Distributive rainfall/runoff modelling to understand runoff to baseflow proportioning and its impact on the determination of reserve requirements of the Verlorenvlei estuarine lake, west coast, South Africa

Andrew Watson[1], Jodie Miller[1], Manfred Fink[2], Sven Kralisch[2], Melanie Fleischer[2], and Willem de Clercq[3]

Reviewer 1: Overall, the stated context of this paper is the determination of the ecological reserve, as supported by rainfall/runoff modelling. However, the environmental flow parts of the paper are far too simplified to justify publication." And "I am surprised that the authors did not do some time series water balance modelling of the lake using the simulated inflows and reduced inflows to represent a 'reserve'."

Please note change of title to due comments from reviewer 1

Reviewer 1: Anonymous

1) Many of the references in the introduction are quite old, both those that refer to environmental flow requirement methods, as well as those referring to rainfall-runoff modelling approaches. I would have expected to see more references to the uncertainties inherent in hydrological modelling in a paper where there are limited gauging data to calibrate, assess and validate the model.
Response- Accepted changes made: **References have updated with more relevant literature, although no changes make in regard to referring runoff-model limitation and inclusion of why the models were chosen has been made.**

2) The paper refers to Veloronvlei as both a lake and an estuary, which is it? How often is this water body linked to the sea and therefore how often is the water level influenced by sea water inputs? This is not mentioned in the paper at all apart from a passing reference to a sand bar.
Response- Accepted changes made: **Its an estuarine lake,** (Sinclair et al., 1986), "A sandbar created around a sandstone outcrop (Table Mountain Group) allows for an intermittent connection between salt and fresh water. During storms or extremely high tides, water scours the sand bar allowing for a tidal exchange, with a constant inflow of salt water continuing until the inflow velocity decreases enough for a new sand bar to form (Sinclair et al., 1986)" Line 129-133. **I am afraid there is little information about the coastal exchange, and is something we want to look at into the future as it has a bearing on the lake water level.**

3) The paper also makes no mention of whether the lake/estuary receives any direct inputs from groundwater and while this may not be the case, this issue should at least be addressed as part of the simulation of the water balance.
Response- Rejected paper unchanged: **Regarding the lake receiving direct inputs from groundwater, the daily evaporation rates in the sub-catchment are very high in which case groundwater contributions could be significant, although these volumes are not enough to counteract the daily evaporation potentials.**

4) The introduction refers to setting the ecological reserve, but it only becomes clear later that the paper is focused on the reserve for the lake/estuary and not for the rivers themselves.
Response- Accepted changes made: **Revised paper talks about the reserve as opposed to ecological reserve of each river**

5) Equation 1 provides, what appears to be, the overall water balance equation for the model but makes no reference to a groundwater component.
Response- Rejected paper unchanged:
Reviewer 1 is correct that equation 1 refers to the overall water balance used, and it is not immediately clear how groundwater is part of the model presented, although equation 2 and 3 explain how recharge and interflow is determined, while equation 4 and 5 outline how slow and fast groundwater flow is calculated in the model.

6) The way in which the model is described is incomplete and yet a lot of detail is given. A flow diagram would have helped and I had to go to the journal of hydrology paper to get a real sense of how the model actually works.
Response- Accepted changes made: **A flow diagram has been included which shows the processed followed by the modelling**

7) Why is slope considered to be a major forcing parameter of recharge? Recharge is largely a vertical drainage process and would be influenced much more by the drainage characteristics of the material in the unsaturated zone than the surface slope of the topography.
Response- Rejected paper unchanged: **Regarding the slope factor, this is a component of the J2000 model (Krause et al., 2005) and is a calibration factor used to determine the proportion of percolation to interflow (http://jams.unijena. de/ilmswiki/index.php/Hydrological_Model_J2000). It essentially represents the forces in the triangle of gravitation, normal force and frictional force. The latvertdist parameter is a representation of anisotropy, which modifies the forces triangle.**

Section 4.1.2 indicates that the recharge estimates of the rainfall/runoff model were based on the estimates from MODFLOW – this is equivalent of calibrating one model against another and the validity of this approach needs to be further supported and the inherent uncertainties discussed. Line 372 suggest that the MODFLOW recharge values were 'validated' with J2000 recharge estimates. You cannot validate one model against another, all you can say is that the two models were in broad agreement.
Response- Accepted changes made: **Adjustments have been made throughout the paper to align with the comments above.**

Reviewer 1: Page 16 (and elsewhere) refers to an apparently non-standard use of the Nash-Sutcliffe efficiency statistic and refers to Watson et al., 2018. However, in neither of these papers could I find a definition of these (E2 and E1) statistics. If they are not the standard statistic then they need to be defined.
Response- Rejected. **The Nash-Sutcliffe presented is in standard form of efficiency and will not be discussed in this contribution. Refer to Nepal, S., 2012 for more on this.**

Nowhere in the paper could I find mention of how water use and its impacts on the gauge data (and the inflows into the lake from the ungauged catchment) have been taken into account in the model.
Response- Noted, changes made. "During winter, the majority of the irrigation water needed for crop growth is supplied by the sub-catchment tributaries or lake itself, although the impact of irrigation is still regarded as minimal (Meinhardt et al., 2018) and requires future investigation"
While this is a valid comment, the incorporation of irrigation and groundwater abstraction is a future interest and when the data is available this will be incorporated in a future contribution.

At the same time, Google Earth clearly indicates that there is extensive water use in the catchment (centre pivots, farm dams etc.) that are likely to affect both surface water and groundwater dynamics. The indications are therefore that the model has been setup to represent natural conditions (i.e. ignoring water use), while it has been calibrated against an observed record that

reflects water use (the same comment applies to the earlier paper published in Journal of Hydrology).
Response-Rejected, no changes made. **The reviewer is correct that if you look at current Google Earth imagery of the catchment, there is clearly extensive agricultural development with many centre pivots which would impact streamflow. However, the model was calibrated between 1987 to 1993 (Fig. 7), when agricultural withdrawals from the catchment are far less intense (see Google Earth). Moreover, the model was calibrated for the Kruismans tributary (Fig 1), which has a far lower water footprint as the number of centre pivots are far less than the rest of the sub-catchment even today. Therefore, the calibration was conducted when river flow regimes where relatively unaltered and parameters estimated are valid for this sub-catchment. During the periods where there was no observed data (2007-2018), the data was set as missing values as presumed by the reviewer.**

The presentation and discussion of the streamflow and baseflow results and other results (5.1 to 5.4) would have been clearer if presented in a table(s) supported by some explanatory text. I am surprised that the authors did not do some time series water balance modelling of the lake using the simulated inflows and reduced inflows to represent a 'reserve'. This would have avoided all the simplifications about an average evaporation loss. This would have been simple to do using a reservoir model. The reservoir model outputs using the simulated inputs could then have been converted to depths and compared with the observed depth data offering an additional method of assessing the model results. While some bathymetry data would be needed, I am sure some estimates could have been made, even if detailed bathymetry data are not available.
Response- Accepted changes made: **New figures have been included in the results section with the model incorporating lake ET.**

Page 32 suggests that the 95th percentile is the ecological reserve percentile. This is simply not true. In South Africa (and most other countries) the reserve (or EWR) is expressed as a variable flow regime and never as a fixed FDC percentile. I am afraid that the whole discussion about the reserve indicates that the authors have little understanding of how reserves are estimated in a South African context.
Response- Accepted changes made: **Changes have been made to the paper so that the new version does not conflict with how ecological reserves are determined in South Africa.**

Overall, the stated context of this paper is the determination of the ecological reserve, as supported by rainfall/runoff modelling. However, the environmental flow parts of the paper are far too simplified to justify publication. The paper therefore ends up being mostly focused on the hydrological model. However, there are not enough details provided in this paper to really assess the model or the results and heavy reliance is made on references to an earlier paper published in the Journal of Hydrology
Response- Accepted changes made: **As per above comment.**

Other specific comments: Page 6: The paper refers to the catchment as subcatchment of the Olifants/Doorn quaternary catchment, but actually it is not in the Olifants/Doorn catchment at all.
Response- Noted, Changes made: **With regard to the catchment that the Verlorenvlei system sits in, it is quite clear that Verlorenvlei makes up the southern portion of the Olifants/Doorn Water Management Area (WMA). This is on a wide variety of published material, from Dept of Water Affairs maps to peer reviewed journal articles and numerous consultancy reports. It is not clear to us why the reviewer thinks otherwise.**

Reviewer 1: Page 6: Reference is made to the lake supporting Karroid and Fynbos biomes, but these are terrestrial biomes that have no connection to any aquatic requirements. The paper also attributes the dual support of these biomes to the intermittent connection between salt and fresh water, which is clearly not correct and the salinity regime of the lake has nothing to do with the terrestrial biomes prevalent in the catchment. Page 6 mentions something about the salt and freshwater regimes of the lake, which will be critical to any environmental assessment, but no details are given and later in the paper this issue is totally ignored
Response- Accepted changes made:" The estuarine lake hosts both Karroid and Fynbos biomes, with a variety of vegetation types (e.g Arid Estuarine Saltmarsh, Cape Inland Salt pans) being sensitive to reduced inflow of freshwater (Helme, 2007)"

Page 18: How do gauging station limitations result in good objective functions? This makes no sense to me. A casual glance at Fig 4 does not seem to support the conclusion that there were more gauge exceedance in the calibration period relative to the validation period. It would have been better to state how many were in each period. It is also not clear what the modellers did with these periods (set the observed data to missing values perhaps?).

Response- Noted
Regarding Fig 4, streamflow exceeds the cut-off threshold of 3.675 m.3.s-1 (DT limit) for the station more frequently during the calibration, as this is during a wet cycle, with average rainfall of 413 mm/year as opposed to the dry cycle, which has an average of 330 mm/year (Fig. 4). We accept that a probability could be used to ascertain how often the cut-off threshold was exceeded but this is not the objective of this contribution and would make the already lengthened revised version far longer than intended.

I could not find Table 1 in the submission.
Response- Reject, no changes made: **Page 14**

The title of Figure 6 does not seem to make

Page 28 says 'BFI values are generally below 1'. In fact BFI values are defined by baseflow/total flow and therefore are ALWAYS less than or equal to 1.
Response- Reject, no changes made: **As this paper is focused on understanding river flow regime dynamics, this is particular important for the readership, and while it might seem like it will always be less than 1, CV values are spoken in the same line and require a range for understanding. In that same vain, if its obvious then why have other articles stated this?**

Reviewer 2: D.S. Stampoulis

1) The manuscript is not easy to read, due to the lack of a comprehensive structure that would help the reader easily understand the science and methodology. Please consider providing a more reader-friendly version of this paper, perhaps by changing the outline into a more compact one
Response- Accepted changes made: **The manuscript structure ahs been revised, in particular the methodology has been improved to be easier to follow.**

2) The authors needs to provide more information about the study area. Climatology-related information could be supported by a map or graph (time series). More detailed description about the regional hydrology is required.

__**Response-**__ Accepted changes made: **New figure included which shows how the rainfall has varied for the last 52 years. This leads onto how rainfall varies spatially across the catchment, with a significant different between the valley and mountains and the different geological formations.**

3) Most of the references in the introduction are outdated. The authors need to make sure that they have conducted a thorough literature review.
__**Response-**__ Accepted changes made: **As per reviewer 1 changes have been made to the references**

4) The model isnot sufficiently described. Please elaborate.
__**Response-**__ Accepted changes made: **New flow chart has been included to describe how the model works.**

5) Are water abstractions taken into account by the model? It seems that this is not the case, and the authors need to clearly state this fact.
__**Response-**__ Accepted changes made: **Please see method section, where a new flow diagram and introduction sentence has been implemented to address this. Final discussion section is also regarding the irrigation and what impact it could have.**

6) The results section is hard to read and follow; lack of supporting tables and graphs render reading a tedious task. The authors seem to have a lot of interesting results, which however, without a proper visualization have little meaning or use. Please consider using summarizing tables or time series or other graphs.
__**Response-**__ Accepted changes made: **The result figures have been revised, with two new figures which a pie chart of the flow contributions and flow component proportions.**

Comparison between models is one thing, however one should not validate one model using the output of another. Please consider using an alternative data set or replace the word "validated" in Line 372 with "compared with".
__**Response-**__ Accepted changes made: **As per reviewer 1, changes made throughout to align with this.**

8) The modeling approach is rather difficult to be transferred to other catchments as is, because of the different level of complexities in the geomorphological structure as well as the unique climatologies that characterize each specific region.
__**Response-**__ Accepted changes made: **Further developments have been made to the discussion which look at how the impacts of dry and wet cycles could impact sensitive ecosystems such as the Verlorenvlei.**

Technical Corrections-
1) Line 191 replace "was" with "were" 2) Lines 272-273 six or seven AWS's? 3) Line 361 Pbias 4) Line 497 In data-scarce
__**Response-**__ Accepted changes made: **Changes made.**

Short comment: S. Andersson

1.1) The authors are encouraged to explain why a combination of these particular models are selected for this particular modelling challenge. What other options exists for combining distributed surface water modelling with distributed groundwater modelling?
__**Response-**__ Accepted changes made: "To better understand river flow variability, a rainfall/runoff model was distributed to incorporate aquifer hydraulic conductivity within model HRUs using calibrated values from a MODFLOW groundwater model (Watson, 2018). The rainfall/runoff model

used was J2000 as this model had previously been set up in the region and model variables were well established (e.g Bugan, 2014; Schulz et al., 2013)".

1.2) The description of the study area states that agriculture is the dominant water user from the sub-catchment. But following this, the manuscript does not take agricultural expansion into account. Would not the increased irrigation in the area affect the streamflow data used for calibration, bringing non-stationary patterns? Is the water use taken into account in the model and how has water use developed during the simulation period? Also land-cover changes would be relevant to take into account, since the land cover data was only based on data from 2009. This is particularly important, to at least discuss, due to the fact that the manuscript presents agricultural expansion to be one of the major threats to the lake.

Response- Accepted changes made: "Agriculture is the dominant water user in the sub-catchment with an estimated usage of 20 % of the total recharge (DWAF, 2003; Watson, 2018), with the main food crop being potatoes. The MG shales and quaternary sediments, which host the secondary and primary aquifer respectfully, are frequently used to supplement irrigation during the summer months of the year. During winter, the majority of the irrigation water needed for crop growth is supplied by the sub-catchment tributaries or the lake itself. The impact of irrigation on the lake is still regarded as minimal (Meinhardt et al., 2018) but requires future investigation."
We agree that a more up to date landcover dataset would be more representative if an active gauging structure existed, although as the gauging data is between 1987-2008, the 2007 landcover dataset is better for the model calibration. A 2013/2014 National Land Cover dataset exists for South Africa, which we will incorporate in future models once the initial model approach has been completed.

1.3) The estuarine nature of the lake is not taken into account or discussed. The evaporative demand is merely roughly approximated in the discussion. I wonder why this was not made with more care, since some of the main conclusions in the manuscript rely on this evaporative demand. The mix of salt and fresh water must mean that there is a dynamic flow exchange between the ocean and the lake. Please consider to explain/discuss why is this not taken into account in the modelling.
Response- Accepted changes made: **Lake ET has been incorporated in the new model. There still remains very little information regarding the sea water exchange and this remains something we would like to address in future papers.**

1.4) The authors are suggested to explain why the two areas for surface and subsurface calibration was selected. The authors are also encouraged to discuss the implications of the calibration and validation limitations, especially in relation to the major calibration data gap and the fact that the measuring gauge had an upper measurement limitation.
Response- Noted. **The surface water calibration was applied to the Kruismans, which is the only tributary with streamflow measurements (This has been stated in the paper). The Krom Antonies was used for the groundwater component as it was believed the most significant in terms of baseflow (Stated in the paper).**

2) Clarity
2.1) One of the main issues with this manuscript is its unclear aim. This is suggested to be written in a more clear and concise way. Following from this, the distinction between general information (e.g. model equations in the J2000 model), previously done work and the novelty of this particular manuscript becomes fuzzy. The authors are strongly recommended to make this clearer. For

instance, when describing the water balance calculations in chapter 3.3, it is also necessary to clarify what information is general for the software used and what is specifically chosen for this study.
Response- Accepted changes made: **New flow diagram included which should clarify this issue and restructuring of the method and results sections**

2.2) A majority of the chapters would benefit from being written more concise and to-the-point. General model information could be left out with reference to the model documentation, the model settings and the results would benefit from being presented in tables.
Response- Accepted changes made: **Results have been revised as well as method.**

2.3) Chapter 4.2.2 is describing the surface water calibration. But the section describing the groundwater calibration is missing (or possibly it is just the headline that is missing). This is a gap that is suggested to be highly relevant for this manuscript.

Response- Accepted changes made: **Heading missing, changes made.**

Technical corrections:
-It is difficult to distinguish the colours in the hydrogeological map in Figure 2.

Response- Accepted changes made

-The text description of Figure 4 has an error; the period of validation should be for 1994-2006.
Response- Accepted changes made

-I would encourage the authors to more carefully describe why this particular lake system was selected for the case study. The manuscript states that the estuarine system is "under threat from climate change and agricultural expansion". The term "under threat" is vague, and the statement is not referenced.
Response- Accepted changes made: "The Verlorenvlei lake, which is approximately 15 km^2 in size draining a watershed of 1832 km^2, forms the southern sub-catchment of the Olifants/Doorn water management area (WMA). The estuarine lake hosts both Karroid and Fynbos biomes, with a variety of vegetation types (e.g Arid Estuarine Saltmarsh, Cape Inland Salt pans) being sensitive to reduced inflow of freshwater (Helme, 2007). A sandbar created around a sandstone outcrop (Table Mountain Group) allows for an intermittent connection between salt and fresh water. During storms or extremely high tides, water scours the sand bar allowing for a tidal exchange, with a constant inflow of salt water continuing until the inflow velocity decreases enough for a new sand bar to form (Sinclair et al., 1986). "

-The authors are referencing to their own unpublished work. This reference is furthermore not included in the reference list. This is problematic with regard to transparency, since no access to this source is given. The authors are encouraged to consider other ways of providing this information, for instance through supplementary materials (if possible).
Response- Accepted changes made

-There is a general issue of missing references, for instance the geological data in chapter 2 and the parameter values in chapter 3.3.2. The reference list needs to be revised, at least one reference is missing (Sigidi, 2018).

<u>Response-</u> Accepted changes made

-The appropriate number of significant figures should be revised. It is not reasonable to give exceedance percentiles with six significant figures (Table 3), due to uncertainties and limitations in input data and models.
<u>Response-</u> Accepted changes made. **Although for flow exceedances it is not possible to use 2 significant figures otherwise streamflow is below 0.00 when in $m^3.s^{-1}$**

-The headline for chapter 4 is missing.
<u>Response-</u> Accepted changes made

Please see attached below for changes made to the revised paper. As there were multiple inputs from various authors track changes became very messy and hard to follow, especially with the addition of new diagrams and therefore were not possible in this response. I have highlighted major sections that were revised to show how this revised version differs from the original, although small changes that were incorporated have not been highlighted and require you to refer to the new manuscript.

Distributive rainfall/runoff modelling to understand runoff to baseflow proportioning and its impact on the determination of reserve requirements of the Verlorenvlei estuarine lake, west coast, South Africa

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Keywords: rainfall/runoff modelling, Verlorenvlei reserve, J2000

Abstract

River systems that support high biodiversity profiles are conservation priorities world-wide. Understanding river eco-system thresholds to low flow conditions is important for the conservation of these systems. While climatic variations are likely to impact the streamflow variability of many river courses into the future, understanding specific river flow dynamics with regard to streamflow variability and aquifer baseflow contributions are central to the implementation of protection strategies. While streamflow is a measurable quantity, baseflow has to be estimated or calculated through the incorporation of hydrogeological variables. In

this study, the groundwater components within the J2000 rainfall/runoff model were distributed to provide daily baseflow and streamflow estimates needed for reserve determination. The modelling approach was applied to the RAMSAR-listed Verlorenvlei estuarine lake system on the west coast of South Africa which is under threat due to agricultural expansion and climatic fluctuations. The sub-catchment consists of four main tributaries, the Krom Antonies, Hol, Bergvallei and Kruismans. Of these, the Krom Antonies was initially presumed the largest baseflow contributor, but was shown to have significant streamflow variability, attributed to the highly conductive nature of the Table Mountain Group sandstones and quaternary sediments. Instead, the Bergvallei was identified as the major contributor of baseflow. The Hol was the least susceptible to streamflow fluctuations due to the higher baseflow proportion (56%), as well as the dominance of less conductive Malmesbury shales that underlie it. The estimated flow exceedance probabilities indicated that during the 2008-2017 wet cycle average lake inflows exceeded the average evaporation demand. During the 1997-2007 dry cycle, average lake inflows are exceeded 85 % of the time by the evaporation demand. The exceedance probabilities estimated here suggest that inflows from the four main tributaries are not enough to support Verlorenvlei, with the evaporation demand of the entire lake being met only 35 % of the time. This highlights the importance of low occurrence events for filling up Verlorenvlei, allowing for regeneration of lake-supported ecosystems. As climate change drives increased temperatures and rainfall variability, the length of dry cycles are likely to increase into the future and result in the lake drying up more frequently. For this reason, it is important to ensure that water resources are not overallocated during wet cycles, hindering ecosystem regeneration and prolonging the length of these dry cycle conditions.

1. Introduction

Functioning river systems offer numerous economic and social benefits to society including water supply, nutrient cycling and disturbance regulation amongst others (Nelson et al., 2009; Postel and Carpenter, 1997). As a result, many countries worldwide have endeavoured to protect river ecosystems, although only after provision has been made for basic human needs (Gleick, 2003; Ridoutt and Pfister, 2010). However, the implementation of river protection has been problematic, because many river courses and flow regimes have been severely altered due to socio-economic development (O'Keeffe, 2009; Richter, 2010). River health problems thought to only result from low-flow conditions and if minimum flows were kept above a critical level, the river's ecosystem would be protected (Poff et al., 1997). It is now recognised that a more natural flow regime, which includes floods as well as low and medium flow conditions, is required for sufficient ecosystem functioning (Bunn and Arthington, 2002; Olden and Naiman, 2010; Postel and Richter, 2012). For these reasons, before protection strategies can be developed or implemented for a river system, a comprehensive understanding of the river flow regime dynamics is necessary.

River flow regime dynamics include consideration of not just the surface water in the river but also other water contributions including runoff, interflow and baseflow which are all essential for the maintenance of the discharge requirements. Taken together these factors all contribute to the determination of what is called the ecological reserve, the minimum environmental conditions needed to maintain the ecological health of a river system (Acreman and Dunbar, 2004; Hughes, 2001). A variety of different methods have been developed to incorporate various river health factors into ecological reserve determination (Bragg et al., 2005). One of the simplest and most widely applied, is where compensation flows are set below reservoirs and weirs, using flow duration curves to derive mean flow or flow exceedance probabilities (e.g. Harman and Stewardson, 2005). This approach focusses purely on hydrological indices, which are rarely ecologically valid(e.g. Barker and Kirmond, 1998).

More comprehensive ecological reserve estimates such as functional analysis are focused on the whole ecosystem, including both hydraulic and ecological data (e.g. ELOHA: Poff et al., 2010; Building Block Methodology: King and Louw, 1998). While these methods consider that a variety of low, medium and high flow events are important for maintaining ecosystem diversity, they require specific data regarding the hydrology and ecology of a river system, which in many cases does not exist, has not been recorded continuously or for sufficient duration (Acreman and Dunbar, 2004). To speed up ecological reserve determination, river flow records have been used to analyse natural seasonality and variability of flows (e.g. Hughes and Hannart, 2003). However, this approach requires long-term streamflow and baseflow timeseries. Whilst streamflow is a measurable quantity subject to a gauging station being in place, baseflow has to be modelled based on hydrological and hydrogeological variables.

Rainfall/runoff models can be used to calculate hydrological variables using distributive surface water components (e.g. J2000: Krause, 2001) but the groundwater components are generally lumped within conventional modelling frameworks. In contrast, groundwater models, which distribute groundwater variables (e.g. MODFLOW: Harbaugh, Arlen, 2005), are frequently setup to lump climate components. In order to accurately model daily baseflow, which is needed for reserve determination, modelling systems need to be setup such that both groundwater and climate variables are treated in a distributive manner (e.g Bauer et al., 2006; Kim et al., 2008). Rainfall/runoff models, which use Hydrological Response Units (HRUs) as an entity of homogenous climate, rainfall, soil and landuse properties (Flügel, 1995), are able to reproduce hydrographs through model calibration (Wagener and Wheater, 2006). However, they are rarely able to correctly proportion runoff and baseflow components (e.g. Willems, 2009). To correctly determine groundwater baseflow using rainfall/runoff models such as the

J2000, aquifer components need to be distributed. This can be achieved using net recharge and hydraulic conductivity collected through aquifer testing or groundwater modelling.

To better understand river flow variability, a rainfall/runoff model was distributed to incorporate aquifer hydraulic conductivity within model HRUs using calibrated values from a MODFLOW groundwater model (Watson, 2018). The rainfall/runoff model used was J2000 as this model had previously been set up in the region and model variables were well established (e.g Bugan, 2014; Schulz et al., 2013). The model was setup for the RAMSAR listed Verlorenvlei estuarine lake on the west coast of South Africa, which is under threat from climate change, agricultural expansion and mining exploration. While the estuarine lake's importance is well documented (Martens et al., 1996; Wishart, 2000), the lake's reserve is not well understood, due to the lack of streamflow and baseflow estimates for the main feeding tributaries of the system. The modelling framework developed in this study aimed to understand the flow variability of the lake's feeding tributaries, to provide the hydrological components (baseflow and runoff proportioning) of the tributaries needed to understand the lake reserve. The surface water and groundwater components of the model were calibrated for two different tributaries which were believed to be the main source of runoff and baseflow for the sub-catchment. The baseflow and runoff rates calculated from the model indicate not only that the lake system cannot be sustained by baseflow during low flow periods but also that the initial understanding of which tributaries are key to the sustainability of the lake system was not correct. The results have important implications for how we understand water dynamics in water stressed catchments and the sustainability of ecological systems in these environments.

2. Study site

Verlorenvlei is an estuarine lake situated on the west coast of South Africa, approximately 150 km north of the metropolitan city of Cape Town (Fig. 1). The west coast, which is situated in the Western Cape Province of South Africa, is subject to a Mediterranean climate where the majority of rainfall is received between May to September. The Verlorenvlei lake, which is approximately 15 km^2 in size draining a watershed of 1832 km^2, forms the southern sub-catchment of the Olifants/Doorn water management area (WMA). The lake hosts both Karroid and Fynbos biomes, with a variety of vegetation types (e.g Arid Estuarine Saltmarsh, Cape Inland Salt pans) sensitive to reduced inflows of freshwater (Helme, 2007). A sandbar created around a sandstone outcrop (Table Mountain Group) allows for an intermittent connection between salt and fresh water. During storms or extremely high tides, water scours the sand bar allowing for a tidal exchange, with a constant inflow of salt water continuing until the inflow velocity decreases enough for a new sand bar to form (Sinclair et al., 1986).

The lake is supplied by four main tributaries which are the Krom Antonies, Bergvallei, Hol and Kruismans (Fig. 2). The main freshwater sources are presumed to be the Krom Antonies and the Bergvallei, which drain the mountainous regions to the south (Piketberg) and north of the sub-catchment respectfully (Sigidi, 2018). The Hol and Kruismans tributaries are variably saline (Sigidi, 2018), due to high evaporation rates in the valley. Average daily temperatures during summer within the sub-catchment are between 20-30 °C, with estimated potential evaporation rates of 4 to 6 $mm.d^{-1}$ (Muche et al., 2018). In comparison, winter daily average temperatures are between 12-20 °C, with estimated potential evaporation rates of 1 to 3 $mm.d^{-1}$ (Muche et al., 2018).

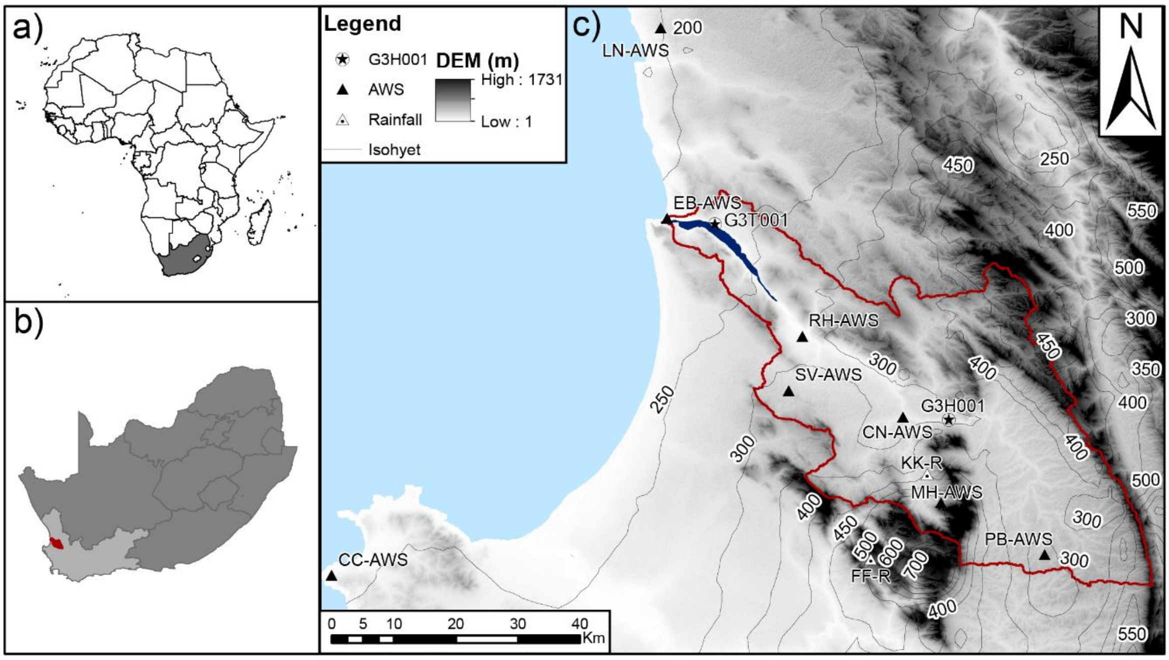

Figure 1: a) Location of South Africa, b) the location of the study catchment within the Western Cape and c) the extend of the Verlorenvlei sub-catchment with the climate stations, gauging station (G3H001), measured lake water level (G3T001) and rainfall isohets

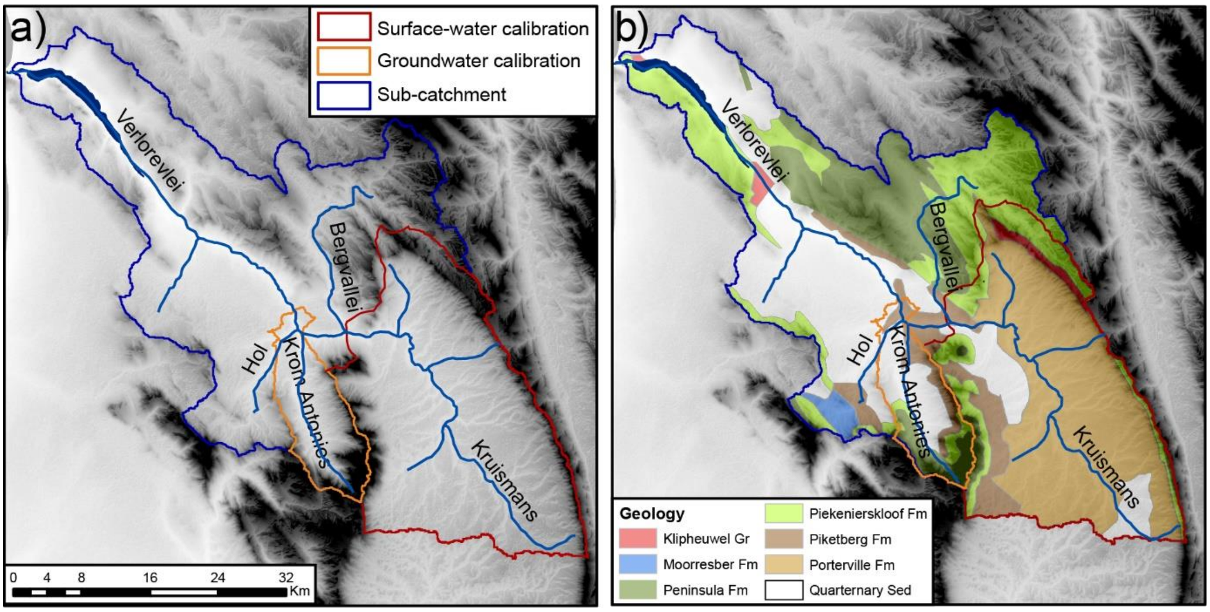

Figure 2: a) The Verlorenvlei sub-catchment with the surface water calibration tributary (Kruismans) and groundwater calibration tributary (Krom Antonies) and b) the hydrogeology of the sub-catchment with Malmesbury shale formations (Klipheuwel, Mooresberg, Porterville,

Piketberg), Table Mountain Group formations (Peninsula, Piekenierskloof) and quaternary sediments

Rainfall for the sub-catchment, recorded over the past 52 years by local farmers at KK-R (Fig. 1) shows large yearly variability (26%) between the Mean Annual Precipitation (MAP)(411 and measured rainfall (Fig. 3). Where rainfall was greater than 500 $mm.yr^{-1}$ (2006-2010), it is presumed that the lake is supported by a constant influx of streamflow from the feeding tributaries. Where rainfall was less than 50 % of the MAP (1965-1969 and 2015-2017), concerns over the amount of streamflow required to support the lake have been raised.

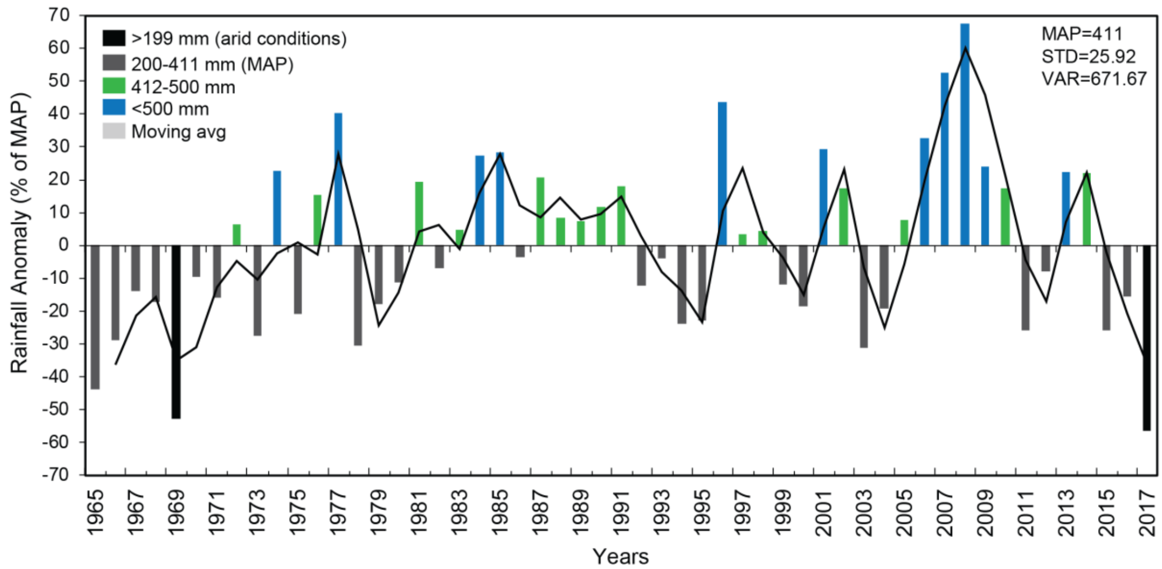

Figure 3: The difference between MAP and measured rainfall (plotted as rainfall anomaly) for 52 years (1965-2017) at location KK-R in the valley of the Krom Antonies (after Watson *et al., 2018*).

While rainfall varies greatly between years in the sub-catchment, it is also spatially impacted by elevational differences. The catchment valley which receives the least MAP 100-350 $mm.yr^{-1}$ (Lynch, 2004), is between 0-350 masl and is comprised of quaternary sediments that vary in texture, although the majority of the sediments in the sub-catchment are sandy in nature. The higher relief mountainous regions of the sub-catchment between 400-1300 masl receive the highest MAP 400-800 mm.yr^{-1} (Lynch, 2004), are mainly comprised of fractured TMG sandstones, (youngest to oldest): Peninsula, Graafwater (not shown), and Piekenerskloof formations (Fig. 2) (Johnson et al., 2006). Underlying the sandstones and quaternary sediments are the MG shales, which are comprised of the Mooresberg, Piketberg and Klipheuwel formations (Fig. 2) (Rozendaal and Gresse, 1994). Agriculture is the dominant water user in the sub-catchment with an estimated usage of 20 % of the total recharge (DWAF, 2003; Watson, 2018), with the main food crop being potatoes. The MG shales and quaternary sediments, which host the secondary and primary aquifer respectfully, are frequently used to supplement irrigation during the summer months of the year. During winter, the majority of the irrigation water needed for crop growth is supplied by the sub-catchment tributaries or the lake itself. The impact of irrigation on the lake is still regarded as minimal (Meinhardt et al., 2018) but requires future investigation. For additional information regarding the study site refer to Watson *et al*., (2018).

3. Methodology

In this study, the J2000 coding was adapted to incorporate distributive groundwater components for the model HRU's (Fig. 4). This was done by aligning the MODFLOW recharge estimates with those of the J2000, through adjustment of aquifer hydraulic conductivity from the MODFLOW groundwater model of the Krom Antonies (Watson, 2018) (Fig. 5). The assigned hydraulic conductivity for each geological formation was thereafter transferred across the entire J2000 model of the sub-catchment. The adaption applied to the groundwater components influenced the proportioning of water routed to runoff and baseflow within the J2000 model. To validate the outputs of the model, an empirical mode decomposition (EMD) (Huang et al., 1998) was applied to compute the proportion of variation in discharge timeseries that attributed to a high and low water level change at the sub-catchment outlet. The streamflow estimates were thereafter compared with the lake evaporation demand, to understand the sub-catchment water balance.

The J2000 model incorporated distributive climate, soil, landuse and hydrogeological information, with aquifer hydraulic conductivity transferred from MODFLOW as described above (Fig. 4). The measured streamflow was used to both calibrate and validate the model, with the landuse dataset being selected according to the period of measured streamflow. Changes in the recorded lake level were used alongside remote sensing to estimate the lake evaporation rate. The impact of irrigation was not included in the model, as there is not enough information available regarding agricultural water use. This is currently one of the major limitations with the study approach presented here and will be the focus of future work. The HRU delineation, model regionalisation, water balance calculations, lateral and reach routing as well as the lake evaporation procedure are presented. Thereafter the input data for the model, the calibration and validation procedures as well as the EMD protocol used, is described.

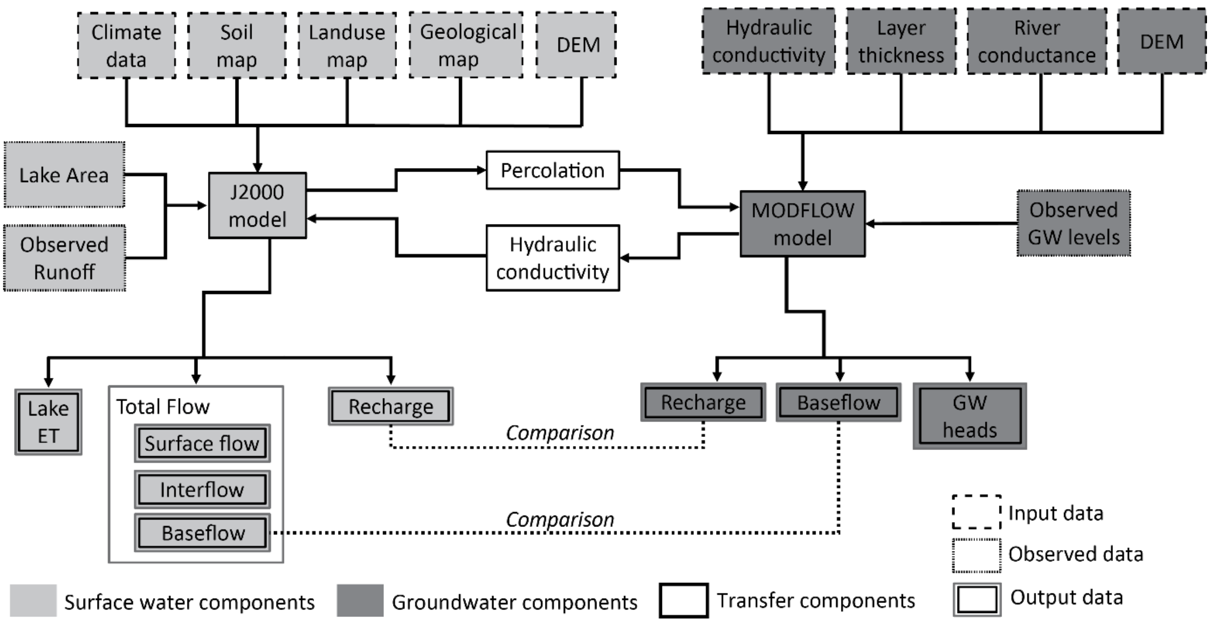

Figure 4: Schematic of the model structure, showing the processors simulated by the J2000 and MODFLOW and the components that were transferred from the MODFLOW model

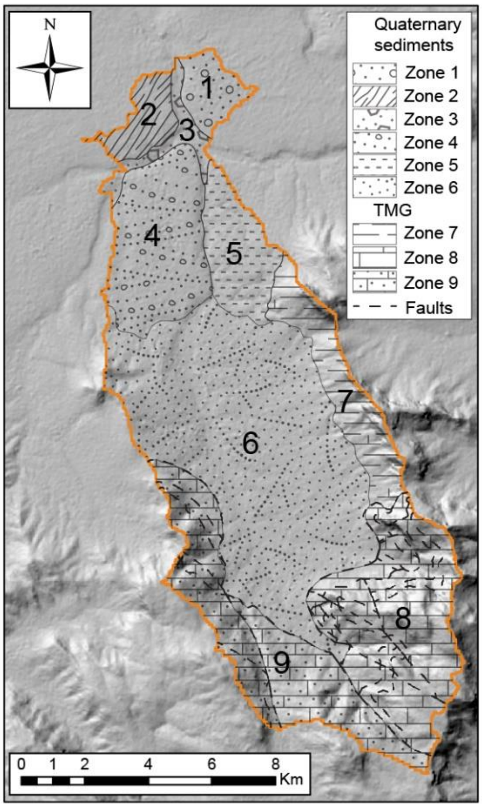

Figure 5: The aquifer hydraulic zones used for the groundwater calibration of the J2000 (after Watson, 2018)

3.1 Hydrological Response Unit Delineation

HRUs and stream segments (reaches) are used within the J2000 model for distributive topographic and physiological modelling. In this study, the HRU delineation made use of a digital elevation model, with slope, aspect, solar radiation index, mass balance index and topographic wetness being derived. Before the delineation process, gaps within the digital elevation model were filled using a standard fill algorithm from ArcInfo (Jenson and Domingue, 1988). The AML (ArcMarkupLanguage) automated tool (Pfennig et al., 2009) was used for the HRU delineation, with between 13 and 14 HRUs/km^2 being defined (Pfannschmidt, 2008). After the delineation of HRUs, dominant soil, land use and geology properties were assigned to each. The hydrological topology was defined for each HRU by identifying the adjacent HRUs or stream segments that received water fluxes.

3.2 Model regionalisation

Rainfall and relative humidity are the two main parameters that are regionalised within the J2000 model. While a direct regionalisation using an inverse-distance method (IDW) and the elevation of each HRU can be applied to rainfall data, the regionalisation of relative humidity requires the calculation of absolute humidity. The regionalisation of rainfall records was applied by defining the number of weather station records available and estimating the influence on the rainfall amount for each HRU. A weighting for each station using the distance of each station to the area of interest was applied to each rainfall record, using an elevation correction factor (Watson et al., 2018). The relative humidity and air temperature measured at set weather stations were used to calculate the absolute humidity. Absolute humidity was thereafter regionalised using the IDW method, station and HRU elevation. After the regionalisation had been applied, the absolute humidity was converted back to relative humidity through calculation of saturated vapor pressure and the maximum humidity.

3.3 Water balance calculations

The J2000 model is divided into calculations that impact surface water and groundwater processors. The J2000 model distributes the regionalised precipitation (P) calculated for each HRU using a water balance defined as:

$$P = R + Int_{max} + ETR + \Delta Soil_{sat} \quad (1)$$

where R is runoff (mm) (RD1 - surface runoff; RD2 - interflow), Int_{max} is vegetation canopy interception (mm), ETR is ‘real’ evapotranspiration and $\Delta Soil_{sat}$ is change in soil saturation. The surface water processes have an impact on the amount of modelled runoff and interflow, while the groundwater processors influence the upper and lower groundwater flow components.

3.3.1 Surface water components

Potential evaporation (ETP) within the J2000 model is calculated using the Penman Monteith equation. Before evaporation was calculated for each HRU, interception was subtracted from precipitation using the leaf area index and leaf storage capacity for vegetation (a_rain) (Supplementary: Table 1). Evaporation within the model considers several variables that influence the overall modelled evaporation. Firstly, evaporation is influenced by a slope factor, which was used to reduce ETP based on a linear function. Secondly, the model assumed that vegetation transpires until a particular soil moisture content where ETP is reached, after which modelled evaporation was reduced proportionally to the ETP, until it became zero at the permanent wilting point.

The soil module in the J2000 model is divided up into processing and storage units. Processing units in the soil module include soil-water infiltration and evapotranspiration, while storage units include middle pore storage (MPS), large pore storage (LPS) and depression storage. The infiltrated precipitation was calculated using the relative saturation of the soil, and its maximum infiltration rate (SoilMaxInfSummer and SoilMaxInfWinter) (Supplementary: Table 1). Surface runoff was generated when the maximum infiltration threshold was exceeded. The amount of water leaving LPS, which can contribute to recharge, was dependant on soil saturation and the filling of LPS via infiltrated precipitation. Net recharge (R_{net}) was estimated using the hydraulic conductivity ($SoilMaxPerc$), the outflow from LPS (LPS_{out}) and the slope ($slope$) of the HRU according to:

$$R_{net} = LPS_{out} \times (1 - \tan\ (slope\ )\ SoilMaxPerc) \qquad (2)$$

The hydraulic conductivity, $SoilMaxPerc$ and the adjusted LPS_{out}.were thereafter used to calculate interflow (IT_f) according to:

$$IT_f = LPS_{out} \times (\tan(slope\ )\ SoilMaxPerc) \tag{3}$$

with the interflow calculated representing the sub-surface runoff component RD2 and is routed as runoff within the model.

3.3.2 Groundwater components

The J2000 model for the Verlorenvlei sub-catchment was set up with two different geological reservoirs: (1) the primary aquifer (upper groundwater reservoir - RG1), which consists of quaternary sediments with a high permeability; and (2) the secondary aquifer (lower groundwater reservoir- RG2), made up of MG shales and TMG sandstones (Table 1).

Aquifer	Formation	Type	RG1_max (mm)	RG2_max (mm)	RG1_k (d)	RG2_k (d)	RG1_active (n/a)	Kf_geo (mm/d)	depthRG1 (cm)
Primary	Quarternary Sediments	Sediments	50	700	100	431	1	500	1750
Secondary/MG	Moorresberg Formation	Shale Greywacke	0	580	0	350	0	950	1750
Secondary/MG	Porterville Formation	Shale Greywacke	0	560	0	335	0	2	1750
Secondary/MG	Piketberg Formation	Shale Greywacke	0	1000	0	600	0	950	1750
Secondary/MG	Klipheuwel Group	Shale Greywacke	0	500	0	300	0	950	1750
Secondary/TMG	Peninsula Formation	Sandstone	0	1000	0	600	0	950	1750
Secondary/TMG	Piekenierskloof Formation	Sandstone	0	600	0	400	0	1	1750

Table 1: The J2000 hydrogeological parameters RG1_max, RG2_max, RG1_k, RG2_Kf_geo and depthRG1 assigned to the primary and secondary aquifer formations for the Verlorenvlei sub-catchment

The model therefore considered two baseflow components, a fast one from the RG1 and a slower one from RG2. The filling of the groundwater reservoirs was done by net recharge, with emptying of the reservoirs possible by lateral subterranean runoff as well as capillary action in the unsaturated zone. Each groundwater reservoir was parameterised separately using the maximum storage capacity (maxRG1 and maxRG2) and the retention coefficients for each reservoir ($recRG1$ and $recRG2$). The outflow from the reservoirs was determined as a function of the actual filling ($actRG1$ and $actRG2$) of the reservoirs and a linear drain function. Calibration parameters $recRG1$ and $recRG2$ are storage residence time parameters. The outflow from each reservoir was defined as:

$$OutRG1 = \frac{1}{gwRG1Fact \times recRG1} \times actRG1 \tag{4}$$

$$OutRG2 = \frac{1}{gwRG2Fact \times recRG2} \times actRG2 \tag{5}$$

where $OutRG1$ is the outflow from the upper reservoir, $OutRG2$ is the outflow from the lower reservoir and $gwRG1Fact$/ $gwRG2Fact$ are calibration parameters for the upper and lower reservoir used to determine the outflow from each reservoir. To allocate the quantity of net recharge between the upper (RG1) and lower (RG2) groundwater reservoirs, a calibration coefficient $gwRG1RG2sdist$ was used to distribute the net recharge for each HRU using the HRU slope. The influx of groundwater into the shallow reservoir ($inRG1$) was defined as:

$$inRG1 = R_{net} \times (1 - (1 - \tan(slope))) \times gwRG1RG2sdist \tag{6}$$

The influx of net recharge into the lower groundwater reservoir ($inRG2$) was defined as:

$$inRG2 = R_{net} \times (1 - \tan(slope)) \times gwRG1RG2sdist \tag{7}$$

with the combination of $OutRG1$ and $OutRG2$ representing the baseflow component that is routed as an outflow from the model.

3.4 Lateral and reach routing

Lateral routing was responsible for water transfer within the model and included HRU influxes and discharge through routing of cascading HRUs from the upper catchment to the exit stream. HRUs were either able to drain into multiple receiving HRUs or into reach segments, where the topographic ID within the HRU dataset determined the drain order. The reach routing module was used to determine the flow within the channels of the river using the kinematic wave equation and calculations of flow according to Manning and Strickler. The river discharge was determined using the roughness coefficient of the stream (Manning roughness), the slope and width of the river channel and calculations of flow velocity and hydraulic radius calculated during model simulations.

3.5 Calculations of lake evaporation rate

The lake evaporation rate was based on the ETP calculated by the J2000 and an estimated lake surface area. The lake was modelled as a unique HRU (water as the land-cover type), with a variable area which was estimated using remote sensing data from Landsat 8 and Sentinel-2 and the measured lake water level at G3T001 (Fig. 1). To infill lake surface area when remote sensing data was not available, a relationship was created between the estimated lake's surface area and the measured water level between 2015-2017. Where lake water level data was not available (before 1999), an average long-term monthly value was used for the lake evaporation calculations.

3.6 J2000 Input data

3.6.1 Surface water parameters

Climate and rainfall: Rainfall, windspeed, relative humidity, solar radiation and air temperature were monitored by Automated Weather Stations (AWS) within and outside of the study catchment (Fig. 1). Of the climate and rainfall data used during the surface water modelling (Watson et al., 2018), data was sourced from seven AWS's of which four stations were owned by the South African Weather Service (SAWS) and three by the Agricultural Research Council (ARC). Two stations that were installed for the surface water modelling, namely Moutonshoek (M-AWS) and Confluence (CN-AWS) were used for climate and rainfall validation due to their short record length. Additional rainfall data collected by farmers at high elevation at location FF-R and within the middle of the catchment at KK-R were used to improve the climate and rainfall network density.

Landuse classification: The vegetation and landuse dataset that was used for the sub-catchment (CSIR, 2009) included five different landuse classes: 1) wetlands and waterbodies, 2) cultivated (temporary, commercial, dryland), 3) shrubland and low fynbos, 4) thicket, bushveld, bush clumps and high fynbos and 5) cultivated (permanent, commercial, irrigated). Each different landuse class was assigned an albedo, root depth and seal grade value based on previous studies (Steudel et al., 2015)(Supplementary: Table 2). The Leaf Area Index (LAI) and vegetation height varies by growing season with different values of each for the particular growing season. While surface resistance of the landuse varied monthly within the model, the values only vary significantly between growing seasons.

Soil dataset: The Harmonized World Soil Database (HWSD) v1.2 (Batjes et al., 2012) was the input soil dataset, with nine different soil forms within the sub-catchment (Supplementary: Table 3). Within the HWSD, soil depth, soil texture and granulometry were used to calculate and assign soil parameters within the J2000 model. MPS and LPS which differ in terms of the soil structure and pore size were determined in Watson et al. (2018), using pedotransfer functions within the HYDRUS model (Supplementary: Table 3).

Streamflow and water levels: Streamflow, measured at the Department of Water Affairs (DWA) gauging station G3H001 between 1970-2009, at the outlet of the Kruismans tributary (Het Kruis) (Fig 1 and 3), was used for surface water calibration. The G3H001 two-stage weir could record a maximum flow rate of 3.68 $m^2.s^{-1}$ due to the capacity limitations of the structure. After 2009, the G3H001 structure was decommissioned due to structural damage, although repairs are expected in the near future due to increasing concerns regarding the influx of freshwater into the lake. Water levels measured at the sub-catchment outlet at DWA station G3T001 (Fig 1) between 1994 to 2018 were used for EMD filtering.

3.6.2 Groundwater parameters

Net recharge and hydraulic conductivity: The hydraulic conductivity values used for the groundwater component adaptation were collected from detailed MODFLOW modelling of the Krom Antonies tributary (Fig. 5) (Watson, 2018). The net recharge and aquifer hydraulic conductivity for the Krom Antonies tributary, was estimated through PEST autocalibration using hydraulic conductivities from previous studies (SRK, 2009; UMVOTO-SRK, 2000) and potential recharge estimates (Watson et al., 2018).

Hydrogeology: Within the hydrogeological dataset, parameters assigned include maximum storage capacity (RG1 and RG2), storage coefficients (RG1 and RG2), the minimum permeability/maximum percolation (Kf_geo of RG1 and RG2) and depth of the upper groundwater reservoir (depthRG1). The maximum storage capacity was determined using an average thickness of each aquifer and the total number of voids and cavities, where the primary aquifer thickness was assumed to be between 15-20 m (Conrad et al., 2004), and the secondary aquifer between 80-200 m (SRK, 2009). The maximum percolation of the different geological formations was assigned hydraulic conductivities using the groundwater model for the Krom Antonies sub-catchment (Watson, 2018). The J2000 geological formations were assigned conductivities to modify the maximum percolation value to ensure internal consistency with recharge values calculated using MODFLOW (Table 1).

3.7 J2000 model calibration

3.7.1 Model sensitivity

The J2000 sensitivity analysis for Verlorenvlei sub-catchment was presented in Watson *et al*., (2018) and therefore only a short summary is presented here. In this study, parameters that were used to control the ratio of interflow to percolation were adjusted, which in the J2000 model include a slope (SoilLatVertDist) and max percolation value. The sensitivity analysis conducted by Watson *et al*., (2018) showed that for high flow conditions (E2) (Nash-Sutcliffe efficiency in its standard squared), model outputs are most sensitive to the slope factor, while for low flow conditions (E1) (modified Nash-Sutcliffe efficiency in a linear form) the model outputs were most sensitive to the maximum infiltration rate of the soil (ie. the parameter maxInfiltrationWet) (Supplementary: Figure 1). The max percolation was moderately sensitive during wet and dry conditions, and together with the slope factor, controlled the interflow to percolation portioning that was calibrated in this study.

3.7.2 Surface water calibration

The surface water parameters of the model were calibrated for the Kruismans tributary (688 km^2) (Fig. 3) using the gauging data from G3H001 (Fig. 6 and Table 1). The streamflow data used for the calibration was between 1986-1993, with model validation between 1994 to 2007 (Fig. 6). This specific calibration period was selected due to the wide range of different runoff conditions experienced at the station, with both low and high flow events being recorded. For the calibration, the modelled discharge was manipulated in the same fashion, with a maximum value of 3.68 m^3/s, so that the tributary streamflow behaved as measured discharge.

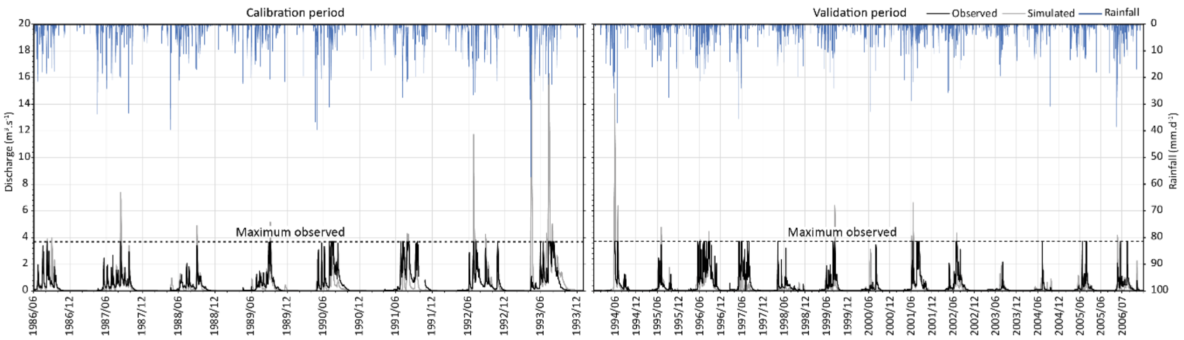

Figure 6: The surface water calibration (1986-1993) and validation (1994-2006) of the J2000 model using gauging data from the G3H001

An automated model calibration was performed using the “Nondominating Sorting Genetic Algorithm II” (NSGA-II) multi-objective optimisation method (Deb et al., 2002) with 1023 model runs being performed. Narrow ranges of calibration parameters (FC_Adaptation, AC_Adaptation, soilMAXDPS, gwRG1Fact and gwRG2Fact) were chosen to (1) ensure that the modelled recharge from J2000 was within an order of magnitude of recharge from the MODFLOW model; (2) to achieve a representative sub-catchment hydrograph. As objective functions, the E2, E1and the average bias in % (Pbias) were utilized for the calibration (Krause et al., 2005) (Table 2). The choice of the optimized parameter set was made to ensure that E2 was better than 0.57 (best value was 0.57) and the Pbias better than 5% (Table 1). From the automated calibration, 308 parameter sets were determined with the best E1 being chosen to ensure that the model is representative of low flow conditions (Table 1).

3.7.3 Model validation

Observed vs modelled streamflow: For the surface water model validation, the streamflow records between 1994-2007 were used, where absolute values (E1) and squared differences (E2) of the Nash Sutcliffe efficiency were reported. The Pbias was also used as an objective function to report the model performance by comparison between measured and modelled streamflow (Table 2). Although gauging station limitations resulted in good objective functions from the model, the performance of objective functions E1, E2, Pbias reduced between the validation and calibration period (Table 2). During the calibration period there was a good fit between modelled and measured streamflow (Pbias=-1.82), with a significant difference between modelled and measured streamflow during the validation period (Pbias=-19.2). The calibration was performed over a wet cycle (1986-1997), which resulted in a more common occurrence of streamflow events that exceeded 3.68 $m^3.s^{-1}$, thereby reducing the number of calibration points. In contrast the validation was performed over a dry cycle (1997-2007), which resulted in more data points as few streamflow events exceeded 3.68 $m^3.s^{-1}$.

	Calibration 1987-1993	**Validation 1994-2007**
E1	0.55	0.53
E2	0.57	0.56
LogE1	0.28	0.10
LogE2	0.46	0.19
AVE	-19.24	-269.20
R^2	0.62	0.58
Pbias	-1.82	-19.23758
KGE	0.79	0.67417

Table 2: The objective functions E1, E2, logarithmic versions of E1 and E2, average error (AVG) coefficient of determination R2, Pbias and Kling Gupta efficiency (KGE) (Gupta et al., 2009) used for the surface water calibration (1987-1993) and validation (1994-2007)

The J2000 and MODFLOW recharge estimates: With adjustment of hydraulic conductivities from MODFLOW to J2000 it was possible to converge the net recharge estimates between 1.3 % with a range of recharge of 0.65-10.03 % for the J2000 and 0.3-11.40 % for MODFLOW. J2000 estimates had an average value of 5.30 % while MODFLOW was 5.20 % for the eight hydraulic zones of the Krom Antonies. The coefficient of determination (R^2) between net recharge from the J2000 and MODFLOW was 0.81. Across the entire dataset J2000 overestimated groundwater recharge by 2.75 % relative to MODFLOW, although the coefficient of determination produced an R^2 of 0.92 which is better than during the validation period.

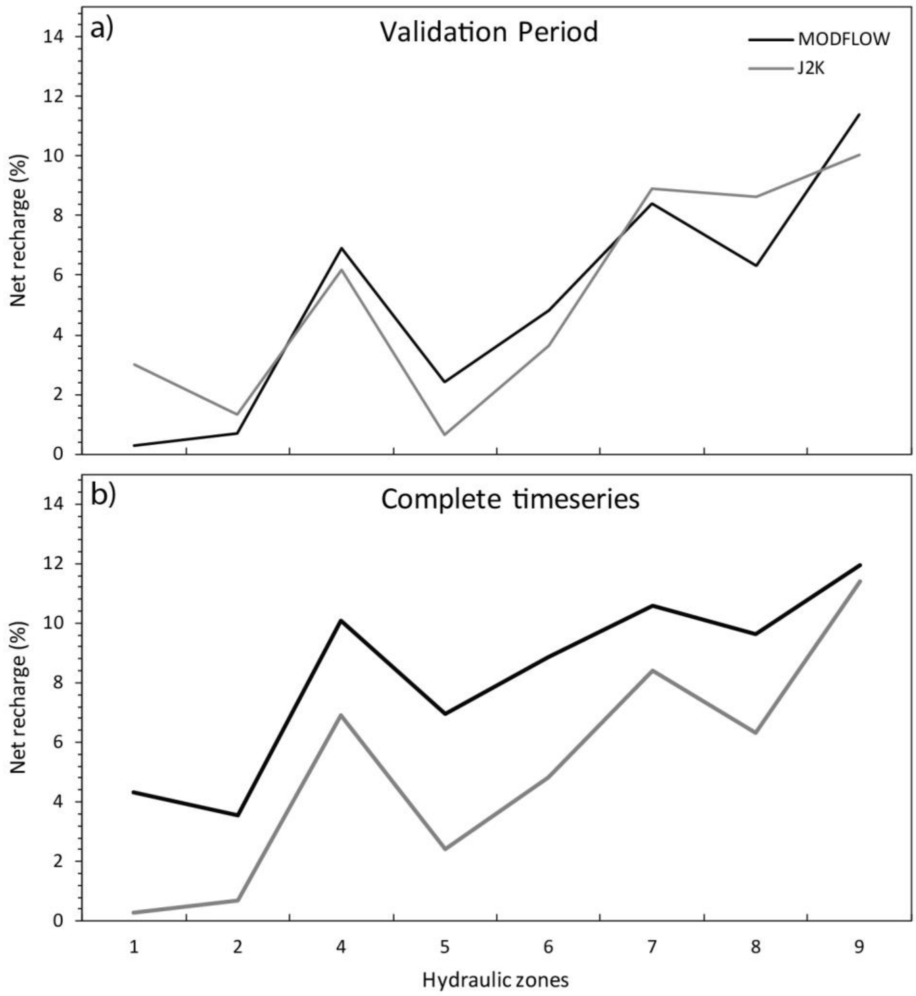

Figure 7: The groundwater calibration for each hydraulic zone with a) net recharge for the J2000 and MODFLOW during the model calibration (2016) and b) the net recharge deviation between MODFLOW and J2000 across the entire modelling timestep (1986-2017)

3.8 EMD filtering

To account for missing streamflow data between 2007-2017, an Empirical Mode Decomposition (EMD) (Huang et al., 1998) was applied to the measured water level data at the sub-catchment outlet (G3T001)(Fig. 1) between 1994 to 2018 (Fig 8a). EMD is a method for the decomposition of nonlinear and nonstationary signals into sub-signals of varying frequency, so-called intrinsic mode functions (IMF), and a residuum signal. By removing one or more IMF or the residuum signal, certain frequencies (e.g. noise) or an underlying trend can be removed from the original time series data. This approach was successfully applied to the analysis of river runoff data (Huang et al., 2009) and forecasting of hydrological time series (Kisi et al., 2014). In this study, EMD filtering was used to remove high frequency sub-signals from simulated runoff and measured water level data to compare the more general seasonal variations of both signals (Fig. 8b).

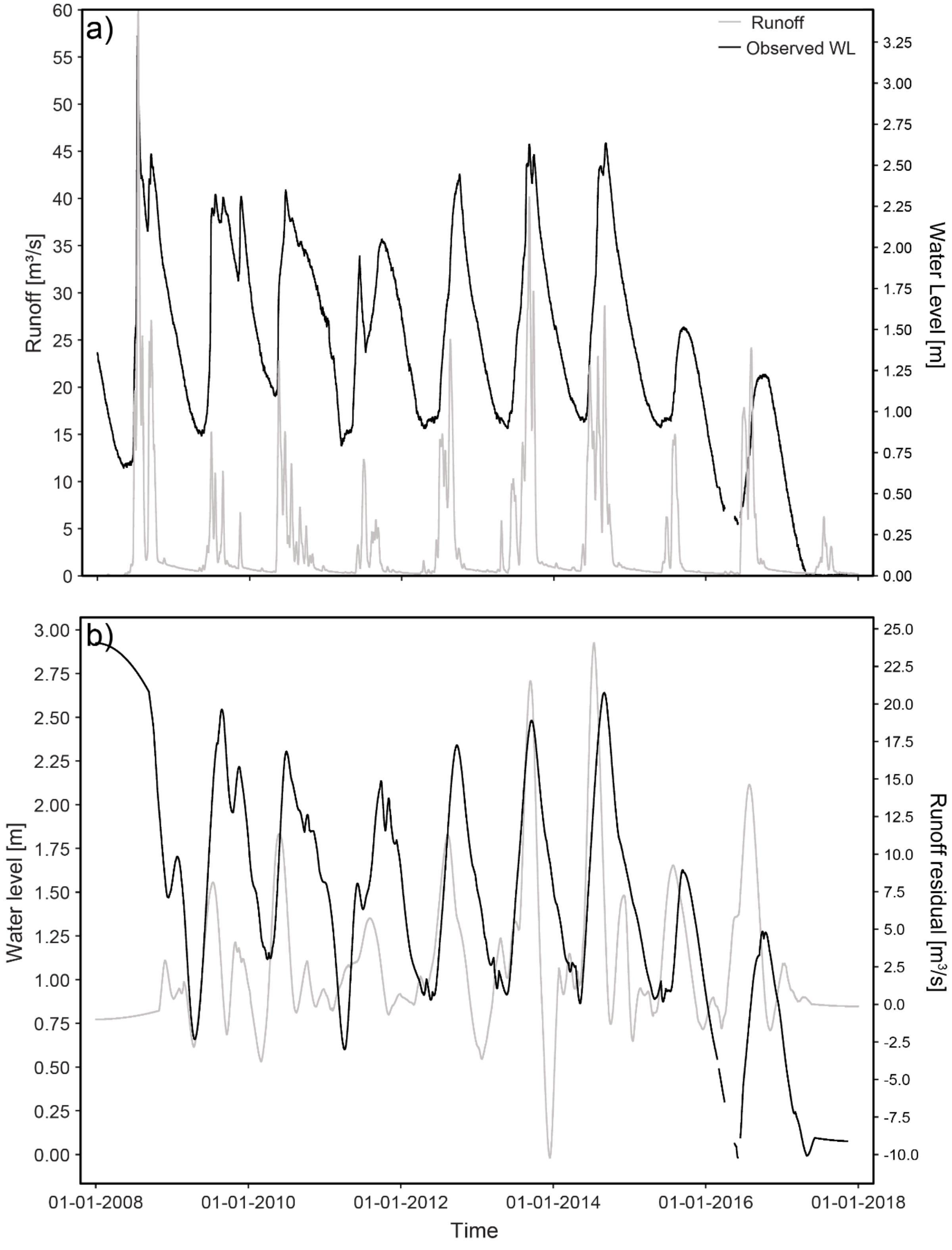

Figure 8: a) The water level fluctuations at station G3T001 with modelled runoff and b) the EMD filtering showing the variation in discharge timeseries attributed a water level change at the station

4. Results

The J2000 model was used to simulate both runoff and baseflow, with runoff being comprised of direct surface runoff (RD1) and interflow (RD2) and baseflow simulated from the primary (RG1) and secondary aquifer (RG2). Below, the results of the modelled streamflow and baseflow are presented, along with the total flow contribution of each tributary, the runoff to baseflow proportioning and stream exceedance probabilities. The coefficient of variation (CV) was used to determine the streamflow variability of each tributary, while the baseflow index (BFI) was used to determine the baseflow and runoff proportion.

4.1 Streamflow and baseflow

Streamflow for the sub-catchment shows two distinctively wet periods (1987-1997 and 2007-2017), separated by a dry period (1997-2007) (Fig. 9). Yearly sub-catchment rainfall volumes between 1987-1997 were between 288 and 492 mm/yr^{-1}, with an average of 404 mm.yr^{-1}. For this period, average yearly streamflow between 1987-1997 was 1.4 m^{3}.s-^{1}, with an average baseflow contribution of 0.63 m^{3}.s^{-1}. The modelled streamflow reached a maximum of 48 m^{3}.s^{-1} in 1993, when 5 m^{3}.s^{-1} of baseflow was generated after 58 mm of rainfall was received. Between 1997-2007 (dry period) sub-catchment yearly rainfall was between 222 and 394 mm/yr-^{1} with an average of 330 mm.yr^{-1} (Fig. 9). For this period, average yearly streamflow between 1997-2007 was 0.44 m^{3}.s^{-1}, with an average baseflow contribution of 0.18 m^{3}.s^{-1}. The modelled streamflow reached a maximum of 11 m^{3}.s^{-1} in 2002, with a baseflow contribution of 2.5 m^{3}.s^{-1} after 28 mm of rainfall was received. Between 2007-2017 (wet period) sub-catchment yearly rainfall was between 231 and 582 mm.yr^{-1} with an average of 427 mm.yr^{-1} (Fig. 9). Over this period, average yearly streamflow between 2007-2017 was 2.5 m^{3}.s^{-1} with an average baseflow contribution of 1.3 m^{3}.s^{-1}. The modelled streamflow reached a maximum of 52 $m^3.s^{-1}$ in 2008, with 13 $m^3.s^{-1}$ of baseflow generated after two consecutive rainfall events each of 25 mm.

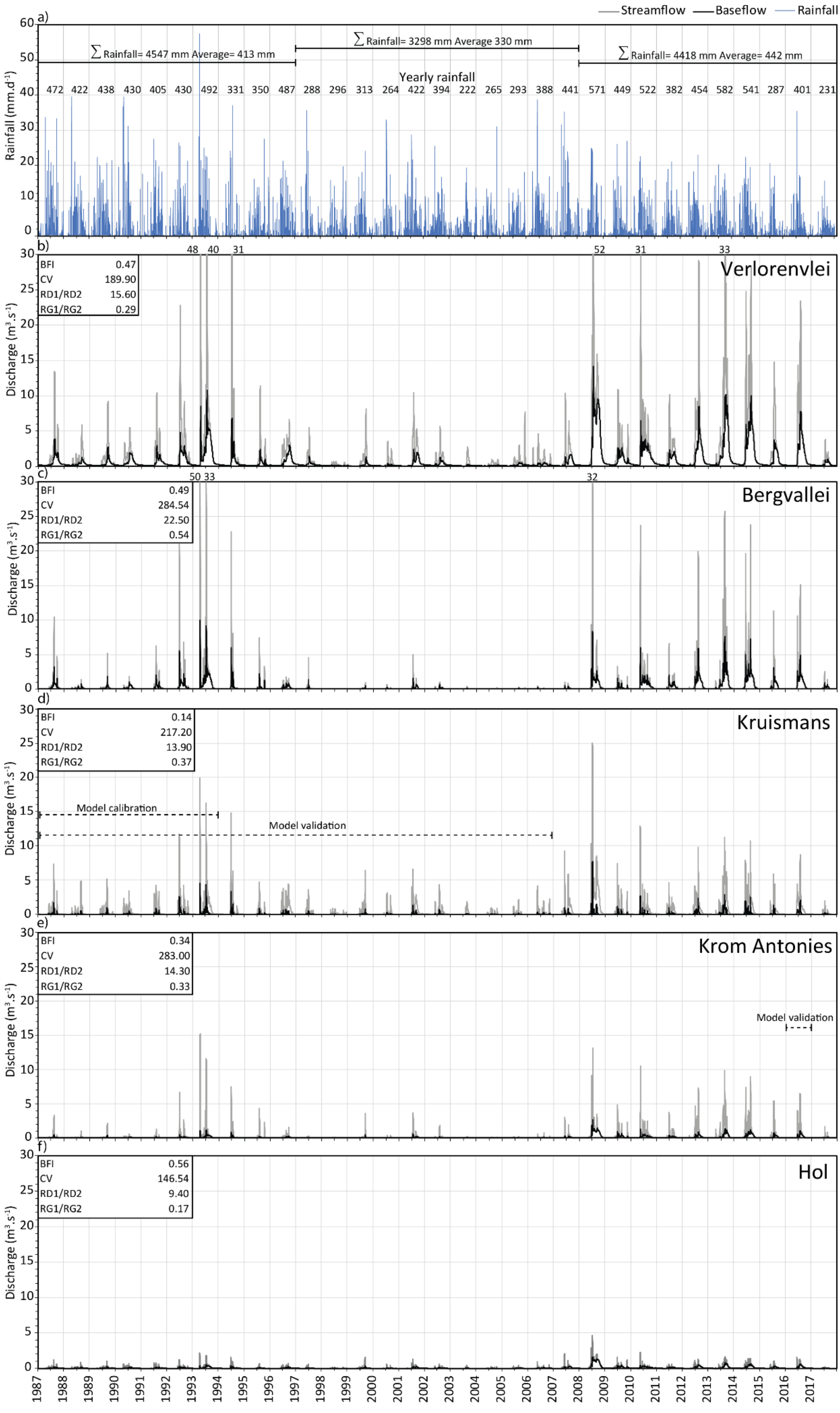
Streamflow
Baseflow
Rainfall
a)
∑ Rainfall= 4547 mm Average= 413 mm
∑ Rainfall= 3298 mm Average 330 mm
∑ Rainfall= 4418 mm Average= 442 mm
Yearly rainfall
472 422 438 430 405 430 492 331 350 487 288 296 313 264 422 394 222 265 293 388 441 571 449 522 382 454 582 541 287 401 231
Rainfall (mm.d⁻¹)
b)
Verlorenvlei
BFI 0.47
CV 189.90
RD1/RD2 15.60
RG1/RG2 0.29
48 40 31 52 31 33
Discharge (m³.s⁻¹)
c)
Bergvallei
BFI 0.49
CV 284.54
RD1/RD2 22.50
RG1/RG2 0.54
50 33 32
d)
Kruismans
BFI 0.14
CV 217.20
RD1/RD2 13.90
RG1/RG2 0.37
Model calibration
Model validation
e)
Krom Antonies
BFI 0.34
CV 283.00
RD1/RD2 14.30
RG1/RG2 0.33
Model validation
f)
Hol
BFI 0.56
CV 146.54
RD1/RD2 9.40
RG1/RG2 0.17
1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017

Figure 9: a) The average sub-catchment rainfall between 1987-2017 showing wet cycles (1987-1997 and 2008-2017), the modelled streamflow and baseflow inflows for the b) Verlorenvlei, c) Bergvallei, d) Kruismans, e) Krom Antonies and f) Hol with estimated BFI, CV, RD1/RD2, RG1/RG2

4.2 Tributary contributions

The four main feeding tributaries (Bergvallei, Kruismans, Hol and Krom Antonies) together contribute 81% of streamflow for the Verlorenvlei, with the additional 19% from small tributaries near Redelinghuys (Fig. 10). The Kruismans contributes most of the total streamflow with 32 %, although due to the sub-catchment being the largest of the tributaries (688 km^2), the area weighted contribution is 15 % (Fig. 10). The Bergvallei (320 km^2), which is smaller than the Kruismans, contributes 29 % of the total flow with an area weighted contribution of 28 %. The Krom Antonies has the largest area weighted contribution of 30 % due to its small size (140 km^2) in comparison to the other tributaries, although the Krom Antonies contributes only 13 % of the total flow (Fig. 10). The Hol (126 km^2) contributes the least total flow with 7 %, with a weighted contribution of 17 % (Fig. 10).

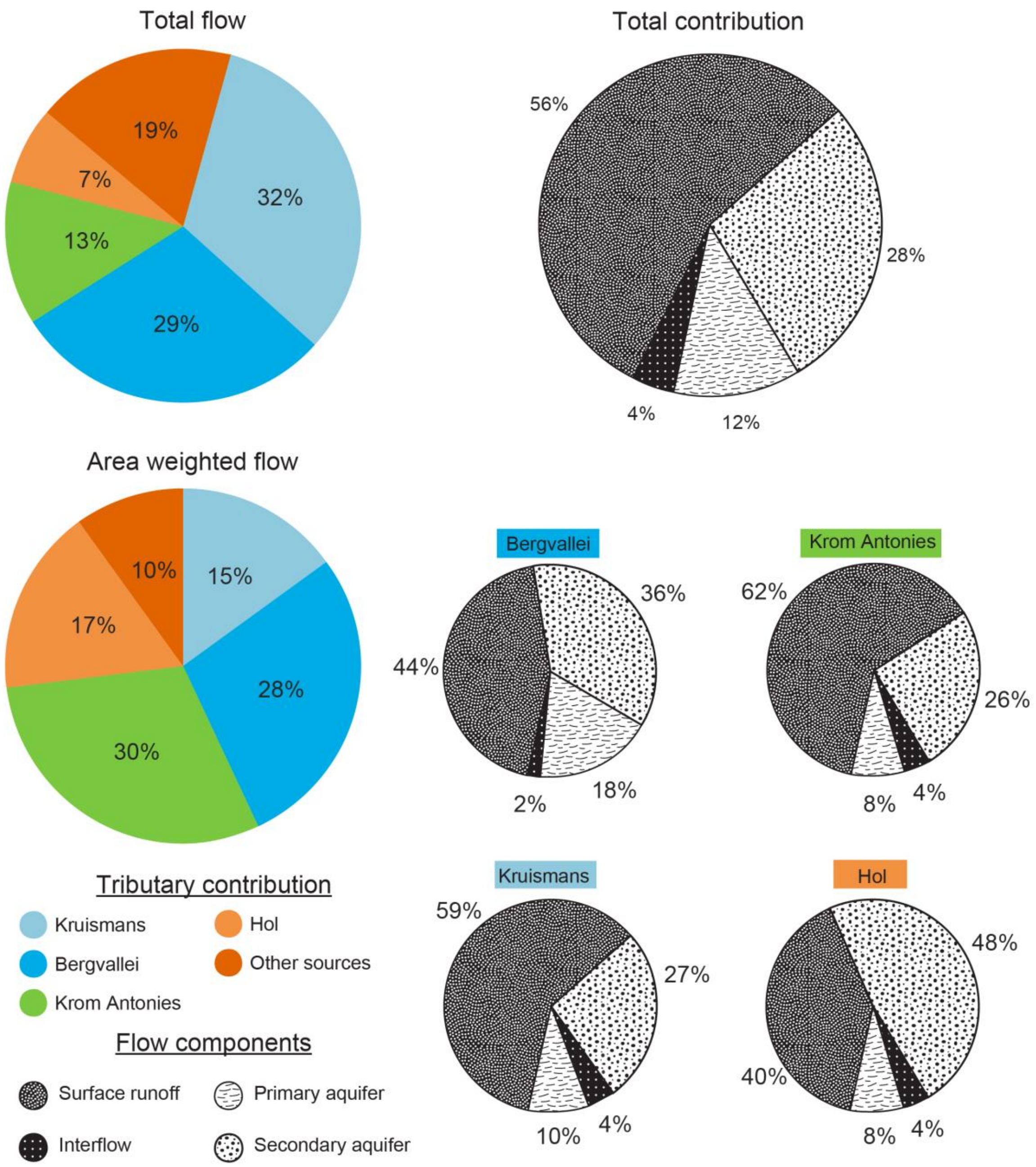

Figure 10: The Verlorenvlei reserve flow contributions (total flow and area weighted flow) of the Kruismans, Bergvallei, Krom Antonies and Hol as well as flow component separation into surface runoff (RD1), interflow (RD2), primary aquifer flow (RG1) and secondary aquifer flow (RG2).

4.3 Flow variability

Streamflow that enters Verlorenvlei has a large daily variability with a coefficient of variation (CV) of 189.90 (Fig. 9). This is mainly due to high streamflow variability from the Kruismans (32%) with a CV of 217.20, which is the major total flow contributor (Fig 10). The Bergvallei and Krom Antonies, which both have high streamflow variability with CV values of 284.54 and 283.00 respectfully (Fig. 9), further contribute to the high variability of streamflow that enters the lake. While the Hol reduces the overall streamflow variability with a CV of 146.54, it is a minor total flow contributor (7%) and therefore does not reduce the overall streamflow variability significantly (Fig. 10).

Streamflow that enters Verlorenvlei is dominated by surface runoff which makes up 56 % of total flow, with groundwater and interflow contributing 40 % and 4 % respectfully (Fig. 10). The large surface runoff dominance in streamflow entering the lake, is due to a high surface runoff contribution from the Kruismans and Krom Antonies, which contribute 26 % of total flow from surface runoff. However, for the Bergvallei and Hol, surface runoff contributions are less dominant with 16 % of the total, while the total groundwater contribution is 20 % from these tributaries. Across all four tributaries, the secondary aquifer is the dominant baseflow component with 28 % of total flow, with the primary aquifer contributing 12 %. The Bergvallei and Kruismans contribute the majority of primary aquifer baseflow with 8 % of the total. The secondary aquifer baseflow is mainly contributed by the Kruismans and Bergvallei, where together 18 % of the total is received. Interflow across the four tributaries is uniformly distributed with 0.3 – 1 % of the total flow being contributed from each tributary.

4.4 Flow exceedance probabilities

The flow exceedance probability, which is a measure of how often a given flow is equalled or exceeded was calculated for each of the tributaries as well as the lake water body. The results for the flow exceedance probabilities includes flow volumes which are exceeded 95%, 75%, 50%, 25 % and 5 % of the time. The 95 percentile corresponds to a lake inflow of 0.054 $m^3.s^{-1}$ or 4,702 $m^3.d^{-1}$, with between 0.001-0.004 $m^3.s^{-1}$ from the feeding tributaries (Fig. 11 and Table 3). The 75-percentile flow, which is exceeded 3/4 of the time corresponds to an inflow of 0.119 $m^3.s^{-1}$ or 10,303 $m^3.d^{-1}$, with between 0.005-0.015 $m^3.s^{-1}$ from the feeding tributaries. Average (50 percentile) streamflow flowing into the Verlorenvlei is 0.237 $m^3.s^{-1}$ or 20,498 $m^3.d^{-1}$, with between 0.012-0.012 $m^3.s^{-1}$ from the feeding tributaries. The 25-percentile flow, which is exceeded ¼ of the time corresponds to a lake inflow of 1,067 $m^3.s^{-1}$ or 92,204 $m^3.d^{-1}$ with between 0.044-0.291 $m^3.s^{-1}$ from the feeding tributaries. The lake inflows that are exceeded 5 % of the time correspond to 6.939 $m^3.s^{-1}$ or 599,535 $m^3.d^{-1}$ with between 0.224-2.49 $m^3.s^{-1}$ from the feeding tributaries.

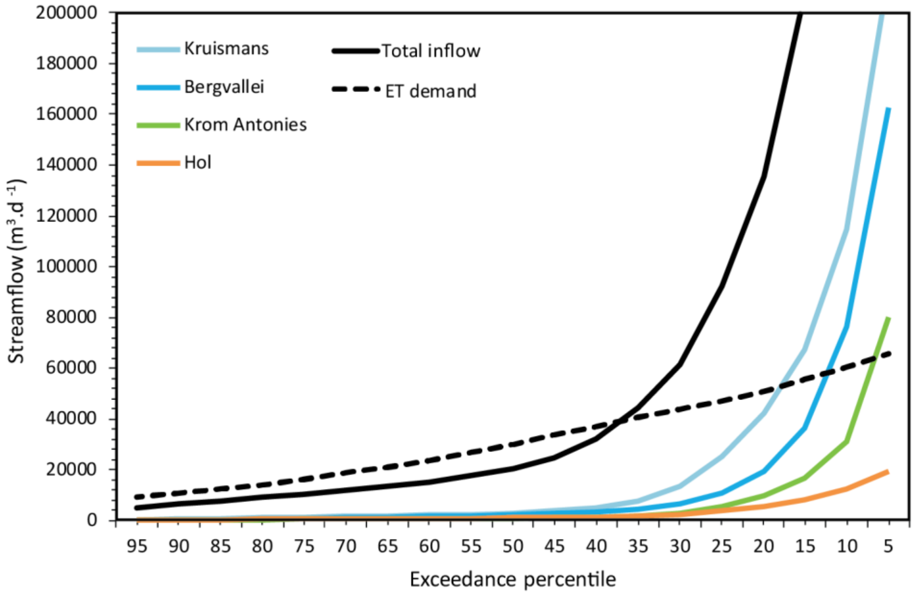

Figure 11: The streamflow exceedance percentiles and evaporation demand of the Verlorenvlei reserve, with the contributions from each feeding tributary

Exceedance percentile	Lake ET $m^3.d^{-1}$	Verlorenvlei $m^3.s^{-1}$	$m^3.d^{-1}$	Kruismans $m^3.s^{-1}$	$m^3.d^{-1}$	Bergvallei $m^3.s^{-1}$	$m^3.d^{-1}$	Krom Antonies $m^3.s^{-1}$	$m^3.d^{-1}$	Hol $m^3.s^{-1}$	$m^3.d^{-1}$
95	9158	0.054	4702	0.004	346	0.001	69	0.001	109	0.002	176
90	10956	0.074	6356	0.007	604	0.002	191	0.003	232	0.003	269
85	12559	0.088	7628	0.010	830	0.004	366	0.004	319	0.004	353
80	14249	0.104	8979	0.012	1072	0.007	596	0.005	392	0.005	434
75	16330	0.119	10303	0.015	1291	0.010	839	0.005	459	0.006	508
70	18653	0.136	11759	0.018	1517	0.013	1104	0.006	534	0.007	587
65	21152	0.155	13373	0.021	1791	0.016	1381	0.007	602	0.008	676
60	23791	0.176	15180	0.024	2104	0.019	1657	0.008	685	0.009	786
55	26979	0.203	17575	0.029	2506	0.023	1965	0.009	772	0.011	913
50	30057	0.237	20498	0.035	3032	0.027	2309	0.010	882	0.012	1058
45	33467	0.286	24669	0.043	3755	0.032	2807	0.012	1024	0.014	1222
40	36760	0.371	32023	0.058	5022	0.041	3511	0.015	1258	0.017	1439
35	40391	0.516	**44598**	0.089	7699	0.053	4613	0.020	1745	0.021	1790
30	43814	0.710	61310	0.156	13511	0.076	6599	0.033	2824	0.029	2481
25	47062	1.067	92204	0.291	25182	0.123	10619	0.062	5387	0.044	3814
20	50997	1.571	135726	0.489	42242	0.223	19295	0.110	9511	0.065	5655
15	55797	2.399	207275	0.780	**67408**	0.421	36354	0.192	16594	0.096	8262
10	60162	3.759	324746	1.324	114432	0.885	**76477**	0.359	31045	0.141	12191
5	65418	6.939	599535	2.490	215152	1.884	162795	0.929	**80305**	0.224	19312

Table 3: The streamflow exceedance percentiles and lake evaporation demand for the Verlorenvlei reserve, with the contributions from the Kruismans, Bergvallei, Krom Antonies and Hol ($m^3.s^{-1}$ and $m^3.d^{-1}$)

5. Discussion

The adaptation of the J2000 rainfall/runoff model was used to understand the flow contributions of the main feeding tributaries, the proportioning of baseflow to surface runoff as well as how often the inflows exceed the lake evaporation demand. Before a comparison with previous baseflow estimates can be made and the impact of evaporation on the lake reserves assessed, the model limitations and catchment flow dynamics must also be assessed.

5.1 Model limitations and performance

A major limitation facing the development and construction of comprehensive modelling systems in sub-Saharan Africa is the availability of appropriate climate and streamflow data. For this study, while there was access to over 20 years of streamflow records, the station was only able to measure a maximum of 3.68 $m^3.s^{-1}$, which hindered calibration of the model for high flow events. As such, the confidence in the model's ability to simulate high streamflow events using climate records is limited. While the availability of measured data is a limitation that could affect the modelled streamflow, discontinuous climate records also hindered the estimations of long time series streamflow.

Over the course of the 30-year modelling period, a number of climate stations used for regionalisation were decommissioned and were replaced by stations in different areas. This required adaption of climate regionalisation for simulations over the entire 30-year period to incorporate the measured streamflow from the gauging station. To account for missing streamflow records since 2007, an EMD filtering protocol was applied to the runoff data (Fig. 6). The results from the EMD filtering showed that after removing the first nine IMFs, the local maxima of both signals match the seasonal water level maxima during most of the years. While considerable improvement can be made to the EMD filtering, the results show some agreement which suggested that the simulated runoff was representative of inflows into the lake.

5.2 Catchment dynamics

Factors that impact on streamflow variability are important for understanding river flow regime dynamics. Previously, factors that affected streamflow variability such as CV and BFI values were used to determine how susceptible particular river systems were to drought (e.g Hughes and Hannart, 2003). While CV values have been used to account for climatic impacts such as dry and wet cycles, BFI values are associated with runoff generation processes that impact the catchment. For most river systems, BFI values are generally below 1 implying that runoff exceeds baseflow. In comparison CV values can be in excess of 10 implying high variability in streamflow volumes (Hughes and Hannart, 2003). In this study, these two measurements have been applied to tributaries as opposed to quaternary river systems, to understand the streamflow input variability into the Verlorenvlei.

The highest proportion of streamflow needed to sustain the Verlorenvlei lake water level is received from the Bergvallei tributary, although the area weighted contribution from the Krom Antonies is more significant (Fig. 10). However, CV values for the Bergvallei indicate high streamflow variability. This is partially due to the high surface runoff component in modelled streamflow within the Bergvallei in comparison to the minor interflow contribution, suggesting little sub-surface runoff. While streamflow from the Bergvallei tributary is 54% groundwater, which would suggest a more sustained streamflow, due to the TMG dominance as well as a high primary aquifer contribution, baseflow from the Bergvallei is driven by highly conductive rock and sediment materials. Similarly, CV values for the Krom Antonies indicate high streamflow variability due to the presence of a high baseflow contribution from the conductive TMG and primary aquifers. Although the Krom Antonies has a larger interflow component, which would reduce streamflow variability, the dominant TMG presence within this tributary partially compensates for the subsurface flow contributions.

In contrast, the Hol has a much smaller daily streamflow variability in comparison to both the Bergvallei and the Krom Antonies (Fig. 9). While streamflow from the Hol tributary is mainly comprised of baseflow (56%), the dominance of low conductive shale rock formations as well as a large interflow component results in reduced streamflow variability. While the larger shale dominance in this tributary not only results in a more sustained baseflow from the secondary aquifer, it also results in a large interflow component due to the limited conductivity of the shale formations. Compounding the more sustained baseflow from the Hol tributary, the reduced extent of the primary aquifer results in a dominance in slow groundwater flow from this tributary. Similarly, the Kruismans is dominated by shale formations which result in a larger interflow contribution, although due to the limited baseflow contribution (37%) the streamflow from this tributary is highly variable, which impacts on its susceptibility to drought.

The results from this study have shown that while the Krom Antonies was initially believed to be the major flow contributor, the Bergvallei is in fact the most significant, although streamflow from the four tributaries is highly variable, with baseflow from the Hol tributary the only constant input source. The presence of conductive TMG sandstones and quaternary sediments in both the Krom Antonies and Bergvallei, results in quick baseflow responses with little flow attenuation. The potential implication of a constant source of groundwater being provided from the Hol tributary, is that if the groundwater is of poor quality this would result in a constant input of saline groundwater, with the Krom Antonies and Bergvallei providing freshwater only after sufficient rainfall has been received.

5.3 Baseflow comparison

The groundwater components of the J2000 model were adjusted using aquifer hydraulic conductivity from a MODFLOW model of one of the main feeding tributaries of the Verlorenvlei. The Krom Antonies was selected as it was previously believed to be the largest input of groundwater to Verlorenvlei (Fig. 2). Baseflow for the Krom Antonies tributary was previously calculated using a MODFLOW model (Watson, 2018), by considering aquifer hydraulic conductivity and average groundwater recharge. As average recharge was used, baseflow estimates from MODFLOW are likely to fall on the upper end of daily baseflow values estimated by the J2000 model. For the Krom Antonies sub-catchment, Watson, (2018) estimated baseflow between 14,000 to 19,000 $m^3.d^{-1}$ for 2010-2016 using MODFLOW. Similar daily baseflow estimates from the J2000 were only exceeded 10 % of the time, with average estimates (50%) of 1,036 $m^3.d^{-1}$ over the course of the modelling period (Fig. 9).

The MODFLOW estimates were applied over the course of a wet cycle (2016). In comparison to the MODFLOW estimates (14,000 to 19,000 $m^3.d^{-1}$) average baseflow from J2000 for 2016 was 8, 214 $m^3.d^{-1}$. The daily timestep nature of the J2000 is likely to result in far lower baseflow estimates, as recharge is only received over a 6-month period as opposed to a yearly average estimate. One possible implication of this is that while common groundwater abstraction scenarios have been based on yearly recharge, abstraction is likely to exceed sustainable volumes during dry months or dry cycles and this could hinder the ability of the aquifer to supply baseflow. While the groundwater components of the J2000 have been distributed to allow for improved baseflow estimates, the groundwater calibration was applied to the Krom Antonies. However, this study showed that Bergvallei has been identified as the largest water contributor. In hindsight, the use of geochemistry to identify dominant tributaries could have aided the groundwater model adaption. While it would have been beneficial to adapt the groundwater components of the J2000 using the dominant baseflow contributor, considering the geological heterogeneity between tributaries is more important for identifying how to adapt the groundwater components of the J2000. While the distribution of aquifer components improved modelled baseflow, including groundwater abstraction scenarios in baseflow modelling in the sub-catchment is important for future water management for this ecologically significant area.

5.4 The Verlorenvlei reserve and the evaporative demand

For this study, exceedance probabilities were estimated through rainfall/runoff modelling for the previous 30 years within the Verlorenvlei sub-catchment. The exceedance probabilities were determined for each tributary, as well as the total inflows into the lake. These exceedance probabilities were compared with the evaporative demand of the lake, to understand whether inflows are in surplus or whether evaporation demand exceeds inflow.

From the exceedance probabilities generated in this study, the lake is predominately fed by less frequent large discharge events, where on average the daily inflows to the lake do not sustain the lake water level. This is particularly evident in the measured water level data from station G3T001, where measured water levels have a large daily standard deviation (0.62) (Watson *et al*., 2018). With climate change likely to impact the length and severity of dry cycles, it is likely that the lake will dry up more frequently into the future, which could have severe implications on the biodiversity that relies on the lake's habitat for survival. Of importance to the lake's survival is the protection of river inflows during wet cycles, where the lake requires these inflows for regeneration.

While the impact of irrigation could not be incorporated, over allocation of water resources may potentially have a significant impact on the catchment water balance, especially during wet cycles when ecosystems are recovering from dry conditions. The increased irrigation during wet cycles as a result of agricultural development, could be a further impact on the recovery of sensitive ecosystems. This type of issue is not limited to Verlorenvlei but applies to many wetlands or estuarine lakes around the world, while they have been classified as protected areas, water resources within the catchments are required for food security. As climate change drives increased temperatures and variability in rainfall, the ± 10-year cycles of dry and wet conditions may no longer be valid anymore, where these conditions may shorten or lengthen. With the routine breaking of weather records across the world (Bruce, 2018; Davis, 2018), it is becoming increasingly evident that conditions are changing and becoming more variable, which could impact sensitive ecosystems around the world, highlighting the need for effective water management protocols during times of limited rainfall.

6. Conclusion

Understanding river flow regime dynamics is important for the management of ecosystems that are sensitive to streamflow fluctuations. While climatic factors impact rainfall volumes during wet and dry cycles, factors that control catchment runoff and baseflow are key to the implementation of river protection strategies. In this study, groundwater components within the J2000 model were distributed to improve baseflow and runoff proportioning for the Verlorenvlei sub-catchment. The J2000 was distributed using groundwater model values for the dominant baseflow tributary, while calibration was applied to the dominant streamflow tributary. The model calibration was hindered by the maximum gauging station resolution, which reduced the confidence in modelling high flow events, although an EMD filtering protocol was applied to account for the resolution limitations and missing streamflow records. The modelling approach would likely be transferable to other partially gauged semi-arid catchments, provided that groundwater recharge is well constrained. The daily timestep nature of the J2000 model allowed for an in-depth understanding of tributary flow regime dynamics, showing that while streamflow variability is influenced by the runoff to baseflow proportion, the host rock or sediment in which groundwater is held is also a factor that must be considered. The modelling results showed that on average the streamflow influxes were not able to meet the evaporation demand of the lake. High-flow events, although they occur infrequently, are responsible for regeneration of the lake's water level and ecology, which illustrates the importance of wet cycles in maintaining biodiversity levels in semi-arid environments. With climate change likely to impact the length and occurrence of dry cycle conditions, wet cycles become particularly important for ecosystem regeneration, especially for semi-arid regions such as the Verlorenvlei.

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