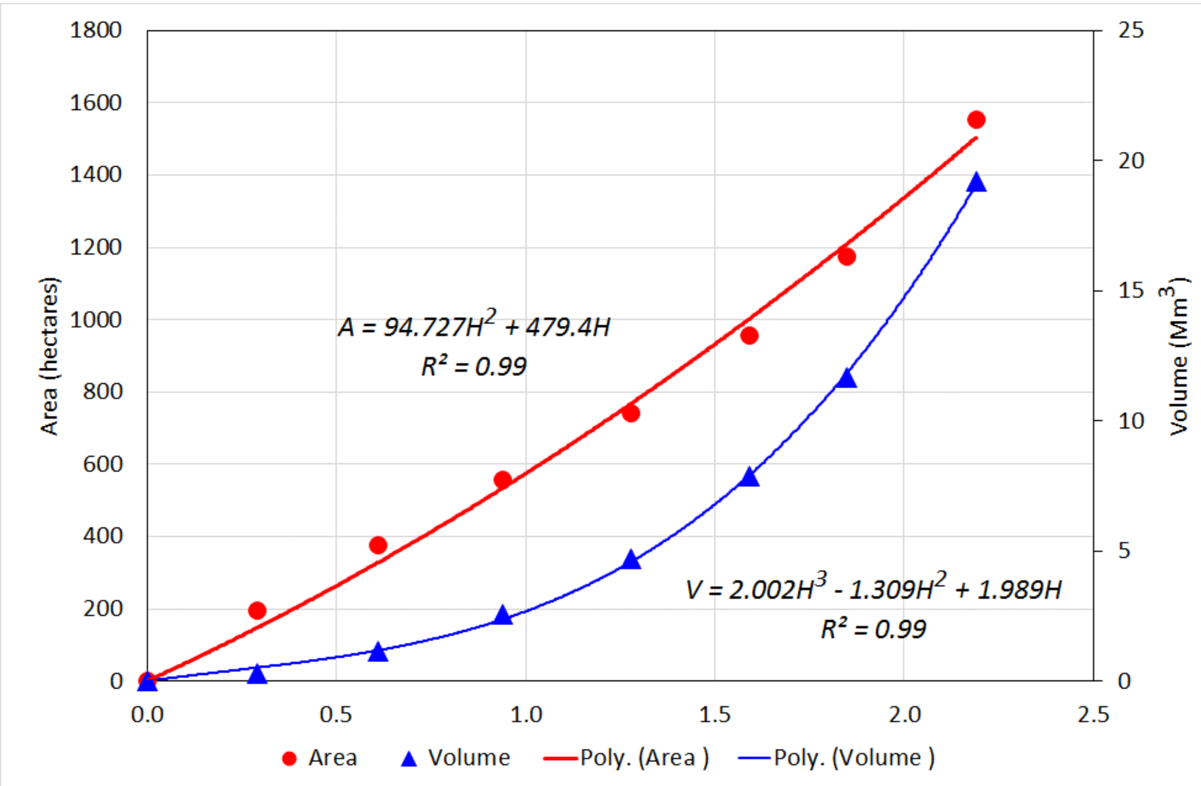


Figure 7.3: Variation of surface area (*A*) and storage of water (*V*) with water depth (*H*) in the Soetendalsvlei.

The relationship between surface area (*A* in ha) and water depth with respect to the deepest part of the lake (*H* in metres) is represented by the following equation (r^2 = 0.99):

$$A = 479.4H + 94.727H^2 \quad (7.1)$$

The relationship between volume of water stored (*V* in million cubic metres) and water depth (*H* in metres) is represented by the following equation (r^2=0.99):

$$V = 2002H^3 - 1.309H^2 + 1.989H \qquad (7.2)$$

Based on the bathymetric survey results, the storage capacity of Soetendalsvlei at a depth of 2.25 m is 20 million cubic metres, with a surface area of 1558 hectares.

7.3 Water balance analysis

A daily water balance model has been used to simulate changes in water storage in the Soetendalsvlei (Equation 7.3).

$$S_{t+1} = S_t + Q_t - O_t - A_t\left(E_t - P_t\right) \qquad (7.3)$$

where

S_t = volume of water stored (m^3) on day *t*,

Q_t = Nuwejaars River inflows (m^3/day)

O_t = outflows from the lake through the Heuningnes River (m^3/day)

A_t = surface area of the lake (m^2)

E_t = daily evaporation rate (m/day)

P_t = daily precipitation over the lake (m/day)

River inflows into the Soetendalsvlei were estimated from flow measurements of the Nuwejaars River at Elandsdrift. Weather data from the Visserdrift Station located on the shoreline were used to estimate E_t using the Penman equation, and rainfall over the lake, P_t.

The outflows, O_t, (m/day) are a function of the volume of water stored in the lake. It has been assumed that outflows only occur when the volume of water stored, S_t, exceeds S_{min} (Equation 7.4).

$$\begin{aligned} O_t &= \alpha\left(S_t - S_{\min}\right)^{\beta} && \text{if } S_t > S_{\min} \\ O_t &= 0 && \text{if } S_t \le S_{\min} \end{aligned} \qquad (7.4)$$

The parameters α and β were estimated by minimising the following objective function

$$\text{minimize} \sum_{t=1}^{n}\left(H_{t,obs} - H_{t,sim}\right)^2 \qquad (7.5)$$

where $H_{t,obs}$ = measured average daily lake level (m), $H_{t,sim}$ = predicted average daily lake level from simulated S_t. Lake levels are being monitored using OTT pressure transducers with data loggers on two locations on the Soetendalsvlei.

The relationship between S_t and $L_{t,sim}$ was established from data collected during the bathymetric survey.

$$H_t = 0.0007\, S_t^{0.482} \tag{7.6}$$

The surface area of the lake, A_t, required to estimate volume of precipitation over and evaporation from the lake is predicted from S_t (Equation 7.7).

$$A_t = 4346.1 S_t^{0.486} \tag{7.7}$$

The parameters for predicting outflows, O_t, from S_t in Equation (7.4) were estimated to be α = 1 x 10^{-7}, β = 1.847, S_{min} = 11.248 Mm^3.

The above water balance model of Soetendalsvlei does accurately represent changes in storage due to river inflows and outflows, rainfall and evaporation (Figure 7.4). The root mean square error (RMSE) between measured and predicted lake levels is 0.06 m, while the coefficient of determination is 0.98.

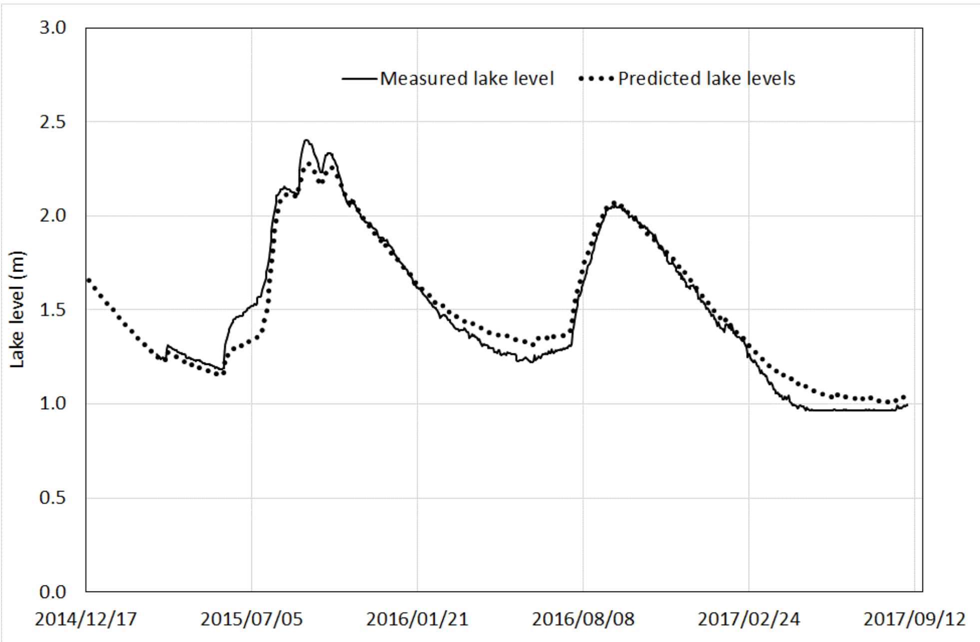


Figure 7.4: A comparison of measured lake levels and those predicted using the water balance model of Soetendalsvlei

Flows of the Nuwejaars River into the Soetendalsvlei contributed 88% and 80% to water storage in 2015 and 2016, respectively, with the remainder coming from rainfall over the lake (Figure 7.5). However, the total inflows (19.6 Mm^3/yr) for 2016 were less than half of the 2015 inflows, 49.9 Mm^3/yr. During a year with high water storage in Soetendalsvlei, such as in 2015, river outflows (28.9 Mm^3/yr) constituted 66% of the outflows, with the remainder being evaporation losses (14.8 Mm^3/yr). In 2016, evaporation losses (16.2 Mm^3/yr) were more dominant, 78%, than surface outflows (4.5 Mm^3/yr). The study was not able to quantify possible effects of groundwater on water storage in the lake.

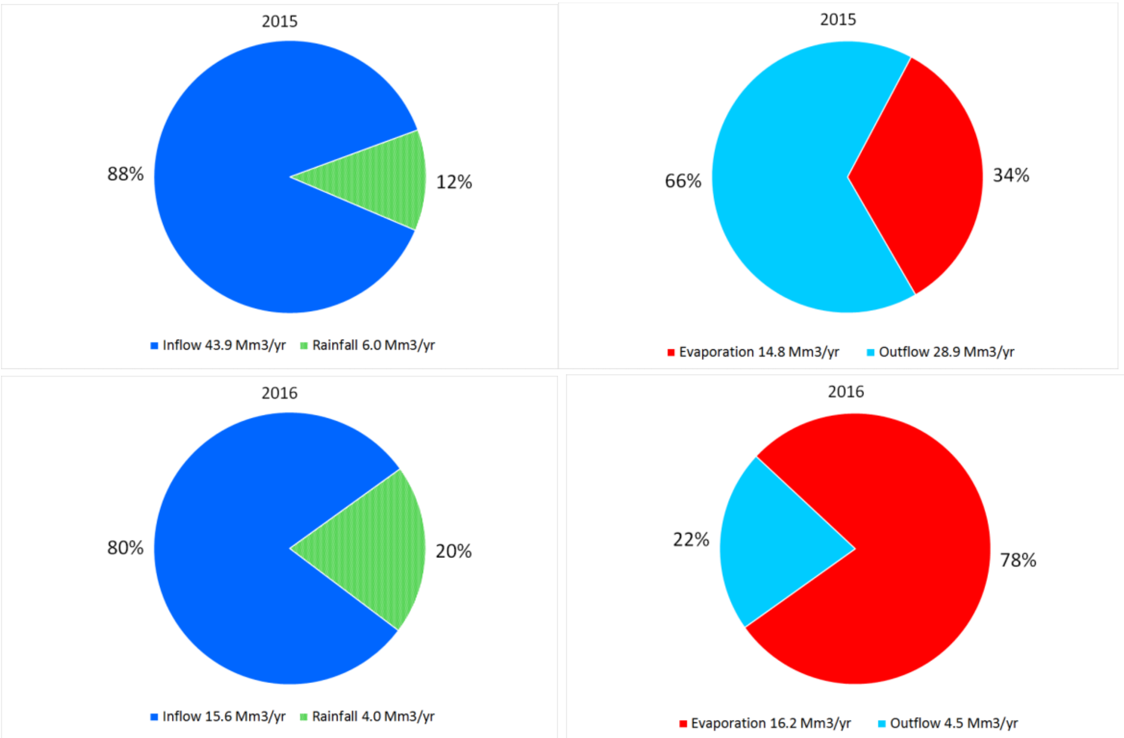


Figure 7.5: Contributions of river inflows, rainfall over the lake, evaporation, and river outflows to 2015 and 2016 water storage in Soetendalsvlei

7.4 Seasonal and annual variation of inundation

The availability of remote sensing images enables monitoring of areas inundated over a lake (Ozesmi & Bauer, 2002; Swenson & Wahr, 2009; Song *et al*., 2014; Dörnhöfer & Oppelt, 2016). With little or no historical data on either the lake water level, or, consequently, the inundated areas of Soetendalsvlei, the use of remote sensing offers a viable option for assessing the inundation dynamics of this lake. The study examined the spatial and temporal variations of inundation between 1989 and 2017 using Landsat images.

The Modified Normalised Difference Water Index (MNDWI) (Xu, 2006) was used to delineate water bodies from Landsat images. A total of 110 Landsat images from the Landsat 8 OLI/TIRS, Landsat 7 ETM+ and Landsat 5TM archives were processed to provide a time series of inundation for Soetendalsvlei. The Landsat images have a temporal resolution of 16 days but, due to cloud cover, the available time series for Soetendalsvlei is not at regular intervals. Thus, the available time series depicted in Figure 7.6 shows the extent of lake inundation when cloud-free images were available. The monthly rainfall observed at Zeekoevlei, which is 5 km north-east of the lake, is also included in Figure 7.6. The time series of MNDWI estimates of inundation of Soetendalsvlei, for the period 1989 to 2017, shows significant annual and seasonal variations.

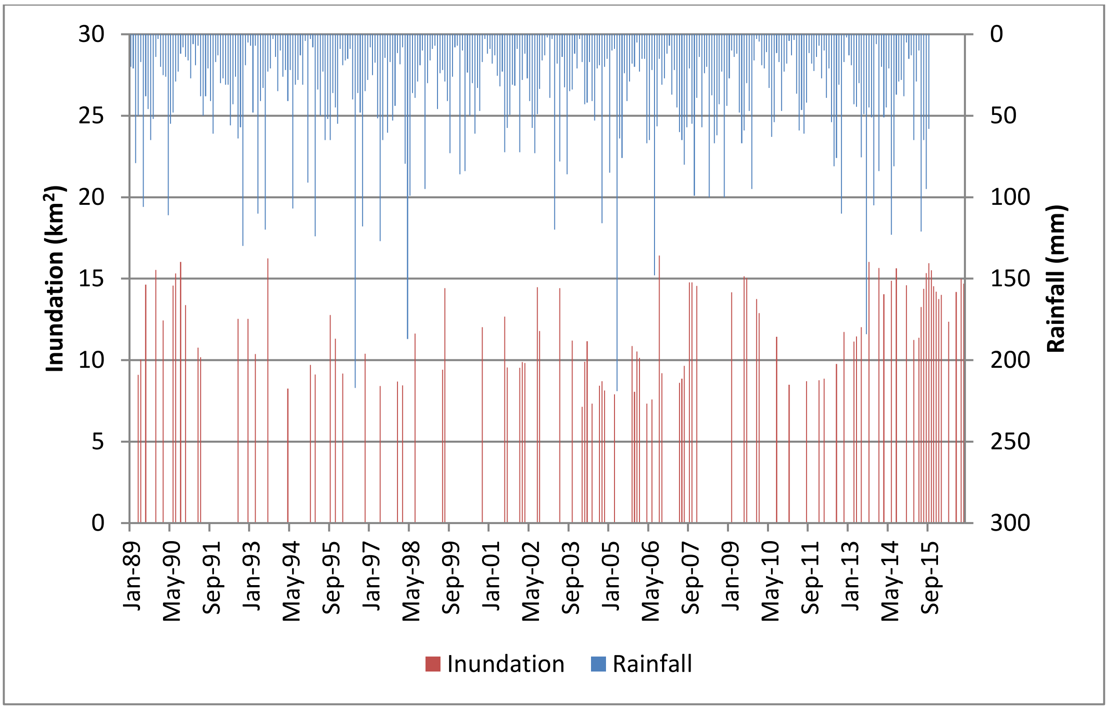


Figure 7.6: Time series of lake inundation and rainfall for Soetendalsvlei (29 April 1989–4 January 2017)

The seasonal and monthly variation in inundation for Soetendalsvlei is illustrated in Figure 7.7 by whisker box plots. The spring season (September, October and November) has the highest average and maximum lake inundation. The interquartile range reflects surface inundation of between 10.01 and 14.8 km^2. December and January have significantly high median values of inundation, 13.68 km^2 and 11.51 km^2 respectively. March, April and May have the lowest median values of inundation.

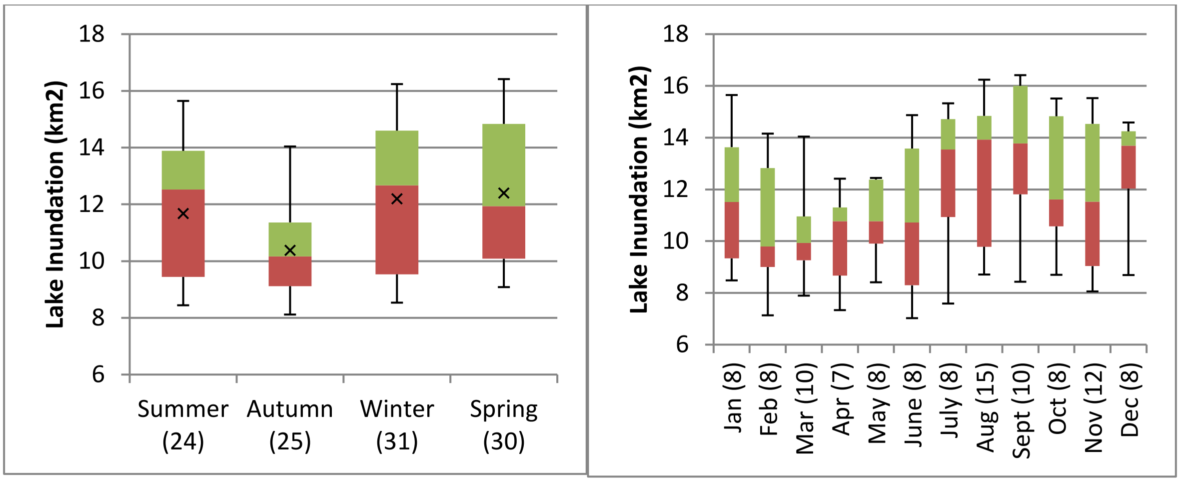


Figure 7.7: Seasonal (left) and monthly (right) variation in lake inundation for Soetendalsvlei, based on a Landsat time series (1989–2016). Numbers in brackets represent the number of Landsat images which were processed. The cross or figure 'x' denotes the average inundation.

Based on the analyses of 110 Landast images, from 1989 to 2016, the frequency of inundation, or hydroperiod, for Soetendalsvlei is illustrated in Figure 7.8. The lake area that is permanently inundated (100% inundation frequency) with surface water covers an area of 5.832 km^2. This permanently inundated area is mainly subdivided into two areas of open water in the northern and southern parts of Soetendalsvlei. The bathymetric results indicate that these pools of open water are the deepest sections of the lake, with depths averaging 2.2 m. The lake area of Soetendalsvlei that is covered with emergent vegetation experiences different degrees of flooding, ranging from 26% to 99% of the time. This area, which extends from the area of permanent open water of the lake to the western shoreline, varies in depth, ranging from 1 to 2 m.

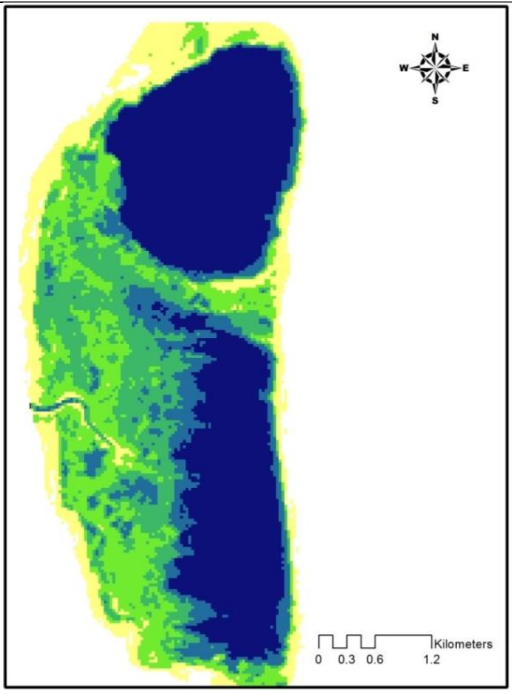
	Inundation Frequency			Area (km^2)
		1–25%	Intermittently inundated	2.34
		26–50%	Seasonally inundated	3.00
		51–75%		3.28
		76-99%		2.67
		100%*	Permanently inundated	5.8
				17.12

Figure 7.8: Hydroperiod for Soetendalsvlei

Results from the MNDWI hydroperiod analyses indicate the occurrence of smaller pools of water along the western shoreline of Soetendalsvlei, with a relatively high inundation frequency of between 76% and 99%. Possible reasons for this could be ponding due to the occurrence of a clay substrate; through-flow from groundwater into and from the adjacent salt marshes; depressions created by the interplay between the sediment and vegetation; separation of pools due to the occurrence of high-density vegetation.

The maximum extent of flooding for the entire lake area of Soetendalsvlei occurs about 25% of the time. The spatial extent of inundation within this category varies between a minimum of 15.10 km^2 and a maximum of 16.24 km^2.

In areas where no *in situ* hydrological information is available, remote sensing provides a means of monitoring the temporal and spatial water balance dynamics of lakes. The inundation maps derived from this research demonstrate the potential of monitoring a shallow lake within a semi-arid environment using the MNDWI. The maps provide an understanding of the spatial variation of flooding, and thus add value to research related to water-dependent ecosystems. The seasonal variation of inundation may especially be relevant for avifauna monitoring and research in the Agulhas Plain, particularly if future bird count monitoring at Soetendalsvlei coincides with Landsat overpass. The time series of inundation generated from the Landsat archive provides a reasonably accurate, although irregular, historical account of surface flooding for Soetendalsvlei. With no hydrological data available for Soetendalsvlei prior to March 2015, the time series of inundation offers baseline hydrological information.

7.5 Effects of Soetendalsvlei on the Heuningnes River

Since the Heuningnes River had been ungauged, the frequency of occurrence of outflows from Soetendalsvlei into this river was previously unknown. The lake model developed in this project and analysis of the area inundated by this lake enables an assessment of when outflows occurred. The lake model showed that the threshold water storage in Soetendalsvlei for outflows to occur is 11.2 Mm^3. Based on the lake model results, and verification with water level measurements in the Heuningnes River at Vissersdrift immediately downstream of Soetendalsvlei, outflows in the period 2015 to 2017 occurred during the following periods: August 2015–December 2015, and August 2016–November 2016 (Figure 7.9). There were no outflows during the whole of 2017 as a result of the drought. Despite the lack of outflow from the Soetendalsvlei, river flows were observed along the Heuningnes River at 1.2 km downstream of the lake. These flows are due to base flows which seem to be due to subsurface flow of water from the Soetendalsvlei. Lack of surface outflow does, as expected, result in low discharges in the downstream Heuningnes River. Salinity in the Heuningnes River is mainly influenced by intrusion of sea water due to tidal activity. However, the cessation of outflows from Soetendalsvlei does also affect salinity along this river (van der Ende, 2015).

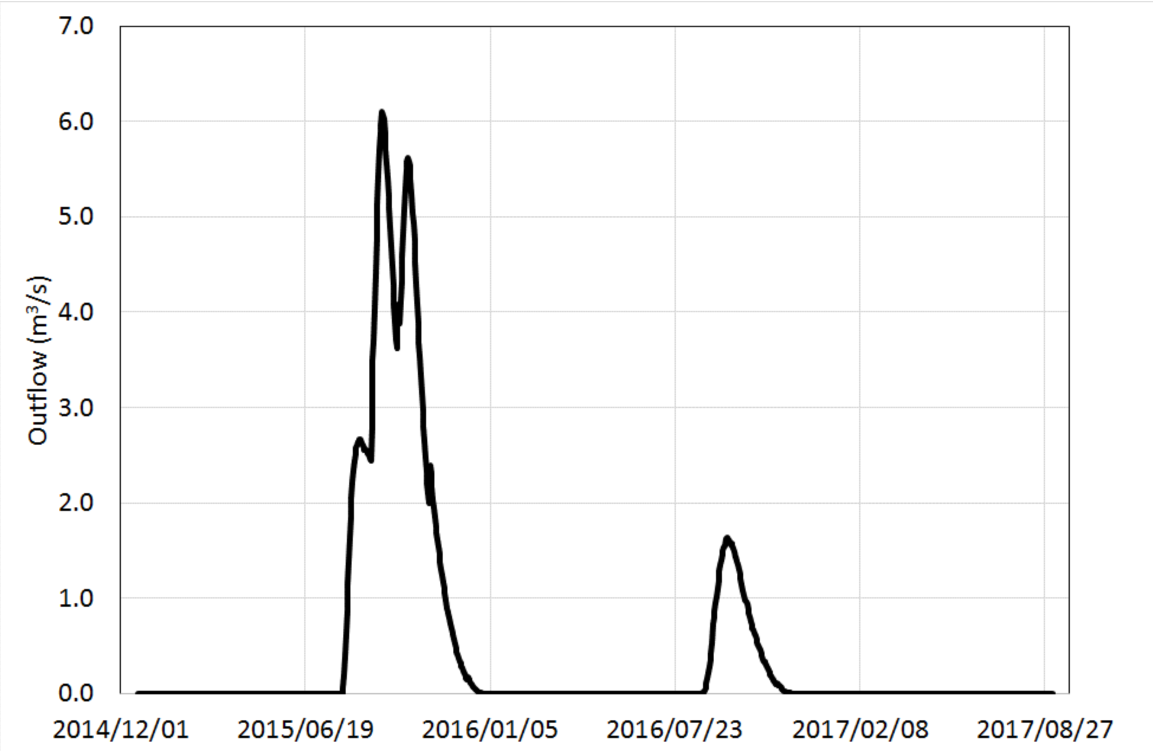


Figure 7.9: Temporal variation in January 2015–September 2017 outflows from the Soetendalsvlei, flowing into the downstream Heuningnes River, predicted by the lake model

Estimation of the inundated area of the Soetendalsvlei, using Landsat images from 1989 to 2017, allows for a long-term analysis of how frequently water storage exceeded the threshold for outflows. Since some images could not be included, due to cloud cover, it is not possible to present this frequency on a monthly basis. The surface area did not exceed the threshold for outflows for some periods in 72% of the years between 1989 and 2017. Thus, outflows were not experienced for periods of varying duration in 72% of the years. This result shows that the cessation of outflows from Soetendalsvlei is a common event, and ecosystems occurring along the Heuningnes River have adjusted to this variability of outflows.

8 WATER USE BY INVASIVE ALIEN TREES

8.1 The occurrence of invasive alien plants

This chapter deals with the second aim of the study, which was to establish the effects of land use on river flows, and therefore inflows into the Soetendalsvlei. Consultations held with landowners and other stakeholders in the Nuwejaars Catchment revealed that the land use/land cover change with a potentially significant effect on water resources was the rapid invasion of alien trees in both riparian and non-riparian areas. The study therefore focused on investigating the effects of this land cover change on water resources.

The Heuningnes Catchment is one of the heavily infested regions in the Western Cape. These invasive alien plants reduce biodiversity (Nowell, 2011). *Eucalyptus*, *Pinus* and *Acacia* (*Acacia longifolia, A. cyclops* and *A. saligna*) are the dominant species in this catchment (Visser *et al.*, 1999; Nowell, 2011). These species account for 93% of the alien plants that have heavily infested the mountains and riparian zones of the Heuningnes Catchment (Figure 8.1). According to the National Invasive Alien Plant Survey done by Kotzé *et al.* (2010), the invasive alien plants have affected 265.1 km^2 or 35% of the Nuwejaars Catchment. Invasive alien plants are therefore affecting all areas with natural vegetation since the rest is cultivated land, water bodies, and bare land.

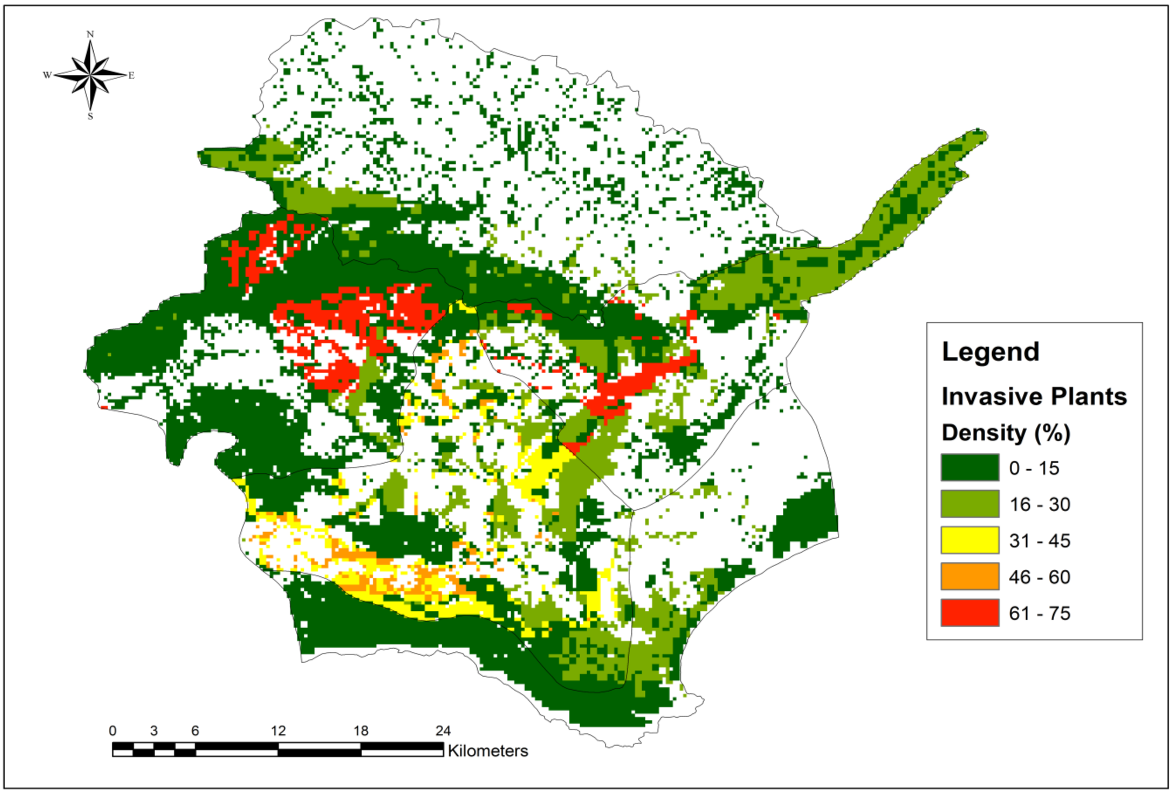


Figure 8.1: Distribution and density of alien vegetation in the Heuningnes Catchment (Kotzé *et al.*, 2010)

Members of the Nuwejaars Wetland Special Management Area and residents of Spanjaardskloof have on-going activities for clearing invasive alien plants. There is, however, inadequate knowledge about water use rates by invasive alien plants occurring on hillslopes and riparian zones; such information will assist in prioritising areas for clearing activities. The coordinator of the clearing operations by the Nuwejaars Wetland Special Management Area reported that the evergreen, *Acacia longifolia* (long-leaved wattle), was one of the problematic species invading both hillslopes and riparian zones. There is, however, no information about the water use rate of this species.

8.2 Establishment of a plant water use monitoring system

The heat pulse velocity (HPV) of the heat ratio technique was used to quantify rates of transpiration by *A. longifolia*. This method is considered to be accurate and reliable for quantifying directly water use by woody plants. The advantages of the method include minimal disturbance to the tree. The HPV method provides an appropriate temporal resolution of sap flow rates, detects low and reverse flow rates, and allows automatic collection and storage of data. Sap velocities can be monitored in all weather conditions.

8.3 Site selection

The selection of sites to monitor the transpiration rates of an invasive alien tree involved several reconnaissance visits to potential study sites in the catchment. The selection criteria for study sites were the following:

(i) A site invaded by actively growing *Acacia longifolia* trees

(ii) A site that is accessible

(iii) The relevant landowners give permission to install the equipment and to visit the site at least twice a month

(iv) A site where equipment is unlikely to be vandalised

Two sites, one on a hillslope and another in a riparian zone of the Nuwejaars River, were selected. The hillslope site was on the southern slopes of the Bredasdorp hills in Spanjaardskloof. The riparian site was located within the Zoetendals Farm, and in the Moddervlei 30 m from the Nuwejaars River channel. Both sites were located in private properties; permission to access the sites every two weeks was granted by the landowners.

8.4 Selection of trees

Each HPV system monitored three trees simultaneously from June 2016 until June 2017. The criteria for selecting trees to be monitored included the following:

(i) relatively straight trunks with no knots
(ii) different stem sizes at breast height
(iii) trees actively growing and close to each other (2–5 metres) to suit the HPV cable lengths.

Trees measured during the stem survey were categorised into three size classes, based on their circumference; namely, small (0–10 cm), medium (11–20 cm) and large (> 20 cm). Trees selected at the riparian site had circumferences between 18 and 58 cm. The largest instrumented tree on the hillslope had a circumference of 40 cm.

8.5 Installation of the heat pulse velocity sap flow system

When representative trees were selected on both sites, the thickness of the sapwood areas (conductive xylem) was measured to determine the depths to which probes must be inserted in the selected trees. This was done by injecting blue methylene dye into the stem through a 1.8 mm-diameter drilled hole. The tree was then left for a few hours to allow the uptake of water simultaneously with the injected dye. A corer was then used to core a section of the stem to identify areas with conductive xylem vessels in the stem. From the sample, the sapwood area, heartwood, and bark thickness were measured to determine the depths to which the thermocouples were to be inserted so as to avoid the heartwood.

A drilling template was used to drill holes into which the probes were to be inserted. A 1.8 mm-diameter hole in the centre was used to insert heaters. The other two 2 mm-diameter holes were 6 mm below and above the central hole, for inserting thermocouples. The depths to which the thermocouples were inserted on the hillslope site ranged between 10 and 50 mm, and between 12 and 40 mm at the riparian site. Each tree had four probe sets that were inserted at different depths. This was done to account for the radial variation of the sapwood area. Each probe set had a heater inserted in the central holes which released a pulse of heat (lasting about 0.5 seconds) at hourly intervals. The temperature was measured pre-and post-heat release. All the thermocouple cables were connected to a multiplexer that allowed multiple measurements and recording of data to take place. The multiplexer and heater cables were then connected to a custom-made relay control module which functions as a switch that alerts the system to record or take measurements every hour. A CR 1000 data logger stored all the data collected. A 105AH battery which was charged and changed every two weeks powered the monitoring system. A strong box was then used to safely store all the equipment (Figure 8.2).

Figure 8.2: Sap flow monitoring system installed on the hillslope

Each site had a weather station nearby. At the hillslope site, the weather station was 1.75 km away in a south-westerly direction. The weather station for the riparian site was 50 m away, just outside the tree stand.

8.6 Processing of HPV sap flow data

The downloaded HPV data were regularly checked for quality. Data of unacceptable quality were replaced by values interpolated using data with acceptable quality collected before and after the affected time interval. In cases where there were many successive bad data points, patching was done using correlations between the probe data either with good data from other probes. To identify the true zero of each probe, either due to probe misalignment or other causes, the instrumented trees were felled and measurements were continued for one to two days. The HPV signals were subsequently adjusted to match the zero flow conditions imposed by excising the trees.

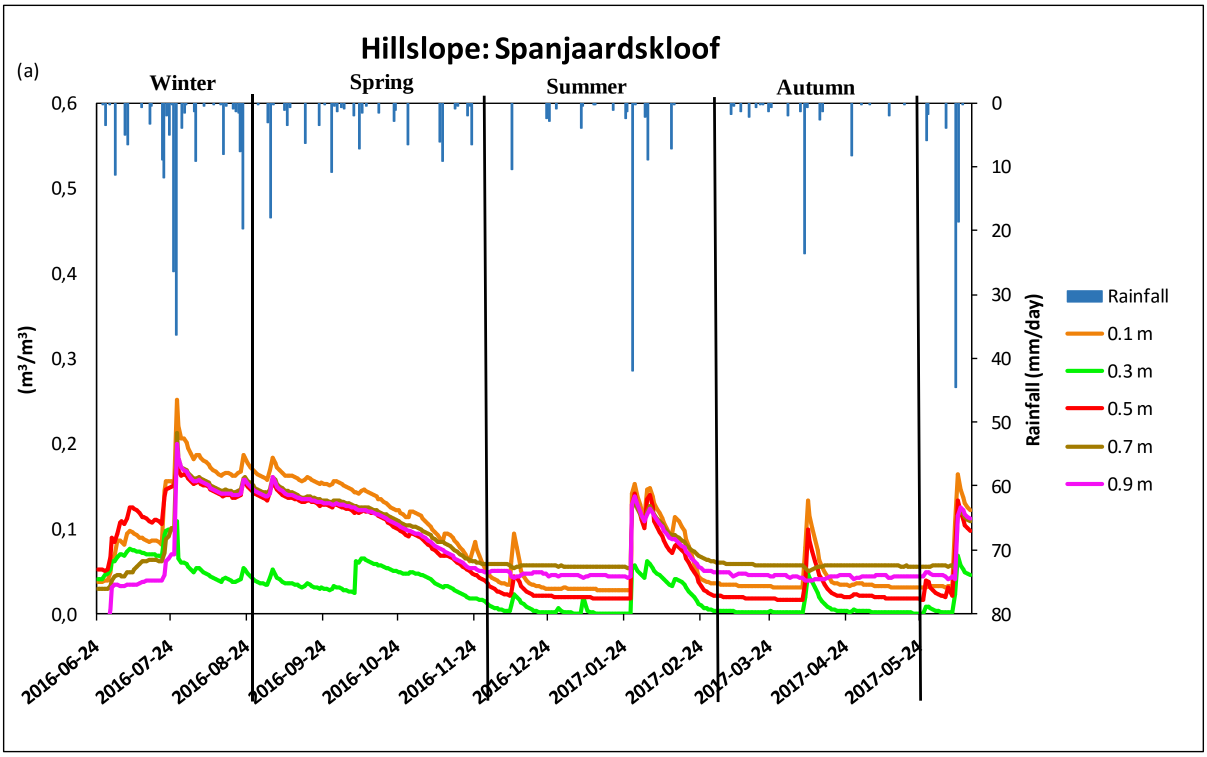
At the end of the study period, wood samples for the trees monitored were collected from the stems close to the probe installation positions and enclosed in zip-lock bags to determine the wood density and moisture fraction of the wood. Wounding corrections were implemented according to the procedure by Swanson and Whitfield (1981).

8.7 Monitoring of soil water content

A one-metre pit was dug next to the sap flow system. The disturbed soil material was stacked up next to the pit during excavation. This was done to ensure that the bulk density would resemble the natural state of the soil at the site and therefore prevent preferential flow. The variation of soil water at different depths and the response of the soil to rainfall was monitored using five Decagon EM50 5TE soil moisture sensors inserted horizontally at depths of 0.1, 0.3, 0.5, 0.7, and 0.9 m below the ground. The sensors measured temperature (°C), EC (mS/cm), and volumetric water content (m^3/m^3) simultaneously. After the installation, sensors were then scanned to check if they worked. Thereafter, the excavated pit was backfilled and compacted carefully, taking into consideration the sensitivities of the sensors and cables.

8.8 Response of soil water content to rainfall events

Seasonal changes in soil water content were observed. The soils had, as expected, high water content during the wet winter, and low water content during summer (Figure 8.3). In the wet winter season in June 2016, the soil water content was 0.25 and 0.55 m^3/m^3 on the hillslope and riparian sites, respectively. During summer (December 2016), the soil moisture content at both sites ranged between 0.03 and 0.09 m^3/m^3. Figure 8.3a shows that the summer rainfall received on the hillslope caused the soils not to dry out completely, and there was 0.16 m^3/m^3 soil water in January 2016. In contrast, a consistent decline in soil water content was observed from December 2016 at the riparian site (Figure 8.3b).



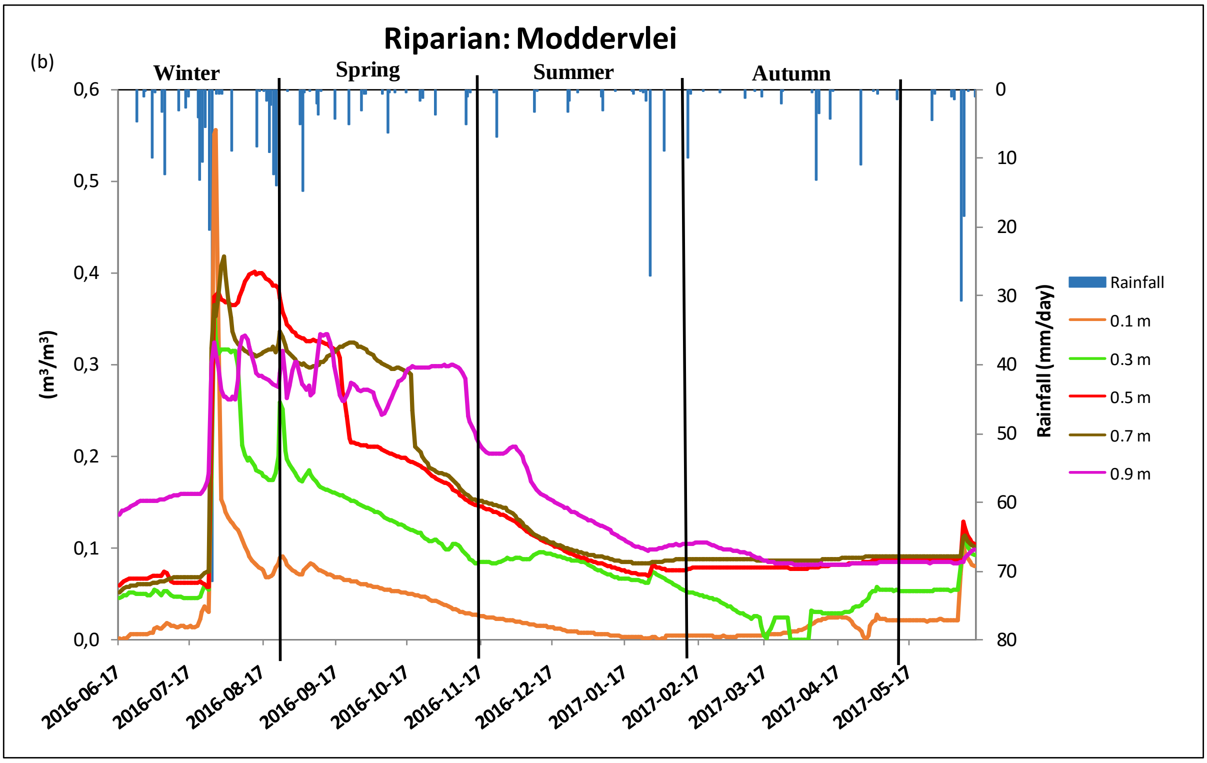


Figure 8.3: Seasonal soil water content variations at different depths on the hillslope (a) and riparian site (b).

The first major rainfall event during the study period occurred on 25–26 July 2016. The response of the soils to this rainfall event was observed during the early hours of 26 July (Figure 8.4). The shallow soil profile (10 cm) on the hillslope was the first to respond and maintained high moisture content throughout the day (Figure 8.4a). The maximum soil water content occurred towards the end of the rainfall event on the hills (11:00 AM). A decline in soil water content was observed at different depths after the rain had stopped (12:00 PM). This is shown by the soil moisture content at 90 cm profile declining from 0.4 m^3/m^3 to 0.2 m^3/m^3.

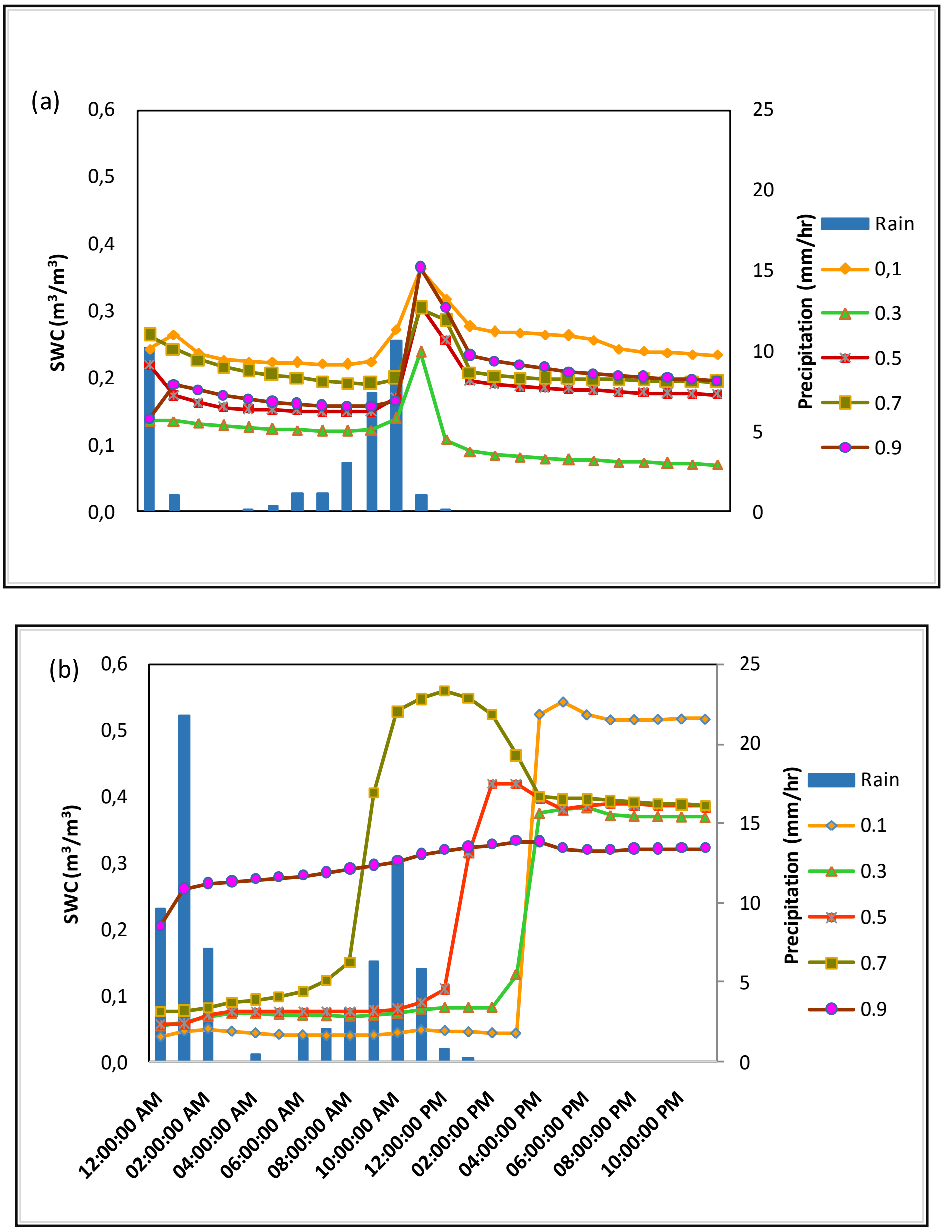


Figure 8.4: Soil water response to the rainfall event that occurred on 26 July 2016, at (a) hillslope and (b) the riparian site

At the riparian site, the soil profile at 90 cm responded first to rainfall, but there was not much variation for most of the day in this profile (Figure 8.4b). Coincidentally to the declining water content on the hillslope around mid-day, a sharp increase in soil moisture content was measured around the same time (12:00 PM), specifically at 50–70 cm depth in the riparian site. A delayed response was observed at shallow depth (10–30 cm), which had a maximum soil moisture content of 0.3–0.5 m^3/m^3 around 03:00 PM. These results indicate that the response of soils to this rainfall event was from the shallow soil profile to the deep profiles at 90 cm and/or below. This downward movement of water occurred when it was raining. As the rain stopped, soil water content immediately declined. Unusual soil responses were observed on the riparian site. The deeper soil gained high soil water content earlier than the shallow soils. This is evidence of the existence of preferential downward flow of water through macropores such as animal burrows.

8.8 Plant water use rates

Total evaporative demand during the study period, June 2016 to June 2017, measured 1520 mm at the riparian site compared to 1450 mm on the hillslope site. The riparian site had higher rates of evapotranspiration as a result of high wind speeds, 7.1 m/s experienced at Moddervlei in comparison to 4.7 m/s measured on the hillslope. The annual transpiration rate of *A. longifolia* during the study period was 596 mm at the riparian site compared to 241 mm on the hillslope (Figure 8.5).

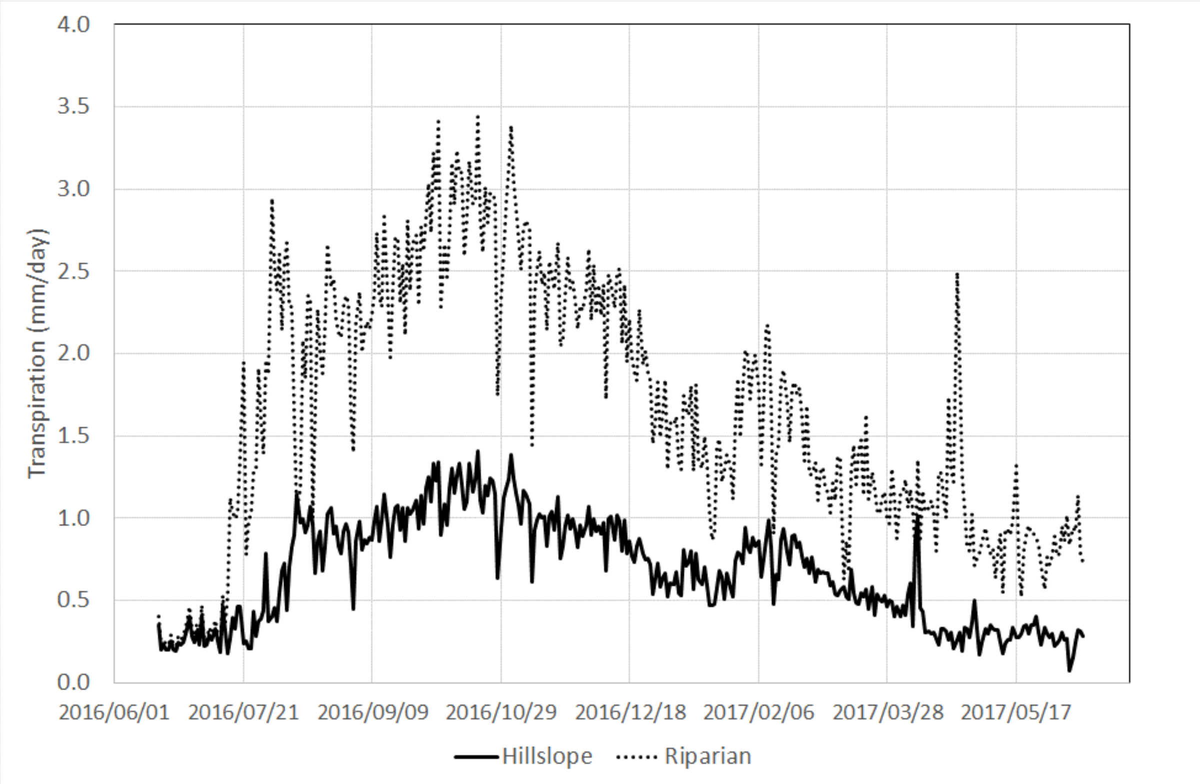


Figure 8.5: Transpiration rates of Acacia longifolia at the hillslope and riparian sites

These results show that the riparian trees used more water than the hillslope trees, which was expected and agrees with results of previous studies (e.g. Le Maitre *et al.*, 2000). Similarly, Dzikiti *et al.* (2013) found riparian pines used 36% more water than the non-riparian ones at a site in the Simonsberg Mountains, Western Cape Province. Riparian trees have access to multiple sources of water, which include soil water, stream water and groundwater.

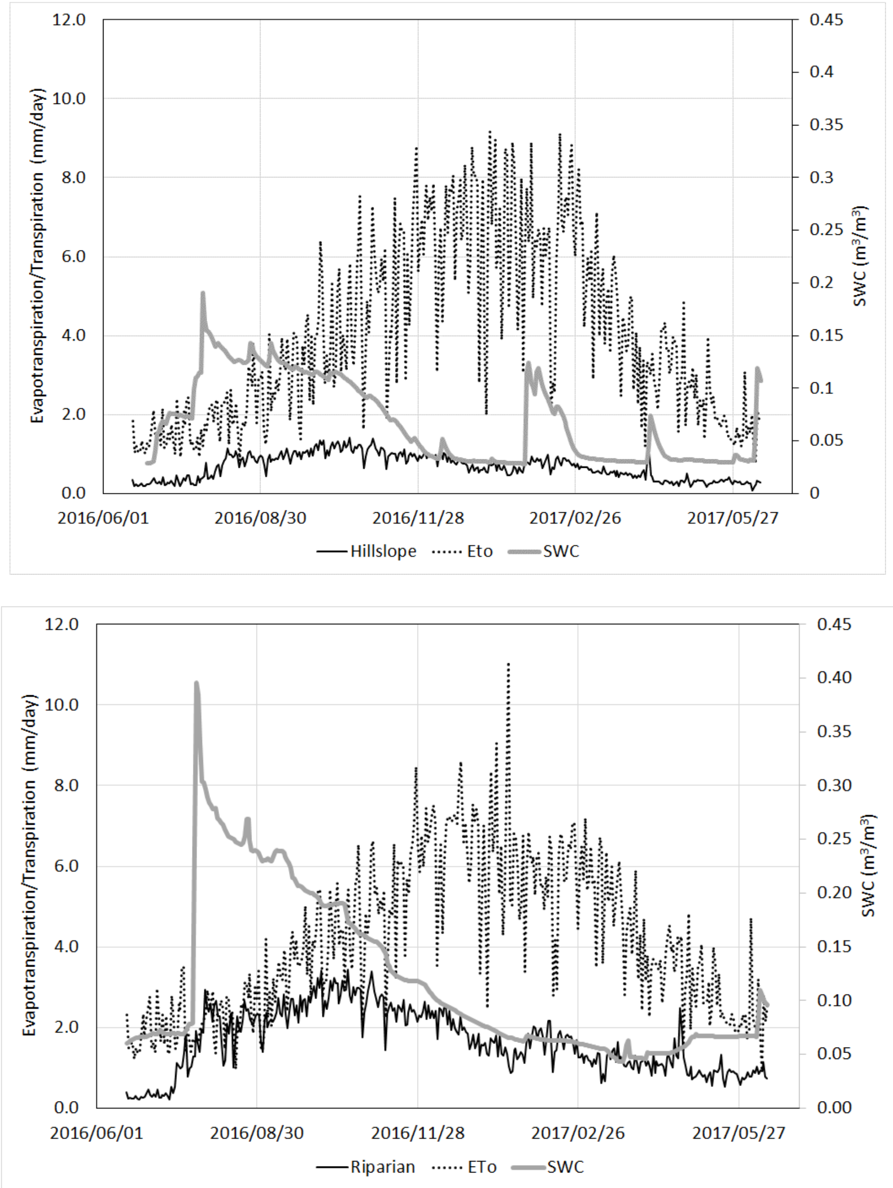


Figure 8.6: Transpiration (water use) dynamics by *A. longifolia* on the hillslope (top) and riparian site (bottom).

The major driver of the transpiration rate at the hillslope site was evaporative demand, while soil water content was the most influential factor at the riparian site (Figure 8.6). As the soil water content declined from November 2017 at the riparian site, transpiration rates also declined, despite the high evaporative demand (Figure 8.6).

The ratio of the measured transpiration rate to the reference evapotranspiration during the period when soil water content was not a limiting factor to transpiration, was used to estimate the unstressed transpiration rate. This ratio was estimated to be 0.39 for the hillslope site, using data collected from 7 August to 23 September 2016. The ratio was 0.90 for the riparian site based on data collected from 26 July to 14 September 2016. These transpiration coefficients were used to estimate the unstressed transpiration rates. For the hillslope site, the unstressed transpiration for the June 2016 to June 2017 period was 579 mm, while this was 1348 mm for the riparian site. Thus, during a relative wet year, *Acacia longifolia* in a riparian zone will consume over twice the amount of water used by the same trees growing on a hillslope site. Boreholes drilled in 2017 at the hillslope site had a water table depth of about 2 m. In a wet year, water table depths will be close to the surface, therefore the invasive alien trees are likely to have access to water and the transpiration rates will be close to the unstressed rates (579 mm). Based on these results, the hypothesis that riparian trees use more water than non-riparian species was accepted in this study.

8.9 Catchment-scale water use by invasive alien plants

The national invasive plant survey by Kotzé *et al.* (2010) found that 26 513 hectares were affected by these plants in the Nuwejaars Catchment. According to Kotzé *et al*., the invasive alien plants covered an equivalent of 7 930 hectares at 100% density. If we assume that 5% of this area is made up of riparian zones with the transpiration rate of invasive alien plants being 596 mm/yr, and for the rest of the condensed area the rate is 241 mm/yr, then the total water use by invasive alien trees in the Nuwejaars Catchment is 20.5 Mm^3/yr. The assumption is that other invasive alien plants have transpiration rates similar to that of *Acacia longifolia*. The estimated water use by the invasive alien plants is of the same order of magnitude as the mean annual runoff (18.8 Mm^3/yr). During a relatively wet year with unstressed transpiration rates being dominant, the total water use by invasive alien plants can be as high as 49 Mm^3/yr. The high unstressed transpiration rate (1348 mm) for the riparian site corroborates the view of local landowners that invasive alien plants cause drying of streams. During this study we observed that even though some streams have substantial base flows derived from spring discharges in their headwaters, they eventually dry up on the lower part, e.g. Jan Swartskraal River. The results of this project do confirm findings of other studies (Holmes *et al,*. 2008; Clulow *et al.,* 2017) that there are gains in groundwater recharge and/or stream flow if alien trees are removed from riparian zones and other parts of a catchment. Versfeld *et al.* (1998) and Le Maitre *et al.* (2015) noted that the *Acacia* taxon had the most extensive invasion by area and is likely to have the greatest impact on water resources in South Africa, although no studies had actually quantified the water use by this species. Clearing of *A. longifolia* should be prioritised in the riparian areas as this will likely lead to some water savings.

9 WATER USE ASSESSMENT

9.1 Introduction

This chapter contributes towards achieving the second aim of the study, i.e. “To establish effects of land uses and water uses on quantity and quality of inflows into the Soetendalsvlei”. The chapter assesses the amount of water used by the main sectors in the Nuwejaars Catchment. The study has used data contained in the Water Authorisation and Registration Management System (WARMS) of the Department of Water and Sanitation, and estimates of water used for crop and livestock production. There are several farm dams used for livestock watering and domestic water supply. However, the potential amount of water that can be stored in these dams is not reflected in WARMS since some of the uses do not require a water licence. The study identified these dams on Google Earth images and then estimated the volume of water stored from the measured surface areas. Crop and livestock census data collected by the Department of Agriculture of the Western Cape Province has been used to estimate water use.

9.2 Water licences

According to the WARMS database, 61 water users have registered their water use. The total volume of water registered in the Nuwejaars Catchment is 4.7 million cubic metres (Table 9.1). This database is being updated and the analysis was based on information that had been captured on this system by 2014.

Table 9.1: Number of water users, and the volume of water used, in quaternary catchment G50B, as reflected in the WARMS database

Water Source	Number of Registrations	Volume of Water Use (m^3)
Dam	3	222 000
River	36	3 184 804
Spring	16	1 106 853
Borehole	6	221 241
Total	61	4 734 898

Most water licences have been allocated for the abstraction of water from rivers (59%) and springs (26%). The main use of water registered is crop irrigation, which is 88% of the total volume of water registered. Most of the registrations are on rivers in the upper part of the Nuwejaars Catchment which has perennial streams (Figure 9.1). There are several wind pumps abstracting water from the Nuwejaars River and its tributaries for livestock watering and domestic use. Such uses of water are not reflected in WARMS as they fall under general authorisations which do not require a water licence, according to the National Water Act of South Africa.

9.3 Farm dams

There are 239 farm dams identified on Google Earth images. Most of these dams are located in the upper part of the Nuwejaars Catchment in Quaternary Catchment GB50 (Figure 9.1). Quaternary Catchment G50C has very low gradients not suitable for rainwater harvesting using dams, and most of the tributaries are not perennial, hence only a few farm dams exist on this part of the Nuwejaars Catchment.

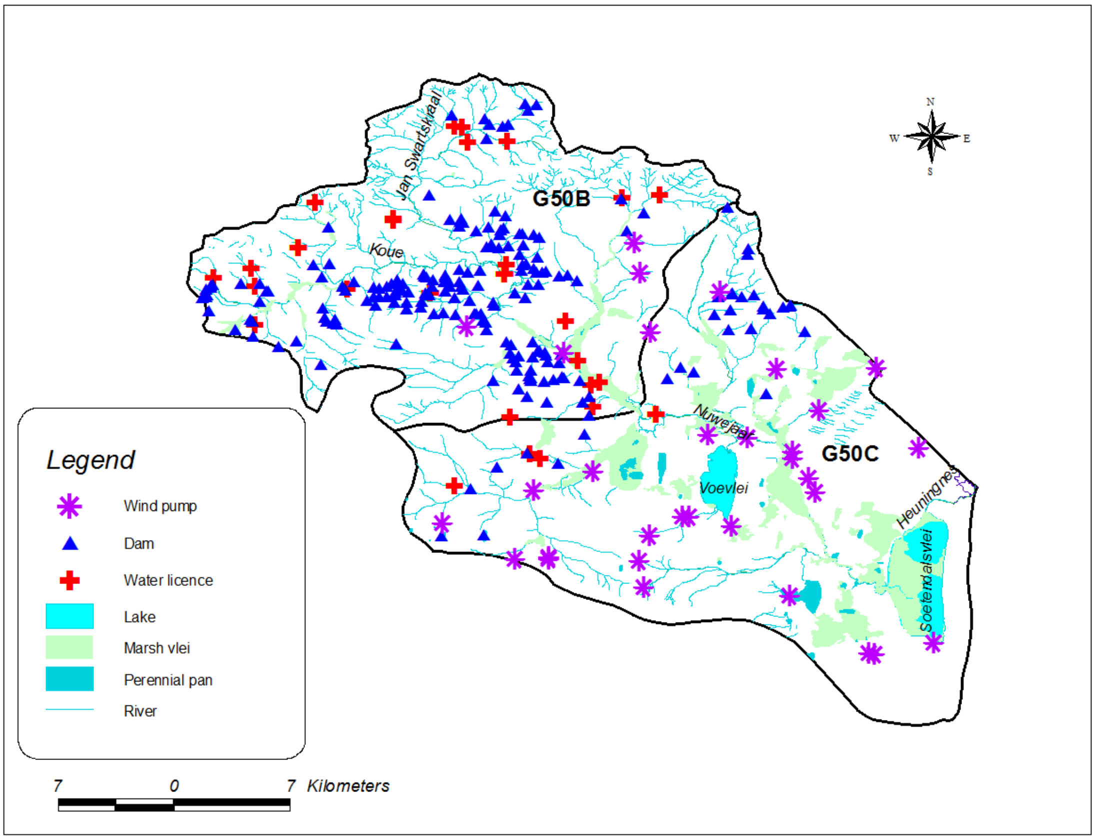


Figure 9.1: Locations of farm dams, wind pumps and water licences in the Nuwejaars Catchment

Most farm dams, 90%, are circular excavations without a dam wall on the downstream part. The remaining 10% have identifiable dam walls on the downstream part. For those dams that are almost circular excavations, they have an average width/length of 30–50 m. Dams with identifiable walls have average lengths of 170 m. Most of the dams, 66%, have surface areas less than 1000 m^2. (Figure 9.2).

McMurray (2004) evaluated seven methods for estimating the volume of water stored in farm dams in South Australia. A sample of 487 dams that had their surface areas and volumes estimated from surveying data was used. The shapes and sizes of the dams, and the terrain in the catchments were similar to those in the Heuningnes Catchment. McMurray (2004) also evaluated methods used in South Africa to estimate the storage capacity of farm dams. The following equation was recommended for estimating the volume of water (V in m^3) stored from the surface area (A in m^2).

$$V = 0.2\,A^{1.25} \qquad \text{if } A < 15\,000 \text{ m}^2 \qquad (9.1)$$

$$V = 2.2\,A \qquad \text{if A} \geq 15\,000 \text{ m}^2$$

This equation was used in this study. The storage capacity of farm dams varies from 35 to 275 000 m^3, and the total storage capacity is 2.1 million cubic metres. The total storage capacity of dams registered in WARMS is 0.222 million cubic metres. Thus, the estimated total storage capacity of farm dams, identified using Google Earth images, greatly exceeds what is reflected in WARMS.

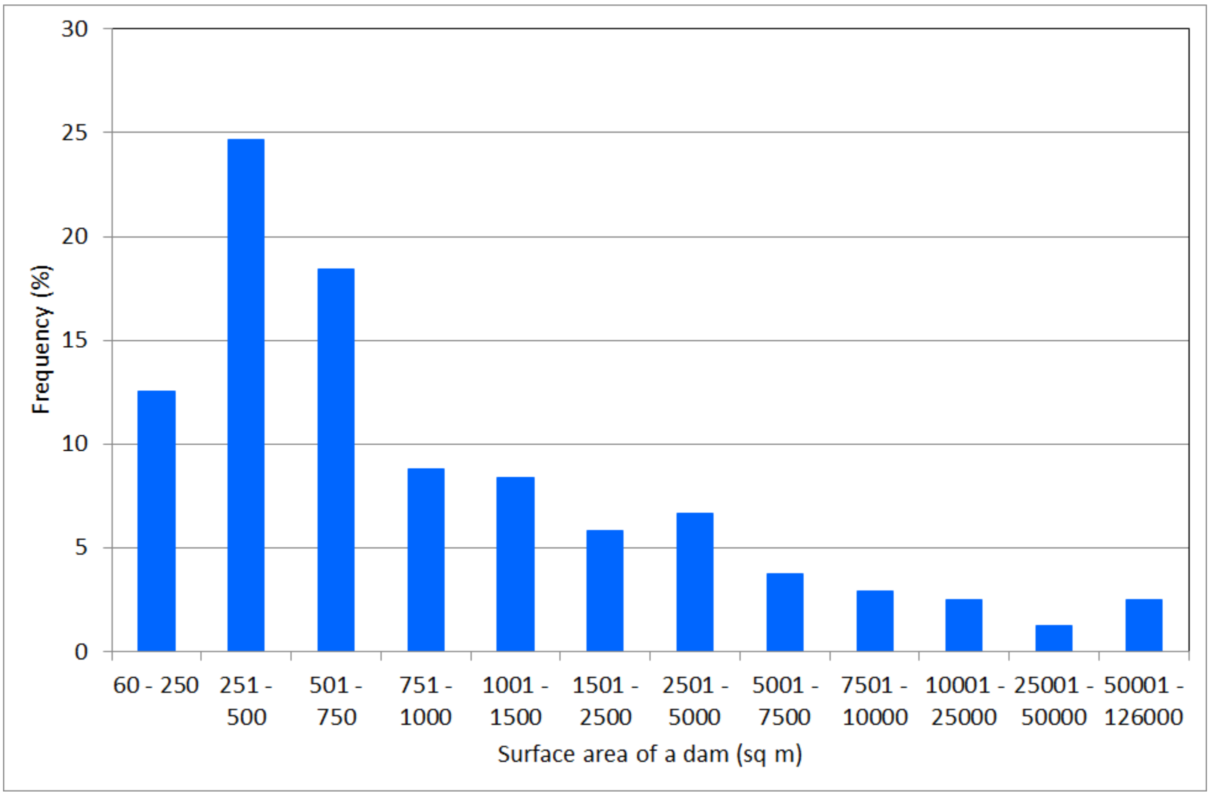


Figure 9.2: Frequencies of surface areas of dams, identified on Google Earth images, in the Nuwejaars Catchment

During the WR2012 assessment, the total surface area of dams in quaternary catchment G50B was estimated to be 0.03 km^2 while this study has found this to be about 0.77 km^2. The WR2012 gives the total volume of water in farm dams for G50B as 0.29 million cubic metres, while this study estimates this to be about 2.1 million cubic metres.

9.4 Crop water use

Data contained in the Cape FarmMapper (https://gis.elsenburg.com/apps/cfm/) of the Western Cape Department of Agriculture was used to establish areas under various crops, including the area irrigated (Figure 9.3). These data are based on a crop census done in 2013. Dryland crop production on 17 291 hectares is dominant in the Nuwejaars Catchment (Table 9.2). The major crops are wheat, barley and canola. Wine grapes, table grapes and olives are produced through drip irrigation on an area of 228 hectares or 1.3% of the total cultivated land in the Nuwejaars Catchment. The following vineyards occur in the study area:

- Zoetendals
- The Berrio
- Black Oyster Catcher on Moddervlei Farm
- Quoin Rock
- Strandveld on Blomfontein and Uintjeskuil
- Land's End

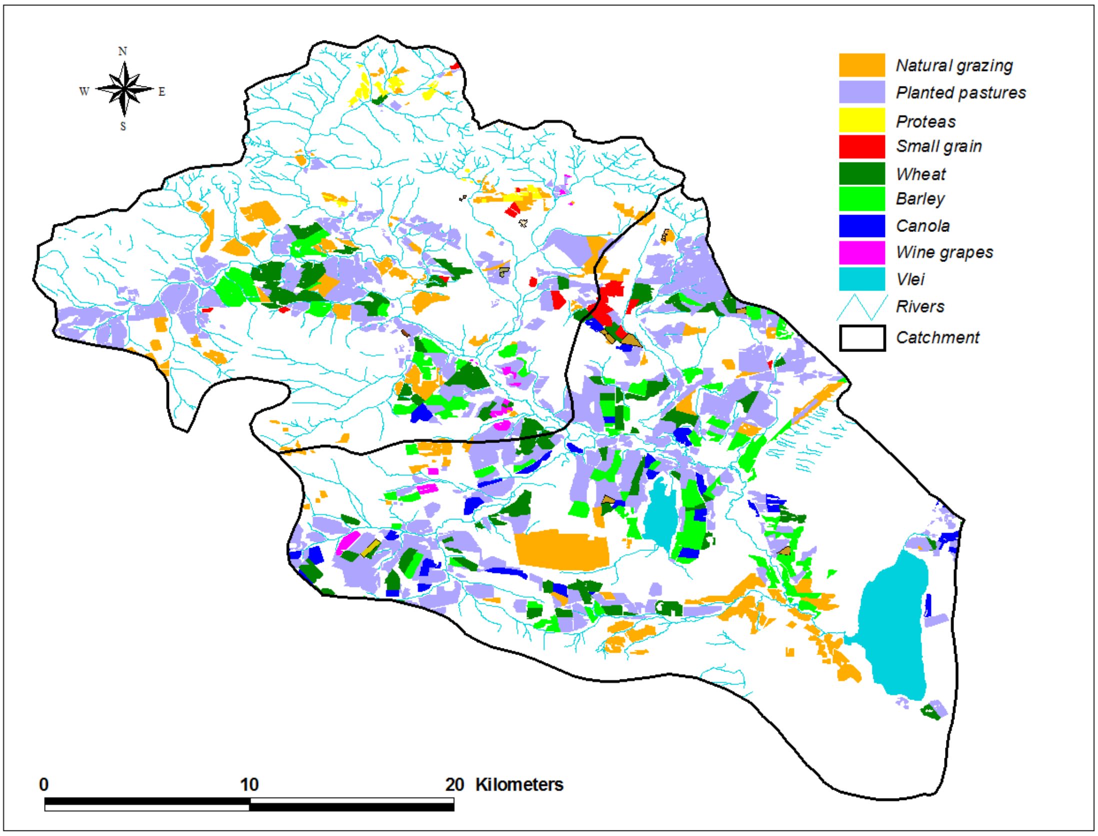


Figure 9.3: Crops produced within the Nuwejaars Catchment, based on the 2013 Crop Census data contained in the Cape Farm Mapper, developed by the Department of Agriculture, Western Cape Province https://gis.elsenburg.com/apps/cfm/

Table 9.2: Areas on which different crops are cultivated in the Nuwejaars Catchment, based on data in the Cape Farm Mapper developed by the Department of Agriculture, Western Cape Province

Crop	Area (hectares)
Dryland	
Barley	2 698
Canola	995
Wheat	2 878
Honey bush	10
Proteas	219
Other flowers	9
Small grain	6
Other vegetables	7
Lupines	92
Planted pastures (perennial), Lucerne/Medics	10 033
Small grain grazing	343
Total	17 291
Drip Irrigation	
Olives	13
Table grapes	26
Wine grapes	189
Total	228
Grand Total	17 519

SAPWAT4 (van Heerden and Walker, 2016) was used to estimate the crop water requirements for both rain-fed and irrigated major crops (Table 9.3). The total volume of water used for crop production in the Nuwejaars Catchment was estimated to be 62.8 Mm^3/yr. Irrigation of table and wine grapes and olives requires about 1.8 Mm^3/yr.

Table 9.3: Volume of water used for crop production in the Nuwejaars Catchment, estimated using SAPWAT4

Crop	Area (Hectares)	Volume of Water Used (Mm^3/yr)
Dryland		
Barley	2 698	7.5
Canola	995	2.3
Wheat	2 878	9.1
Planted pastures	10 033	40.5
Total	16 604	59.4
Drip Irrigation		
Protea	219	0.7 (Irrigation) & 0.9 (Rainfall)
Wine and table grapes, and olives	228	1.1 (Irrigation), & 0.7 (Rainfall)
Grand Total	16 832	62.8

The combined amount of water used for irrigated crops is 1.8 Mm^3/yr from irrigation water and 1.6 Mm^3/yr from rainfall.

9.5 Domestic water use

The major settlement is Elim, which is a Moravian Mission that was established in 1824. Elim had a population of 1412 persons during the 2011 population census. The main source of water for Elim is a spring which is supplemented by a borehole. The Elim Supervisory Board is responsible for operating and maintaining the water supply system. The spring and borehole have an estimated yield of 0.063 million cubic metres per year. Water from the Nuwejaars River is used for small-scale irrigation which includes production of fodder for the local dairy. A sluice gate diverts flows from a tributary of the Nuwejaars River into an unlined canal that conveys water into a storage dam from which water for irrigating dairy pastures is abstracted.

Water consumption by the Elim population was estimated to be 0.028 million cubic metres per year in 2010 (DWA 2011 Reconciliation Strategy for Elim). The Department of Water Affairs (currently known as the Department of Water and Sanitation) reported that 55% of the population had piped water inside their dwellings, 39% had yard taps, and 6% had standpipes. Unaccounted-for water was estimated to be 36%. Wastewater is treated through oxidation ponds located immediately northwest of the town.

Small-scale farming is practised in the Spanjaardskloof area which is 5 km north of Elim. The Cape Agulhas Municipality abstracts water from a spring, located on the Bredasdorp Mountains, for domestic water use by the Spanjaardskloof community which is made up of 150 persons. The Cape Agulhas Municipality indicated that they were supplying this community with 20 m3/day or 7 300 m3/yr. There are about 90 homesteads on large-scale commercial farms in the Nuwejaars Catchment, and each homestead has about 20 people, giving a total population of 1 800 people. Assuming a per capita water consumption of 130 l/day, the total amount of water for domestic use at homesteads is about 85 410 m^3/yr.

9.6 Livestock watering

The livestock census carried out in 2016 and 2017 by the Department of Agriculture of the Western Cape Province was used to estimate water use for livestock watering. Table 9.4 provides the population of different types of livestock in the Nuwejaars Catchment, and the estimated water use. Estimates of daily water consumption by the Department of Water and Forestry Water Quality Guidelines, Agricultural Use: Livestock Watering (DWAF, 1996) were used to determine water use by the livestock in the Nuwejaars Catchment. This guideline provides a range of water consumption, and the average of the lowest and highest rates was used for each type of livestock.

Table 9.4: Populations of different types of livestock and their estimated annual water use in the Nuwejaars Catchment

Type of Livestock	Number of Farms	Population	Daily Water Consumption Rate (litres/day)	Water Consumption (m^3/yr)
Beef cattle	14	2122	30	23 236
Dairy cattle	6	2327	60	50 961
Sheep	38	28331	4	41 363
Pigs	9	2843	15	15 565
Horses	9	407	45	6 685
Ostrich	8	179	not provided	not provided
Total				137 811

Based on the livestock population in the Nuwejaars Catchment, the amount of water required for livestock watering is about 140 000 m3/yr. Dairy cattle are estimated to consume the highest amount of water as they have a high water consumption rate. All the six dairy farms are located on land adjacent to the Nuwejaars River or its tributary which shows that these cattle depend greatly on the flow of this river, e.g. Elim, Weisdrif (Figure 9.4).

Similarly, most farms raising beef cattle are adjacent to the Nuwejaars River (Figure 9.4). Sheep production is the most popular livestock production activity and has the highest livestock population figures. Sheep are raised throughout the whole catchment. Watering of sheep consumes the second highest amount of water among the different types of livestock.

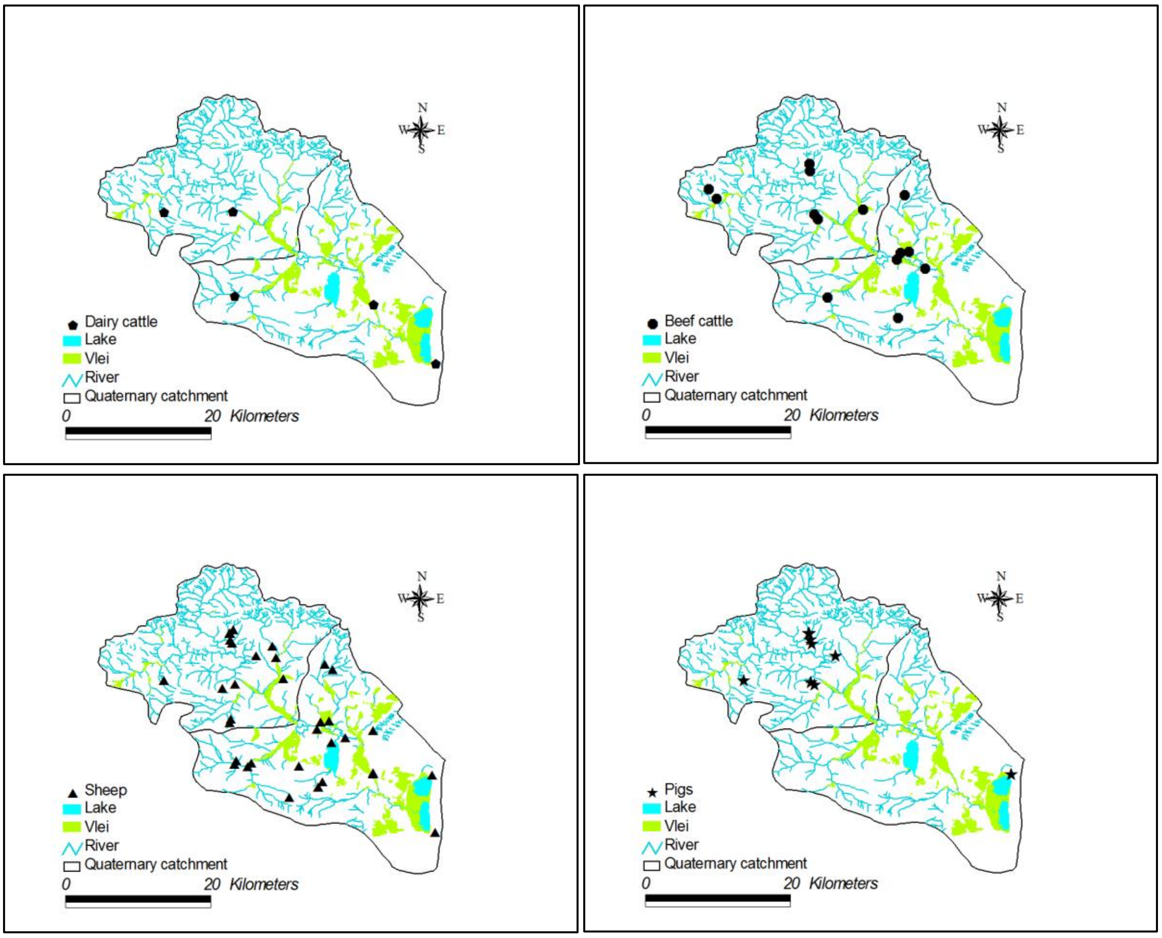


Figure 9.4: Locations where dairy and beef cattle, sheep, and pigs are raised within the Nuwejaars Catchment (Source: Dept of Agriculture, Western Cape Province)

9.7 Impact of water use on catchment water resources

The production of fodder in pastures uses the largest amount of water in the Nuwejaars Catchment. This uses about 40.5 Mm3/yr or 13% of the rainfall. Dryland crop production is the second major use of water taking 18.9 Mm3/yr or 6% of the rainfall. Domestic use of water is negligible. Most of the water for domestic use is from groundwater, mainly from springs. The Nuwejaars Catchment is therefore dominated by green water use.

The total volume of water which can be stored in farm dams is about 11% of the mean annual runoff. The storage of water in these dams may have some effects on available surface water resources during years with below-average rainfall.

The current major uses of water (pasture and dryland crop production) in the Nuwejaars Catchment do not have as direct an impact on river flows as would occur if river water abstraction was dominant. The impact is indirect, through the transformation of the land surface from natural land over to cultivated lands, which affects the partitioning of rainfall. This study has not examined this impact. The Nuwejaars Catchment has a long history of human settlement for agriculture with a considerable number of landowners being the fourth generation farming the same lands. There have not been any recent major changes in land use in this catchment that would have affected inflows into the Soetendalsvlei.

10 CONCLUSION

10.1 Establishment of a living laboratory

The project has successfully developed a catchment monitoring system in the Heuningnes Catchment, particularly in the part drained by the Nuwejaars River, which comprises the following:

- 5 weather stations
- 13 river water level measuring stations
- 2 lake level measuring stations
- 14 monitoring boreholes
- 26 piezometers
- 2 sap flow monitoring systems

All the water level measuring stations, and 11 of the monitoring boreholes have data loggers recording data at 15 to 60 minute intervals. The establishment of this monitoring system has enabled various types of research on water resources in the Nuwejaars Catchment.

The establishment of the above catchment monitoring system has benefited 39 honours, MSc and PhD students.

The development of the Heuningnes Catchment as a living laboratory has fostered institutional collaboration between the University of the Western Cape and the following partners:

- Cape Peninsula University of Technology
- Council for Scientific and Industrial Research
- South African Environment Observation Network
- Breede-Gouritz Catchment Management Agency
- Nuwejaars Wetlands Special Management Area
- University of Twente, The Netherlands

10.2 Spatial and temporal variations of rainfall and evapotranspiration

During 2015, which was a relatively wet year, the upland areas of the Nuwejaars Catchment received 629 mm of rain whereas the southern part of the catchment received 558 mm. Rainfall occurs throughout the year, but about 60% of the annual total rainfall is received during the June to September period. During these months rainfall is received on 10–12 days in a month.

The general perception that rainfall has been decreasing was not supported by the results of the analysis of the 1909 to 2016 monthly rainfall at Zeekoevlei. There was no evidence of change in median or mean annual and seasonal rainfall. There are no trends in the rainfall time series.

10.3 Groundwater

The monitoring boreholes have revealed the existence of a shallow aquifer and a deep aquifer in the study area. The response to rainfall varies at the sites investigated. On some of the hillslope sites, water tables respond to rainfall within a short period, while on other sites, effects of rainfall are not immediately apparent. There is also evidence of deep groundwater moving upwards, indicating that the floodplain wetlands are likely to be discharge areas for regional groundwater flow. There is a close connection between groundwater and surface water systems in the upper catchment. The depth to the water table at drilled sites on hillslopes was less than 2 m. Springs and diffuse interflow contribute substantial flows to rivers, especially during the dry season. Boreholes drilled in the weathered shale had high specific conductance. Shallow groundwater floodplains around Soetendalsvlei have very high salinity.

10.4 Contributions of sub-catchments

There was no significant runoff generated by rainfall events of less than 15 mm/day in the Nuwejaars Catchment. At the beginning of the wet season, significant flows occurred when the cumulative rainfall exceeded 50 mm. The Moddervlei floodplain wetland occurring along the Nuwejaars River can store up to 5.8 Mm^3/yr, which causes significant reduction of peak flows. Water stored in this wetland will drain out until December when the river dries out. During 2015, the Nuwejaars River generated 43.885 Mm^3, which was discharged into the Soetendalsvlei. This flow declined to 15.662 Mm^3 in 2016. Rainfall records at Zeekoevlei show that 2016 received rainfall equivalent to 90% of the long-term average annual rainfall. Thus, the runoff generated in 2015 was close to the mean annual runoff of this catchment. The WR2012 assessment estimated the average annual flow of the Nuwejaars River to be 18.8 Mm^3/yr. Based on the data collected in this project, the WR2012 is considered to be a realistic estimate of the mean annual runoff. Quaternary catchment G50B generates about 70% of the annual flow of the Nuwejaars River. The contributions of sub-catchments to total flow varied from 16% to 27% depending on catchment size, gradient and rainfall.

10.5 Water quality

River water along rivers in the uplands on the upper part of the Nuwejaars Catchment is acidic. As the rivers pass through areas underlain by the Bokkeveld shales in the lowlands, the water becomes alkaline. Dissolved oxygen is high in upland areas and decreases in the wetlands. River flows in the upland areas have low salinity. Flows from Voëlvlei significantly contribute salts to the Nuwejaars River. Outflows of the Soetendalsvlei have higher salinity than the inflows. The differences in pH and salinity throughout the catchment area are due to land cover, groundwater, and underlying geology. Pastures and feeding sites of dairy cows adjacent to the Nuwejaars River at Elim and Weisdrif contribute nutrients to river flows.

10.6 Water balance of the Soetendalsvlei

The bathymetric survey showed that this lake has a maximum depth of about 2.25 metres, a surface area of 1558 hectares, and a storage capacity of 20 million cubic metres. The minimum storage required for the Soetendalsvlei to discharge into the Heuningnes River is 11.248 Mm^3. The highest water levels in this lake occur in September resulting in also the highest rates of downstream discharge. Soetendalsvlei does not frequently discharge flows throughout the year. The 1989–2016 Landsat images showed that lake levels were less than the threshold level for outflows for varying periods during 72% of these years. River inflows contribute 80% to 88%

of the water, with the remainder coming from rainfall over the lake. When lake levels are high, outflows into the Heuningnes River constitute 66% of the losses, with the remainder being evaporation losses. In a year with low lake levels such as in 2016, evaporation losses constituted 78% of the outflows.

The study was not able to establish the influence of surface water-groundwater interactions on water storage in the lake.

10.7 Water use by invasive alien *Acacia longifolia*

Soil water content for the hillslope and riparian sites responded differently to rainfall events. At the hillslope, infiltration caused movement of water from the surface vertically downwards, with shallow soil being wetter than deep soil. At the riparian site, deep soil had higher water content than shallow soils after a rainfall event. This was indicative of preferential downward movement of water through animal burrows, and other macropores.

The annual transpiration rate by *A. longifolia*, during the study period from June 2016 to June 2017, was 241 mm on the hillslope compared with 596 mm at the riparian site. These results suggest that, at the stand level, the riparian trees used more water than the hillslope trees, which was expected. After the wet season, transpiration rates at the riparian site were constrained by soil water content. This was not expected, as the assumption was that due to proximity to the river channel, soil water content will not be a limiting factor. Unstressed transpiration rates were estimated to be 596 mm/yr and 1348 mm/yr for the hillslope and riparian site respectively.

Based on the national invasive plant survey by Kotzé *et al.* (2010), the area in the whole of the Nuwejaars Catchment which has been invaded by invasive alien plants is equivalent to 7 930 hectares, at 100% density of these plants. If other invasive alien plants in the Nuwejaars River, which are mainly Acacia species, have similar transpiration rates to those obtained in this study, then the invasive plants in the Nuwejaars Catchment are using 20.8 Mm^3/yr. This amount could be as high as 49 Mm^3/yr depending on prevailing soil water content. The incremental water use of invasive alien trees was estimated to be in the region of 15 Mm^3/yr.

10.8 Water use

The total volume of water that has been registered by water users on the WARMS database is 4.7 million cubic metres, and most of these registrations (59%) are for abstracting river water for agricultural purposes. The study established that there are 239 farm dams, most of which do not require water licences. The total volume of water stored in farm dams is about 2.1 million cubic metres. There are 228 hectares under irrigation for wine grapes, table grapes, and olives. The total amount of water used is about 1.8 million cubic metres. Dryland crop production used, on average, 18.9 Mm^3/yr, while pastures use 40.5 Mm^3/yr. Use of water for domestic purposes and livestock watering consumes an insignificant amount of water. Water use in the Nuwejaars Catchment is therefore dominated by the use of green water for crop and pasture production.

10.9 Water balance and implications for "new" water

The water balance of the Nuwejaars Catchment was derived using information about average annual rainfall, mean annual runoff, and estimated use of water for crop production. (Table 101.1).

Table 10.1: Water balance of the Nuwejaars Catchment

Water Balance Component	Input (Mm^3/yr)	Output (Mm^3/yr)	Output as % of Rainfall
Rainfall	319.3		
Mean annual runoff		18.8	5.9
Groundwater recharge		4.2	1.3
Dryland cultivation		18.9	5.9
Pastures		40.5	12.7
Irrigated crops		3.4	1.1
Invasive alien plants		20.5	6.4
Farm dams		2.**1**	0.7
Domestic use and livestock watering		0.3	0.1
Total	319.3	108.7	34.0
Actual evapotranspiration (shrublands, etc.)		210.1	66.0

Actual evapotranspiration by shrublands is equivalent to 411 mm/yr. River flows and dryland crop production each account for 6% of rainfall.

New water is likely to be made available by clearing invasive alien trees. If we assume that all the invasive alien trees transpire at rates similar to those measured in this study, the trees in this study used 20.5 Mm^3 in the year from June 2016 to June 2017, which was a relatively dry period. When unstressed transpiration rates are assumed, the water use by these trees can be as high as 49 Mm^3/yr. The riparian areas of most rivers, including the floodplains in the Nuwejaars Catchment, have grasses as the natural vegetation. The measured and unstressed transpirations rates are, respectively, 18% and 168% greater than the rates for perennial grasslands. The alien trees also block channels. This study did not monitor water use by the fynbos vegetation occurring on hillslopes. Assuming that the water use rate of fynbos on non-riparian areas will be similar to seasonal pastures (442 mm/yr), the unstressed water use rate is 36% or 11.6 Mm^3/yr greater than that of fynbos. In an average year without severe water stress, the incremental water use or new water that can be salvaged by clearing invasive plants from riparian and non-riparian areas will be about 15 Mm^3/yr. The solution to finding new water is therefore to clear invasive alien plants, especially along streams that are fed by springs during the dry season.

10.10 Using new water to address competing and conflicting water demands

The work done in this study has demonstrated that by clearing invasive alien trees, there is a potential to make “new” water available. This new water can be used to address existing competing and conflicting water demands. In the Nuwejaars Catchment, the invasive alien trees have a unique effect because of the linkages between groundwater on uplands and rivers throughout the catchment. The invasive alien trees reduce the water table on hillslopes, thereby decreasing spring discharges that maintain dry season flows. When spring discharges reach rivers, the riparian invasive alien trees are consuming water at rates that are over twice the indigenous trees, and thus causing another decline in flows.

Farmers located in the uplands currently perceive that the benefits of their clearing of invasive alien trees mainly accrue to downstream landowners. Part of the water salvaged from clearing of invasive alien trees should be considered for allocation to the upland farmers as an incentive for them to continue clearing these trees. The upland farmers will also benefit from the additional water which will support livestock watering. The BGCMA should continue monitoring river flows on the main rivers and use the information collected to demonstrate to farmers the benefits they are realising, even if no water allocation is done but for livestock watering.

Invasive alien trees on hillslopes are currently decreasing diffuse interflow and spring discharges that sustain dry season flows. Clearing of these trees will increase dry season flows of the respective rivers and the downstream floodplain wetlands along the Nuwejaars River. This will contribute towards enhancing biodiversity, such as through the re-introduction of wildlife like hippopotamuses and buffaloes, which has been proposed by members of the Nuwejaars Wetlands Special Management Area. Future monitoring of river flows may show that there is a potential for allocating some water for vineyards. If this is proven, then the new water arising from clearing of invasive alien trees will have resolved a conflict between water use for biodiversity maintenance and water use for crop irrigation.

Some emerging farmers in the Nuwejaars Catchment wish to be considered for water allocation. Part of the water salvaged from clearing invasive alien plants should be considered for allocation to these emerging farmers. The Breede-Gouritz Catchment Management Agency should use the monitoring system developed in this study to establish the amount of water that can be allocated to these farmers.

This study has tentatively observed that faults occurring in the Nuwejaars Catchment are important for regional groundwater flow. If this is confirmed by further detailed studies, then tapping groundwater occurring in some of the faults will contribute to addressing some water demands, such as irrigation of vineyards. This will go a long way to resolving the conflict between providing water for maintaining biodiversity along the Nuwejaars River, and using the same river for irrigation. The vineyards in this catchment are contributing to the much-needed growth in tourism.

11. RECOMMENDATIONS

11.1 Enhancing the functioning of the living laboratory

There are currently 17 postgraduate students doing research in the Heuningnes Catchment. In order for this living laboratory to continue benefiting these and future students, there is a need to continue maintaining the monitoring equipment and continue investing in replacement of equipment when the need arises.

The Heuningnes Catchment is located in the southern-most part of Africa. Long-term monitoring will facilitate understanding of issues related to global change in this part of Africa. Collaboration with the South African Environment Observation Network (SAEON) to ensure long-term monitoring in the Heuningnes Catchment is necessary.

The role of citizens such as landowners participating in catchment monitoring needs to be explored. Most of the landowners have an interest in understanding their catchment, and are likely to be willing to share data based on their observations.

11.2 Short-term variations of weather elements

Data on weather elements are being collected at 15-minute intervals. There is need for further analysis of data at this time interval to improve understanding of diurnal variations of weather elements in this southern-most part of Africa. Regular calibration of sensors for weather monitoring is necessary.

11.3 Assessment of river flows

The accuracy of rating curves for the river flow measuring stations that have been established needs to be improved through regular discharge measurements during the wet season. Consideration needs to be given to including the following stations in the Department of Water and Sanitation's hydrological monitoring system: a) Nuwejaars River at Elandsdrift, and b) Soetendalsvlei lake level monitoring at the Vissersdrift Homestead.

11.4 Surface water–groundwater interactions

The Nuwejaars River comprises uplands in the Koue and Bredasdorp Mountains, and lowlands dominated by floodplain wetlands. The spatio-temporal dynamics of water resources are influenced by surface water–groundwater interactions in these different parts of the catchment. An improved understanding of these dynamics is critical for sustainable water resources management. Use of either surface water or groundwater, including effects of invasive alien plants on each of these, affects sustainable utilisation of ecosystem services. The role of surface water in recharging groundwater in floodplain wetlands, and, similarly, the role of groundwater in sustaining surface water in floodplain wetlands and lakes (Soetendalsvlei, Voelvlei, Longpan, Roundpan) is not understood. Further research with the following objectives is therefore recommended.

i. To establish the nature of surface water–groundwater interactions from headwaters to lowlands.

ii. To explore the potential of using information about landscapes and fluvial processes to predict locations with different forms of surface water–groundwater interactions along a river.
iii. 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.
iv. To examine how surface water–groundwater interactions influence ecosystems from headwaters to lowlands.
v. To explore opportunities for managing surface water–groundwater interactions at the catchment scale, and how these options can be integrated in a catchment management plan.

11.5 Water use by invasive alien trees

The investigation of water use by *Acacia longifolia* occurring on hillslope and riparian sites has provided some unexpected and interesting results, i.e. water use per tree on the hillslope is higher than at the riparian site. Further investigations to validate these findings are necessary. Water use by other tree species, such as *Acacia saligna*, occurring on both hillslopes and riparian zones, needs to be monitored to establish if the findings made so far are site or species specific. An investigation aimed at scaling up measured water use rates to the catchment scale using remote sensing is necessary. The use of hype-spectral images for mapping areas affected by specific invasive alien species needs to be considered.

11.6 Connectivity and water quality

The water quality investigations undertaken have not adequately demonstrated how the connectivity between surface water in the main channel and off-channel pools along the Nuwejaars River affects water quality. Furthermore, the influence of surface water–groundwater interactions along the whole Nuwejaars River is not well understood. Further studies on these aspects are recommended.

11.7 The ecology of the wetlands

The Heuningnes Catchment hosts several wetlands – some that are saline, freshwater lakes, and floodplain wetlands. Landowners have formed the Nuwejaars Nature Reserve with the aim of achieving sustainable management of the wetlands. There is inadequate knowledge about how the dynamics of both quantity and quality of surface water and groundwater influences these ecosystems, and services derived from them. Studies aimed at improving understanding of the ecology of the wetlands should be considered.

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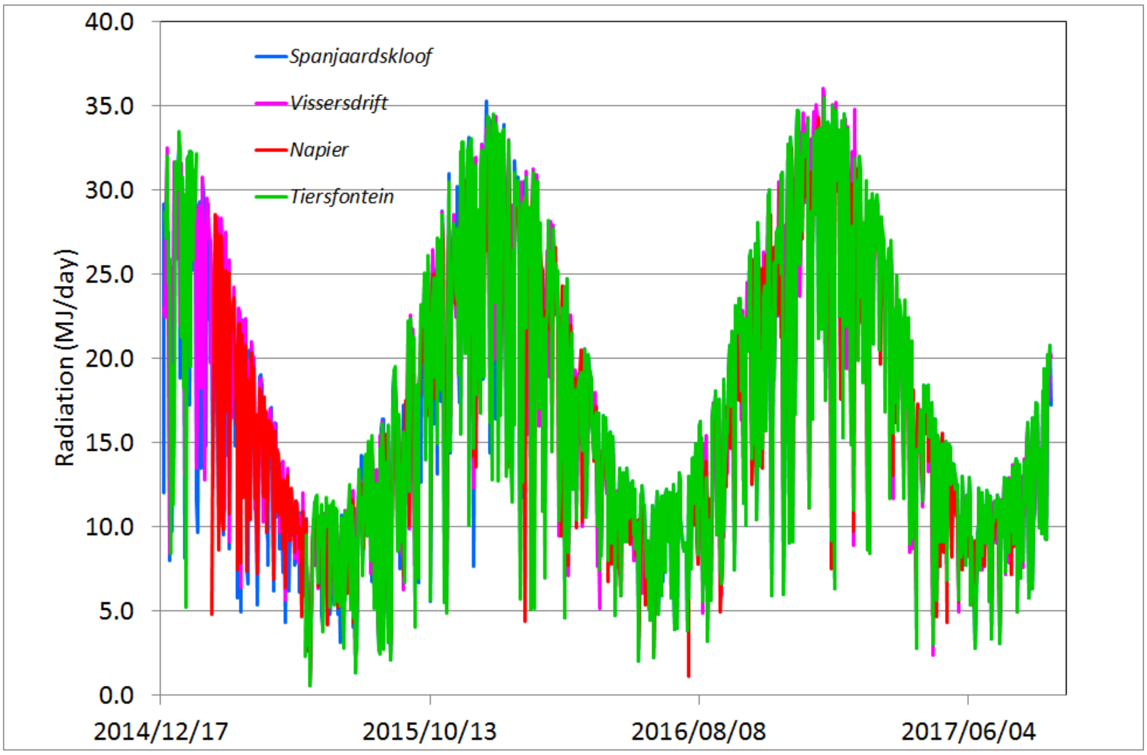
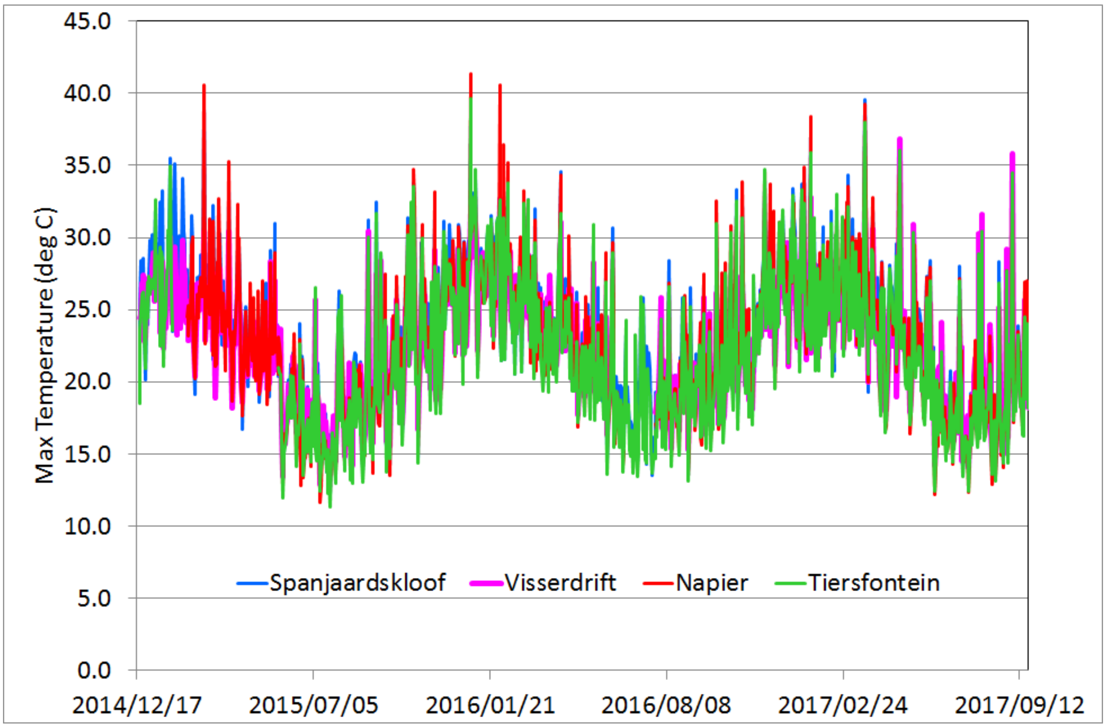
APPENDICES

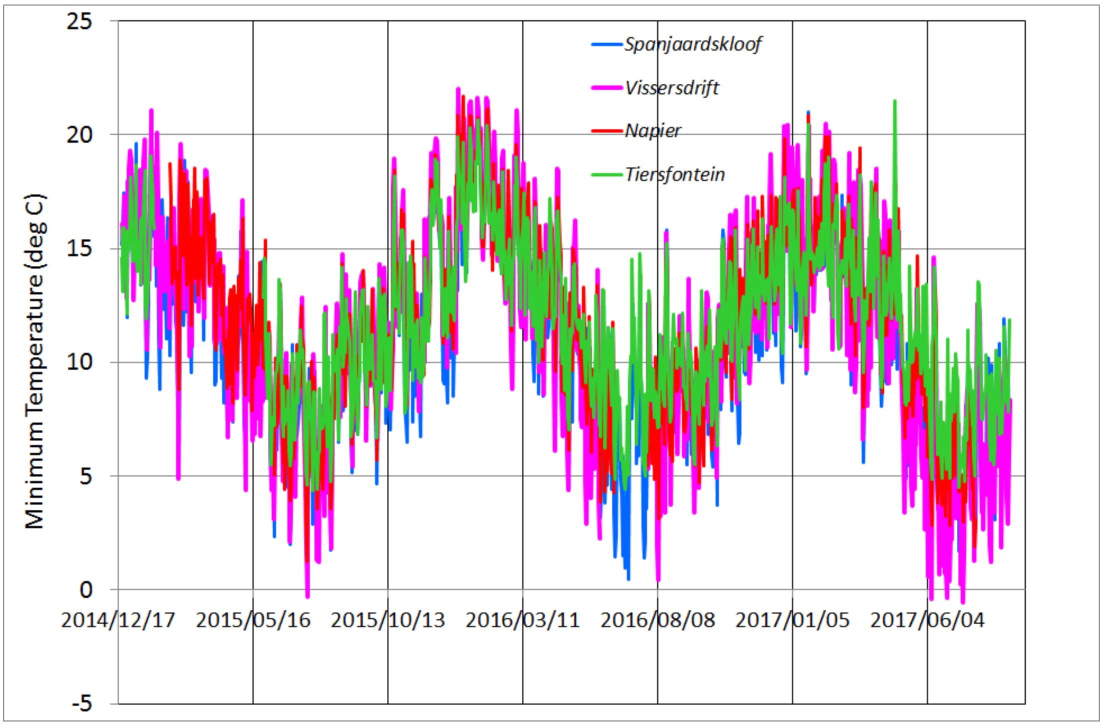
APPENDIX 1: DAILY VARIATION OF SOLAR RADIATION



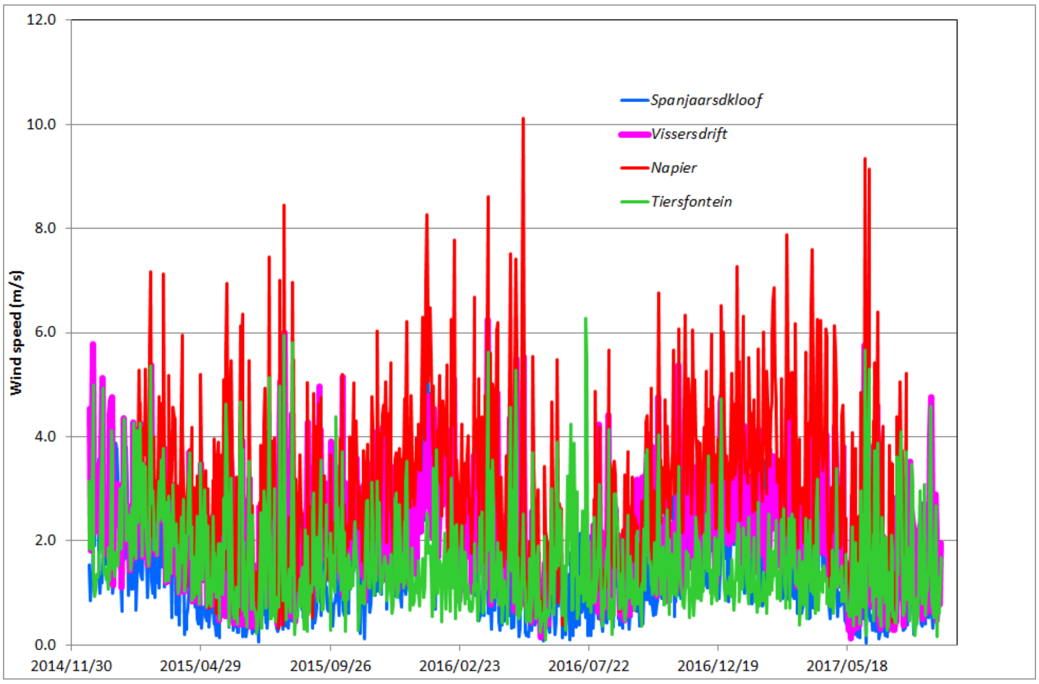
APPENDIX 2: MAXIMUM DAILY TEMPERATURES



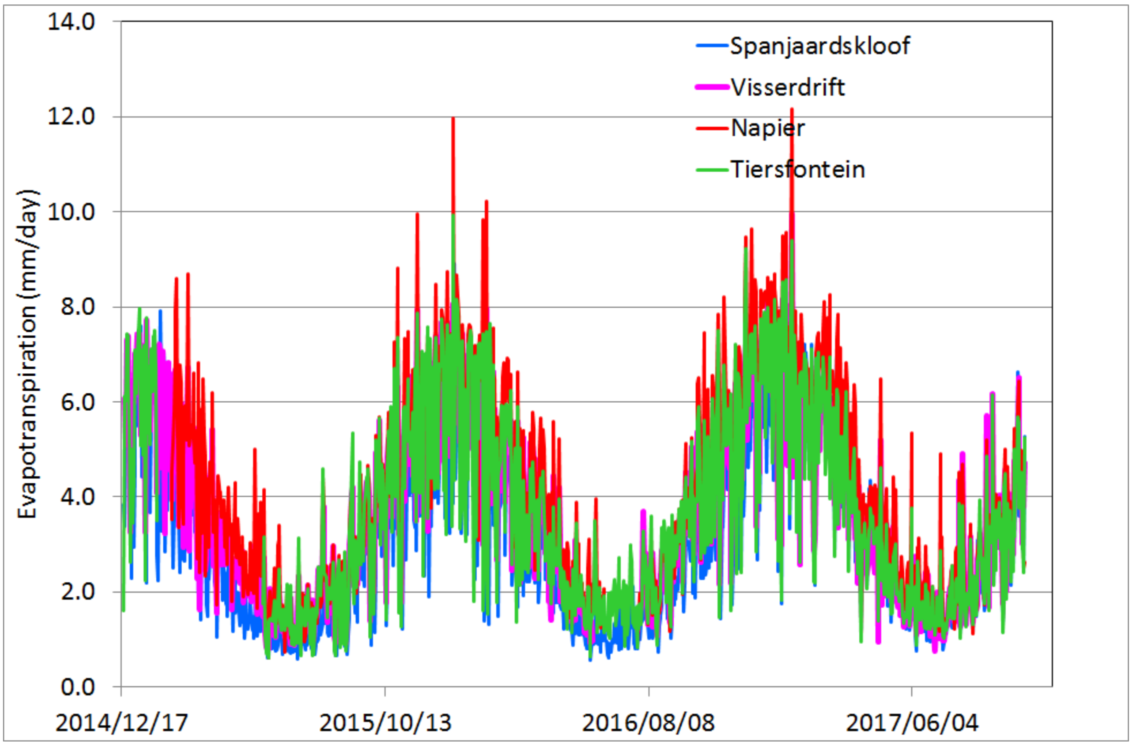
APPENDIX 3: DAILY MINIMUM TEMPERATURES



APPENDIX 4: AVERAGE DAILY WIND SPEED



APPENDIX 5: DAILY SURFACE WATER EVAPORATION RATES



APPENDIX 6: CAPACITY BUILDING

The project funded bursaries for four MSc students who are still continuing with their studies. In total, 38 students have benefited from the establishment of the Heuningnes Catchment as a research site with an operational hydrological data collection system. The table below gives a break-down of these students based on their status and degree programmes.

Number of students who have benefited from the establishment of monitoring systems within the Heuningnes Catchment

Status	**Honours**	**MSc**	**PhD**
Graduated	14	6	1
Continuing		17	
Total	**14**	**23**	**1**

Two technical officers have received informal training on installation and maintenance of hydrological monitoring equipment.

A research open day was held in September 2017 during which the research team, including students, gave presentations to local community members and other stakeholders. This provided an opportunity for informal capacity building of both the community members and the researchers through exchange of information.

APPENDIX 7: CONFERENCE PRESENTATIONS

1) Carolissen, M. and Williams, S. 2017. *Strategies employed by farmers to retain or access water use: A South African case study*. 25-27 October 2017, Waternet/GWPSA Annual Symposium held in Swakopmund, Namibia.
2) Mkunyana, Y. 2017. *Assessing water-use dynamics by invasive Acacia longifolia trees occurring on hillslopes and in riparian zones of the Heuningnes Catchment, Western Cape* 25-27 October 2017, Waternet/GWPSA Annual Symposium held in Swakopmund, Namibia.
3) Mehl, D. 2017. *Influence of valley-bottom wetlands on wet and dry season river flows along the Nuwejaars River, Western Cape, South Africa*. 25-27 October 2017, Waternet/GWPSA Annual Symposium held in Swakopmund, Namibia.
4) Hans, D. 2017. *Assessing the effect of the Kars Wetland on flow attenuation in the Cape Agulhas, South Africa*. 25-27 October 2017, Waternet/GWPSA Annual Symposium held in Swakopmund, Namibia.
5) Ndara, N., Jovanovic. N. and Mazvimavi, D. 2016. *Analysis of monthly MOD16 evapotranspiration rates at sites with different climatic characteristics; Heuningnes and Letaba catchments in South Africa*. Waternet/WARFSA/GWP SA 27-29 October 2016 Annual Symposium, Gaborone, Botswana.
6) Maswanganye, E., Grenfell, M. and Mazvimavi, D. 2016. *A comparison of remotely-sensed precipitation estimates with observed data from rain gauges in the Western Cape, South Africa*. Waternet/WARFSA/GWP SA 27-29 October 2016 Annual Symposium, Gaborone, Botswana.
7) Carolissen, M. 2016. *Ecosystem services: a community value approach – Pilot study*. The 3rd Annual BGCMA Seminar. Goudini Spa, Worcester, March 2016.
8) Carolissen, M. 2017. *Ecosystem services: a community value approach*. The 4th Annual BGCMA Seminar. Caledon, March 2017.