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Application of multi-method approach to assess groundwater–surface water interactions, for catchment management

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Abstract

Globally, the dependence of river systems to delayed discharge of subsurface water to augment flows during dry seasons is well documented. Discharge of fresh subsurface water can dilute concentrated river flow quality during reduced flow. Observed and reported results on the Berg River's declining water quantity and quality are a concern to the regions socio-economic growth and environmental integrity. Understanding the role of subsurface water discharges on the quantity and quality of receiving surface water courses can improve their management during dry periods. A case study was designed and implemented in the upper Berg River catchment in the Western Cape Province of South Africa to assess the influence of groundwater–surface water interaction on water quantity and quality. This study aimed to quantify and characterize the quality of subsurface water available in the upper catchment to improve observed declining water quality downstream. Hydrograph separation provided estimates of water fluxes during 2012–2014 low and high flow periods, while hydrochemical analysis provided insights on impacts of major land use activity in this catchment on water resources. Hydrograph separation analysis indicated that the Berg River is 37.9% dependent on subsurface water discharges annually. Dominant Na–Cl-type water indicates the quality of water from the upper Berg River is largely affected by natural processes including short residence times of aquifer water, rock–water interactions and atmospheric deposition of NaCl ions. These results provide insights for suggesting management options to be implemented to protect subsurface water for continued dilution and water resources management in the lower catchments.

Introduction

Groundwater and surface water (GW–SW) are in hydraulic connectivity over various physiographic environments. Understanding how these resources interact is crucial for the utilization, management and protection of water resources to enhance human activities and sustain ecological demands of water (Fetter 1994; Freeze and Cherry 1979; Levy and Xu 2011; Winter et al. 1998). Globally, the role of GW–SW interactions has been investigated to assess the importance of groundwater discharge to maintaining aquatic ecosystems (Braaten and Gates 2001; Burns et al. 2001), estimating groundwater recharge (Arnold and Allen 1999; Mau and Winter 1997), assessing the role of GW–SW in providing spawning grounds for fish types (Craig 2005; Crosbie et al. 2007; Hayashi and Rosenberry 2002) and overall,

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determining water availability during low flow periods (Ellis 2002; Ladouche et al. 2001; Yang et al. 2014; Zhou et al. 2013). Assessing GW–SW interactions is complex and requires the knowledge of a variety of influential factors including rainfall patterns, underlying geology, plant cover type and type of land use among many others. These factors not only influence the interaction between groundwater and surface water, but also water quality.

The aim of this study was to quantify GW–SW fluxes and characterize the quality of the water that would be able to improve the observed declining water quality in the middle and lower catchments of the Berg River in the Western Cape Province, South Africa. To achieve this aim, a case study was conducted from 2012 to 2014, in which a multi-method approach was applied to determine GW–SW exchanges fluxes using automated base flow separation, while the characterization of groundwater and surface water resources was conducted through hydrochemical analysis.

Studies conducted globally continue to indicate the combined use of multiple methods for assessing GW–SW interactions is most plausible due to the compensation of the spatial and temporal shortfalls of other methods (Binley et al. 2013; Cao et al. 2012; Cey et al. 1998; Fleckenstein et al. 2010; Kaandorp et al. 2018; Kakuchi et al. 2012; Kalbus et al. 2006; Petelet-Giraud et al. 2007; Yang et al. 2014).This study applied a multiple methods to assess GW–SW interaction by estimating groundwater fluxes using the automated base flow separation, while GW–SW quality characterization was done using hydro-chemical analysis.

Self-purification of a river is the ability of a river to purify itself of contaminants by natural processes. Various processes are responsible, including the dilution of polluted surface water with influx of fresher surface water or groundwater, complex biologic and chemical processes (Unland et al. 2015; Whitehead and Lack 1982). It has been suggested that benthic stream biofilms are capable of assimilating and effectively retaining nutrients and are therefore crucial to river self-purification (Dodds 2003; Oberholster et al. 2015). These aquatic biota and streambed substrate configuration are important in the control of nutrient concentrations during low flow, where discharges from subsurface water storages dominate streamflow generation. The discharge of contaminated groundwater can have detrimental effects on river quality, while the discharge of less contaminated water than the river can improve the quality of the river (Conant et al. 2004; Hall 2013; Hobbs et al. 2008; New Jersey Department of Environmental Protection 2016; Oberholster et al. 2013; Opitz and Timms 2016).Conversely, river self-purification can occur if fresher subsurface water discharges into surface water bodies, thereby diluting concentrations in the river channel.

Materials and methods

Study site description

The Berg River catchment in the Western Cape of South Africa is an important source of water to the greater city of Cape Town, its surrounding towns and dependent ecosystems.

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The estimated groundwater potential yield (Table 1) for the Cape Town region is 66 Mm^3/a and 28.3 Mm^3/a for the Berg River Catchment (Meyer 2001; Parsons 2002). Major water uses include agriculture, domestic use and sustaining the environment. Many farms situated in the drier, lower parts of this catchment (Fig. 1) rely heavily on local groundwater and many along the river rely on surface water resources for irrigation (Parsons 2003; Ractliffe 2007). The 174 km^2 headwater catchment is a mountainous sub-catchment (Fig. 2) of the Berg River Water Management Area (S33.95733° and E19.07264°). The area is bound by the Franschhoek and Groot Drakenstein mountains. A Mediterranean macro-climate exists, with warm-dry summers (November-March) and cool-wet winters (April–October). Mean annual precipitation (MAP), mean annual potential evaporation (MAPE) and mean annual runoff (MAR) of 1603, 1475 and 1015 mm/a, respectively. Areas defined by a disproportionate MAR to the geographical are of concern, constitute strategic water sources, termed High Water Yielding Areas (Nel et al. 2013).

The rivers and groundwater flow above and through the Table Mountain Group (TMG) geological formations (Fig. 3). The TMG in the upper catchment is comprised mainly of the chemically inert sandstones of the Peninsula Formation and the relatively mineralized sand, silt and mudstone of the Nardow and Franschhoek Shale Formations. The oligotrophic, acidic and low salinity water in the upper catchment is characteristic of TMG formation water. This highly fractured formation has secondary porosity creating conduits for water and potential contamination. Aquifers in the area are highly productive with conductivities generally less than 70 mS/m (Lasher 2011; Ractliffe 2007). Land use primarily consists of agricultural, natural vegetation cover, forestry and human settlements, with the largest proportion of land allocated to agriculture (Adams 2011; Kotzee 2010; Fig. 4 and Table 1). With these activities, understand GW–SW interactions with recognition of the reported declining surface water quality and also what role this interaction plays in remediating/diluting this contamination is important (Bugan 2008; de Villiers 2007; Jackson et al. 2013; Oberholster et al. 2015).

Table 1 Calculated area and percentage of area of the different Land uses/covers within the upper Berg River catchment

Land use/cover	Area of land use/cover (km^2)	% land use/cover
Agricultural (irrigated and dryland)	30.10	17.31
Forestry (Pine *spp* and clear-felled)	5.15	2.96
Natural cover (Shrub-land and low Fynbos)	136.24	78.33
Urban (residential)	1.97	1.13
Water bodies (rivers, dams and wetlands)	0.47	0.27
Total area	173.93	100.00

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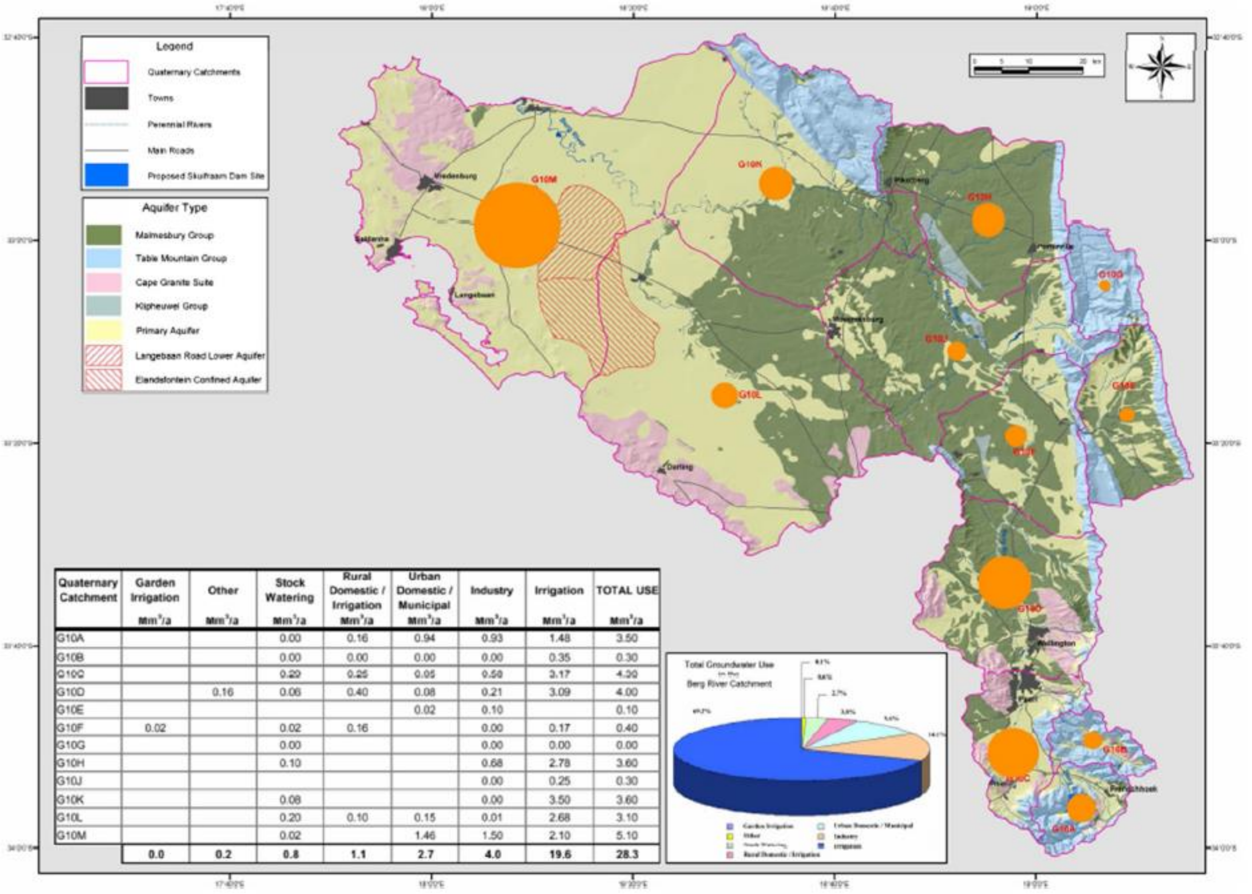

Quaternary Catchment	Garden Irrigation Mm³/a	Other Mm³/a	Stock Watering Mm³/a	Rural Domestic / Irrigation Mm³/a	Urban Domestic / Municipal Mm³/a	Industry Mm³/a	Irrigation Mm³/a	TOTAL USE Mm³/a
G10A			0.00	0.16	0.94	0.93	1.48	3.50
G10B			0.00	0.00	0.00	0.00	0.35	0.30
G10C			0.20	0.25	0.05	0.50	3.17	4.20
G10D		0.16	0.06	0.40	0.08	0.21	3.09	4.00
G10E					0.02	0.10		0.10
G10F	0.02		0.02	0.16		0.00	0.17	0.40
G10G			0.00			0.00	0.00	0.00
G10H			0.10			0.68	2.78	3.60
G10J						0.00	0.25	0.30
G10K			0.08			0.00	3.50	3.60
G10L			0.20	0.10	0.15	0.01	2.68	3.10
G10M			0.02		1.46	1.50	2.10	5.10
	0.0	0.2	0.8	1.1	2.7	4.0	19.6	28.3

Fig. 1 Groundwater abstraction in the Berg River catchment. *Source*: Parsons (2003)

Experimental setup

This study used a network of 29 boreholes and 10 river sampling sites, sparsely situated in the upper Berg River catchment for the characterization of groundwater and surface water quality, as well to establish groundwater flow direction. An additional five stream gauging stations in the upper catchment were also selected for hydrograph separation to derive the quantity of groundwater discharge to surface water over time. Due to the inconsistency in stream flow data and impacts of anthropogenic activities on river flows from four of the five selected stations, station G1H076 situated at the BRM1 research site upstream of the Berg River Dam was selected (Fig. 4). This station exhibited no impacts of abstraction or discharge of water into or out of the stream, thereby conforming to the assumptions set by the method of quantifying groundwater discharge through the separation of a stream hydrograph into this quick and base flow components for a natural un-impacted system.

Data collection methods

There are many techniques that can be considered for hydrograph separation. For continuous (filtering) separation of the different flow components, the techniques may include automated graphical methods, recursive digital filtering and use of additional data like groundwater levels (Tallaksen 1995). To separate the quick-flow and base-flow components from the stream hydrograph obtained in the upper Berg River catchment, a use of

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recursive digital filtering was made. Daily time series stream flow data spanning from September 2012 to September 2014 was retrieved from the https://www.DWA.gov.za/hydrology website (DWS 2013). This period was chosen to investigate the seasonal contributions of subsurface water storages to river flows in the upper Berg River catchment under minimal hydrological and land use/ land cover disturbances. Recession constants (α parameter) of the filter algorithms from studies conducted in fractured rock environments in semiarid catchments globally were consulted to ascertain the most appropriate to use in this study (Brodie and Hostetler 2005; Hughes et al. 2003; Mau and Winter 1997; Welderufael and Woyessa 2010).

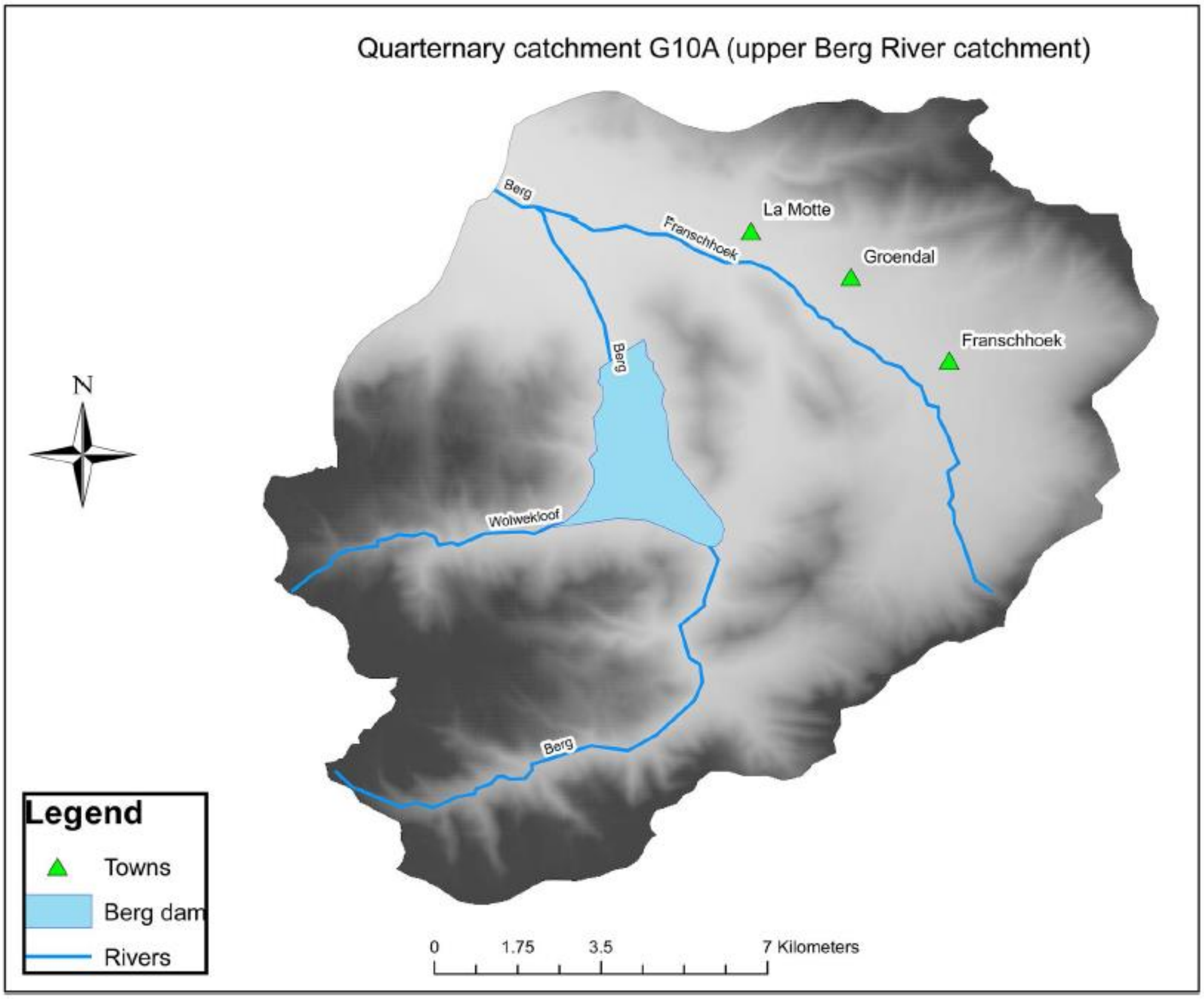

Fig. 2 Geographical location of upper Berg River catchment in relation to Western Cape Province of South Africa

As a general rule, the filter parameter $\alpha = 0.925$ is suggested as starting point for most base flow separations (Smakhtin 2001). Welderufael and Woyessa (2010) and Hughes et al. (2003) suggest the similar filter parameter value $\alpha = 0.925$ for South African catchments. There are many catchments where slightly higher α parameter values (up to 0.997) are appropriate (Hughes et al. 2003). However, an over- or under-estimation of the α parameter can result in substantially increased or decreased low base flow proportions (Hughes et al. 2003). While this approach offers advantages in terms of generating smoother

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base flow response results, it also introduces a further parameter to the application of the equation. Therefore, due to the uncertainty of deriving the Base flow Index (BFI) value from streamflow measurements (Eckhardt 2012) following the suggested recession coefficient parameter ($\alpha = 0.925$) was considered appropriate for this investigation of the base flow contribution to streamflow within a South African catchment.

Finally the selection and application of the Lynne and Hollick Algorithm (Nathan and McMahon 1990) along with the Chapman Algorithm (Chapman 1999; Mau and Winter 1997) were selected on the merit of their objectivity regarding the estimation of the quantity of groundwater discharge to streams. Applying the Elasticity Index (sensitivity analysis) described by (Eckhardt 2012) to the above-mentioned algorithms, the suitability of the chosen α recession coefficient (i.e., $\alpha = 0.925$) was tested. Sensitivity of this recession coefficient was computed to S (BFI/a) = 0.64 for the Chapman Algorithm, which signifies that a relative error of X percent in α parameter estimation causes a relative error of 0.64 times X percent in BFI. For the Lynne and Hollick Algorithm the sensitivity of this recession coefficient was computed to S(BFI/a) = 0.00, indicating a lower relative error of the recession coefficient ($\alpha = 0.925$).

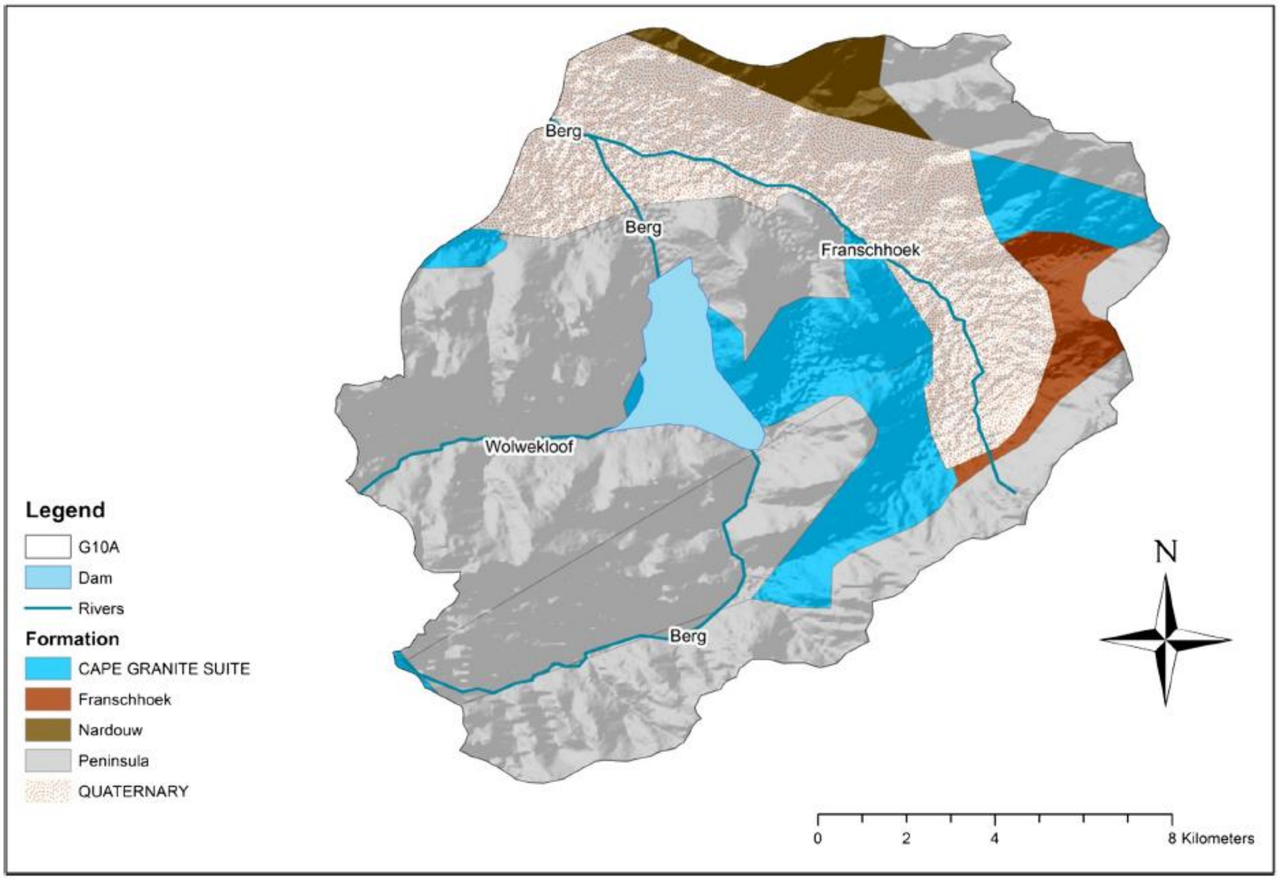

Fig. 3 Major geological formations in the upper Berg River catchment

Time series rainfall data measured at Assegaaibos rain gauge station was retrieved from the https://www.DWA. gov.za/hydrology website and used to compare with base flow separation hydrographs (DWS 2013).

Field water quality parameters were measured with an YSI Professional Plus™ Multi-parameter meter. Field measurements of electrical conductivity (EC) and total dissolved solids (TDS) were taken at all 10 river sampling sites along the Franschhoek, Berg, Stiebeuel, Wolvekloof and Roberts Rivers as well as at the 29 selected boreholes. Along with groundwater and surface water field measurements, samples were also collected for the analysis of major and minor ions dissolved in the groundwater and surface water. Duplicate grab sampling of groundwater and surface water samples was done with a grab sampler/ bailer using acid washed 250 ml polyethylene bottles. Prior to groundwater and surface water sampling, the bottles were rinsed three times with the water that was to be sampled, and then the water sample was collected and stored in a cooler box at 4 °C to prevent any alteration of the chemical properties of the water (Department of Water 2009).

For the sampling of groundwater, where the rope attached to the bailer was insufficient, a submersible pump was inserted into the well. Thereafter the required three borehole volumes to be removed were calculated with the formula
according to (Triplett et al. 2006):

$$\text{Purge volume} = 3\pi \cdot r^2 \cdot h \qquad (1)$$

where r is the radius of the well under investigation and h is the length of the borehole. By setting the pump to pump at 6ℓ/s, it became apparent that a time frame of approximately 15 min was required for the sufficient well volumes to be removed. This exercise served to remove the stagnant water that had been in the well casing so as to attain a sample representative of the general aquifer water characteristics.

Data analysis methods

Base flow separation

The daily time series stream flow data retrieved from the https://www.DWA.gov.za/hydrology website was processed on Microsoft Excel™.

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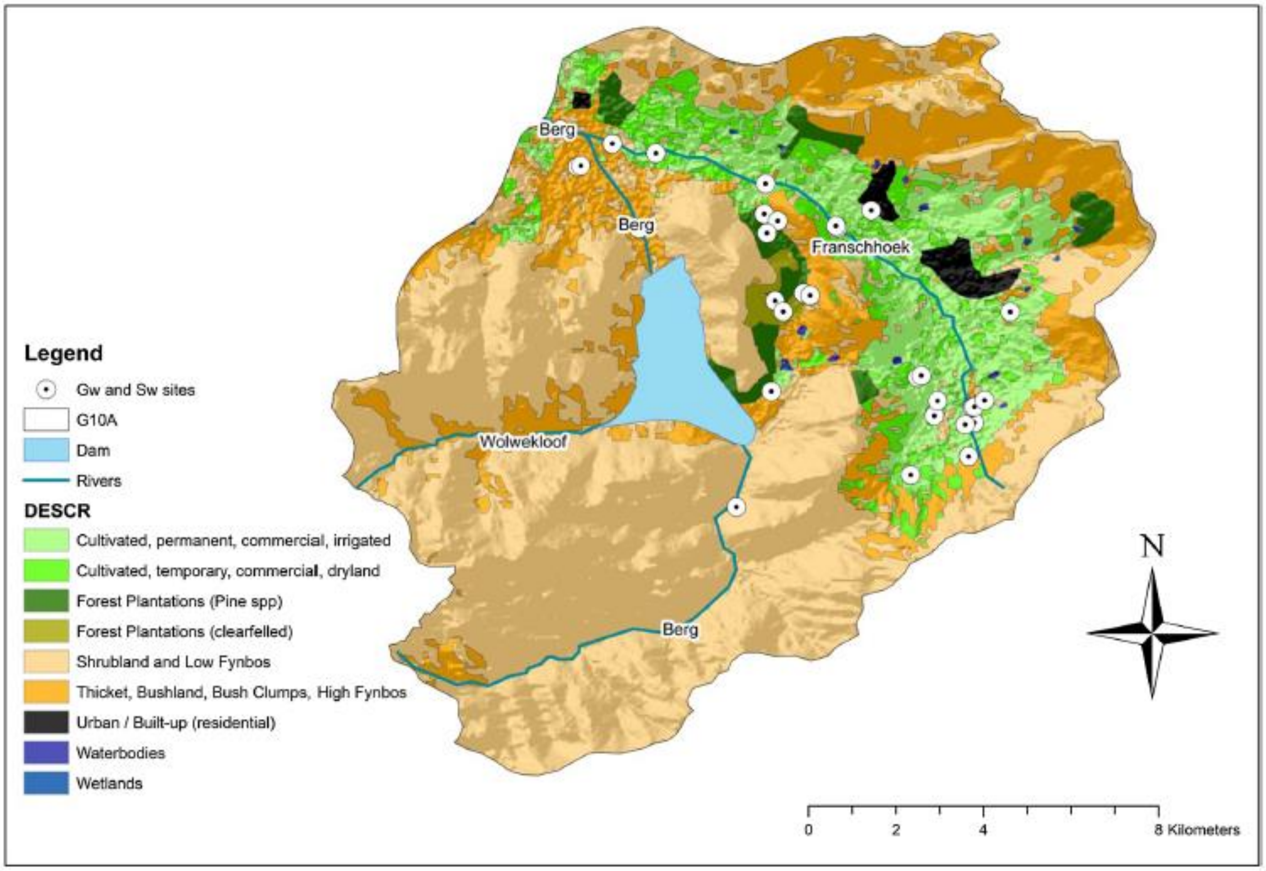

Fig. 4 Major land use in the upper Berg River catchment

To this end, the data were arranged and labeled accordingly to achieve the automated separation using automated recursive digital filters with the least possibility of errors in calculations. Recursive digital filters have no hydrological basis, but aim at generating objective, repeatable and an easily automated index that can be related to the base flow response of a stream, i.e., the Base Flow Index (BFI).

This approach provides an appropriate methodology to assess the influence of the low-frequency component flows on total gauged runoff by removing a high-frequency component (event runoff) from a streamflow time series to determine the low-frequency component (base flow) (Eckhardt and Arnold 2001, Eckhardt 2005). Recursive digital filters selected for the separation of the base flow and direct runoff components of a stream flow hydrograph included the filter algorithms proposed by Lynne and Hollick (1979) and the Chapman (1991).

The α filter parameter of 0.925 was used in all Algorithms (Eqs. 2, 3 and 4). This method constituted an attempt at separating the daily time-step stream flow data. After the review of local literature that incorporated the use of these digital filters, it became apparent that filter parameter of 0.995 was more appropriate in a South African context (Hughes et al. 2003; Welderufael and Woyessa 2010). Contrariwise, Smakhtin and Watkins (1997) determined that fixed value of 0.995 for α filter parameter could be considered

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suitable within the South African context. Their study investigated few time series of stream flows and it was concluded that slightly higher values (up to 0.997) could be more appropriate. Due to such uncertainty within the reviewed literature, the starting value of 0.925 was utilized in this study to assess the appropriateness of such a value and provide a basis for providing a future recommendation for further investigation on the most appropriate α filter parameter for the upper Berg River catchment and similar catchments. This was based on the fact that Smakhtin and Watkins (1997). (Hughes et al. 2003; Smakhtin and Watkins 1997, and Welderufael and Woyessa 2010) all report that changes in α filter parameter from 0.925 to 0.997 have small differences between them.

The recursive digital filters proposed by Lynne and Hollick (Eq. 2) and by Chapman (Eq. 3) were used for the base flow separation procedure (Brodie and Hostetler 2005; Chapman 1991; Chapman and Maxwell 1996; Hughes et al. 2003; Nathan and McMahon 1990; Smakhtin 2001). The filter algorithms proposed are as follows:

$$\mathrm{Qf}(i) = \alpha qf(i-1) + (q(i) - q(i-1))\,(1+\alpha)/2; \tag{2}$$

$$\mathrm{Qf}(i) = (3\alpha - 1)/(3-\alpha)qf(i-1) + 2/(3-\alpha)(q(i) - \alpha q(i-1); \tag{3}$$

$$\mathrm{QB}(i) = Q(i) - qf(i); \tag{4}$$

$$\mathrm{BFI\%} = Qb(i)/qf(i) \tag{5}$$

where $qf_{(i)}$ is the filtered quick-flow component for the ith sampling period, $qf_{(i-1)}$ is the filtered quick flow for the previous sampling period to i, $q_{(i-1)}$ is the original stream flow for the previous sampling period to i and α is the filter parameter, and Qb(i) (Eq. 4) is the filtered base flow at the ith sampling period. These digital filters have no hydrologic basis and have been borrowed from signal analysis to separate the high-frequency quick-flow signal to derive the low-frequency base flow signal as prescribed by Nathan and McMahon (1990). The Base Flow Index (Eq. 5) was calculated as ratio of base flow to total flow (Brodie and Hostetler 2005).

Groundwater and surface water field water quality parameter data were processed on Microsoft Excel™ and presented in tabular format (Table 2), while the concentration range of nitrate–N was spatially presented on a map (Fig. 11). Field water quality data were measured with the YSI Professional Plus™ Multi-parameter meter onsite, while water samples for chemical analysis were collected thereafter for major and minor ion analysis. The collected groundwater and surface water samples were analyzed for major and minor ions using the standard methods, Inductively Coupled Plasma spectroscopy (ICP-OES, MS or AS) according to the American Public Health Association methods (APHA 1992). These methods have been widely utilized for the identification of the major ions, i.e., Cl^-, NO_2^-, SO_4^-, HCO_3^-, Na^+, Mg^{2+}, K^+ and Ca^{2+} among others (Weight 2008). The laboratories chosen both conform to the South African National Accreditation System (SANAS),

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influencing their choice. Results on groundwater and surface water types were presented in graphical (Piper diagrams showing the water types and a map showing the ranges of nutrient concentrations). The concentrations obtained from the laboratory analysis were used to characterize the water type in the catchment as well as to infer any nutrient enrichment occurring as a result of anthropogenic activity (i.e., NO_3^-).

Results and discussion

Hydrological conceptual model

Figure 5a, b shows the hydrological conceptual models of the upper Berg River catchment. This diagram indicates that, locally, the flow of water generally follows the topography, with shallow groundwater water levels observed in the valleys that generate the source of the perennial streams in the areas. Identification for the construction of the Berg River Dam was planned to optimally utilize this condition in the upper catchment by capturing the large runoff generated in the south-west of the catchment (Ractliffe 2007). This area is mountainous and is protected as part of the catchment area of the Berg River Dam, therefore human activities are prohibited in this area that have the potential to change the quality and decrease the quantity of runoff from this area.

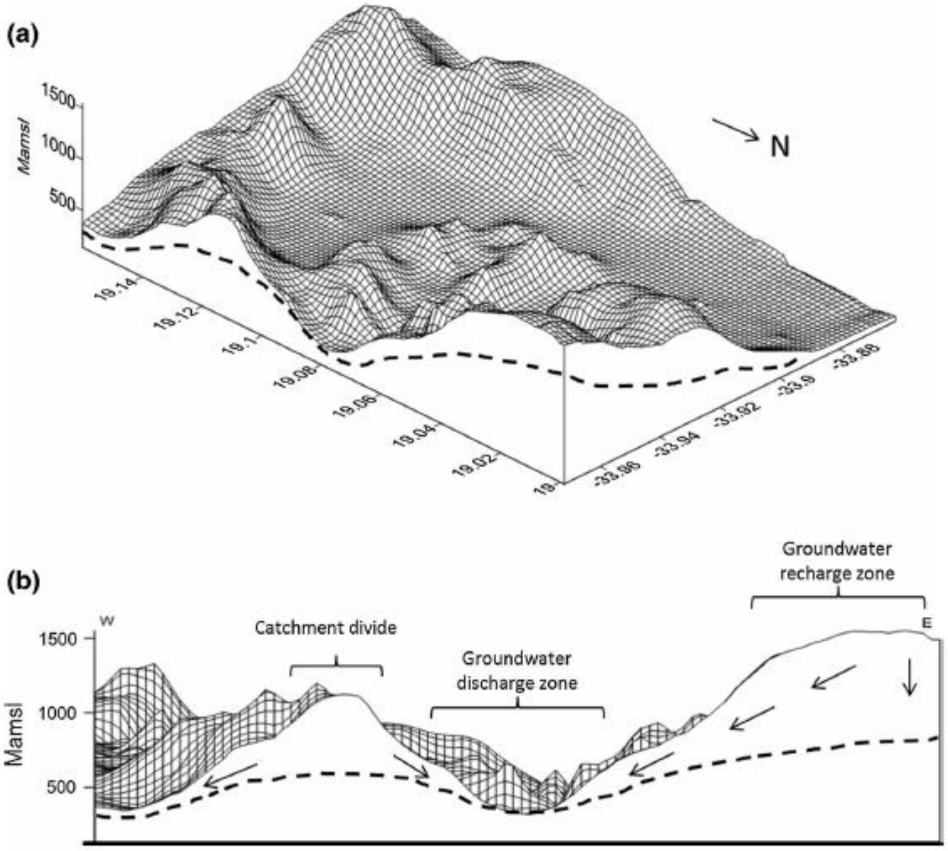

Fig. 5 **a** Surface topography of the upper Berg River catchment, and **b** a generalized catchment conceptual model depicting the zones of recharge and discharge

Groundwater and surface water interactions vary along the topography. In mountainous areas, the flow of ground-water is determined by the topographical conditions in the area and differences in water levels between groundwater and surface water bodies. Locally in the upper Berg River catchment, water moves downslope along the topographical gradient to

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the valleys where it discharges as base flow in the streams, wetlands, and dams. Figure 6 shows the ground-water level map for 2014. Groundwater levels were deepest near the Berg River dam (in the mountains), while the groundwater levels gradually became shallow with distance downstream. The upper mountainous parts of the upper Berg River catchment constitute a significant regional groundwater recharge area. Freeze and Cherry (1979), highlight that near the surface of groundwater recharge areas, the flow of water is directed downward (along the surface topography), while in a discharge area the flow of water is directed upward (due to intercepting surface and water levels).

Base flow separation

Figure 7 shows the daily rainfall recorded at the Assegaaibos rain gauging station between September 2012 and September 2014. From this hyetograph, it is evident that the upper Berg River catchment indeed experiences the wet winter season during the months April–October with the dry season occurring between October and March. Occasional rainfall events occurred during the dry periods due to the mountainous nature of this catchment having an orographic influence to the rainfall patterns. The highest recorded daily rainfall of 180 mm/day was experienced in August 2013, with August 2013 also having the highest mean monthly rainfall of 791.1 mm/m. The pattern of rainfall increases as the winter months proceed and decreases to nearly no rainfall during the dry periods, with occasional sporadic rainfall events. These rainfall events further emphasize the importance of understanding how groundwater and surface water interact to prepare water management and utilization strategies that take into consideration the spatial and temporal variations in rainfall. Figures 8, 9 and 10 show that the Berg Rivers' response to rainfall events can be expected to mimic the hyetograph with minor time lags between the peaks of the hydrograph (high flow) and hyetographs (high rainfall).

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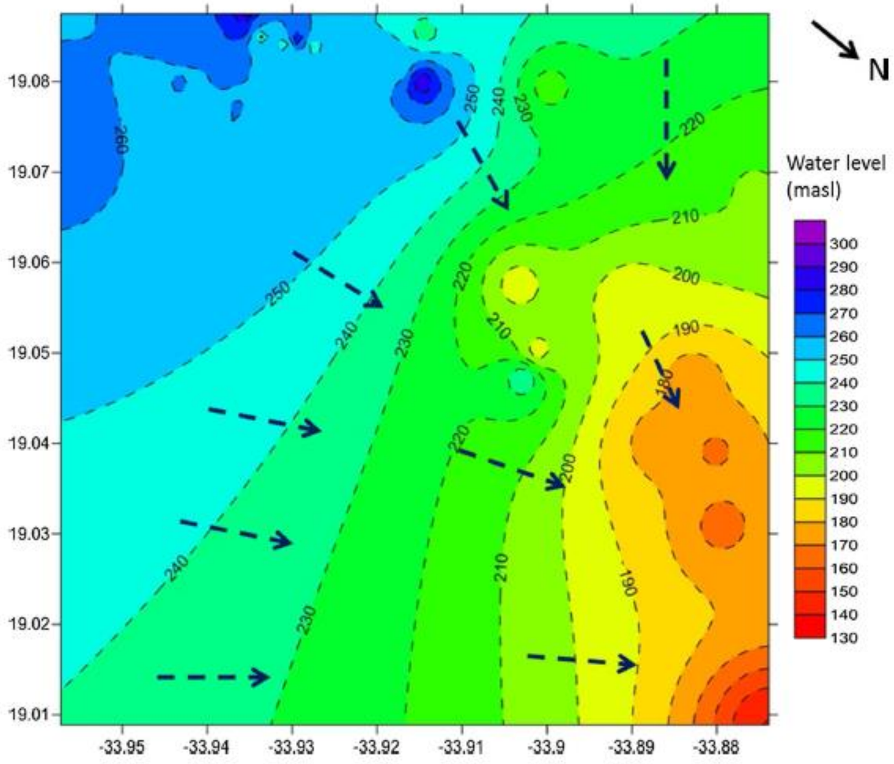
Fig. 6 G10A water level contour map



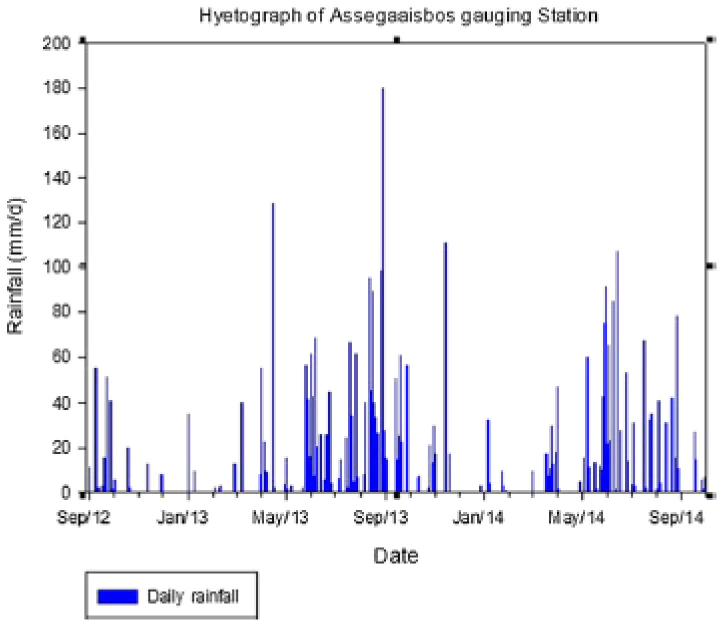


Fig. 7 Hyetograph showing rainfall measured at Assegaaibos gauging station between 2012 and 2014 (G10A-upper Berg River catchment)

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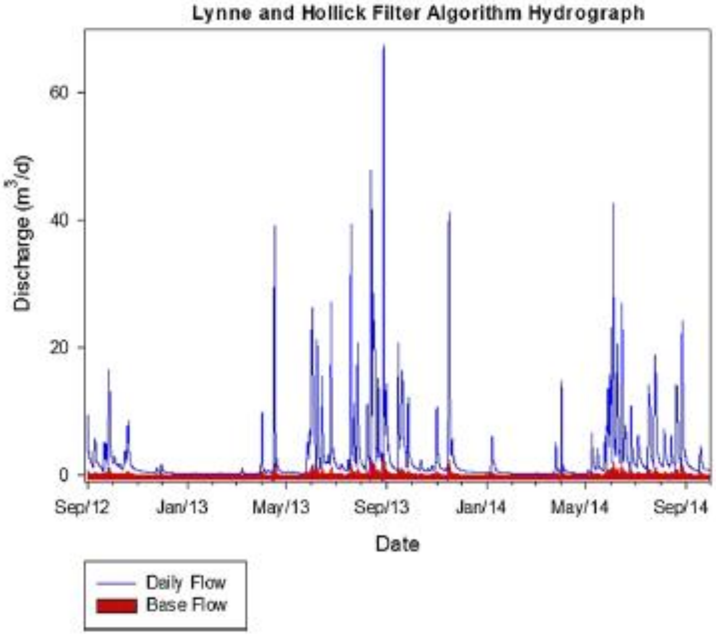

Fig. 8 Flow hydrograph of the upper Berg River (G1H076) separated to daily flow versus Base Flow using the Lynne and Hollick base flow filter algorithm

The hydrograph peaks follow shortly after the peak rainfall. Figures 8, 9 and 10 present the base flow hydrographs separated with the Chapman and the Lynne and Hollick, filter algorithms (Chapman and Maxwell 1996; Lyne and Hollick 1979; Nathan and McMahon 1990), relative to the direct runoff component of the hydrograph.

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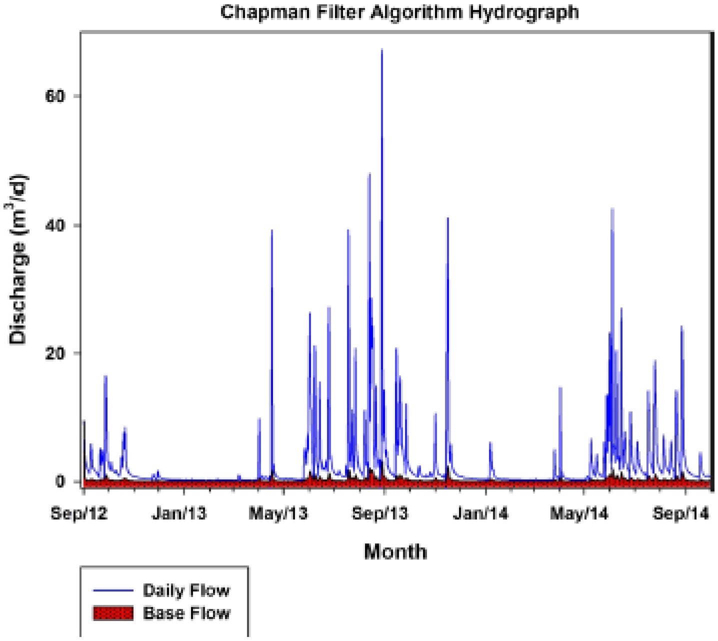

Fig. 9 Flow hydrograph of the upper Berg River (G1H076) separated to daily flow versus base flow using the Chapman base flow filter algorithm

The hydro-graphs maintain similar shapes with respect to the distribution of base flow contribution to stream flow over the hydrologic year, indicating that they all compute a relatively similar base flow contribution from subsurface water storages. Filtered base flow signals indicate a trend of declining stream flow during periods of extended dry weather (November-March), with rapid responses during the rainy periods following rainfall events (April-October). During the rainy season, the base flow discharges are more likely to be mainly interflow fed, rather than groundwater fed as this is the primary groundwater recharge period and mountain seeps along the valley could provide this flow of water. However, further investigation is recommended to identify the exact source of water contributing to stream flows during this period. The two algorithms (Chapman and Lynne and Hollick) computed similar base flow contributions. The mean, standard deviation, maximum and sum of base flow contributions (Table 3) filtered by the two algorithms were 0.214 and 0.203 m^3/day (mean), 0.354 and 0.323 m^3/day (standard deviation), 3.186 and 2.454 m^3/day (Maximum) and 150.108 and 79.992 m^3/day (Sum), respectively. From the descriptive statistics, there is a difference of 0.11 m^3/day in mean base flow between the two algorithms. However, considering the shape of the base flow hydrographs, both algorithms modeled similar base flow contribution from subsurface water storages within the period assessed. The Base Flow Index, which is the percentage ratio between the filtered base flow and the measured discharge at the gauging station (G1H076), is presented in Table 3. This information reveals that on average, the Berg River in the upper reaches is between 7.8 and 8.1% for the Chapman and Lynne and Hollick filter algorithms, respectively. Therefore, approximately 8% of river flows are derived from discharges from subsurface water storages. Although this is relatively small ratio,

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during periods of dry weather, this discharge is crucial to maintaining stream functions and flow.

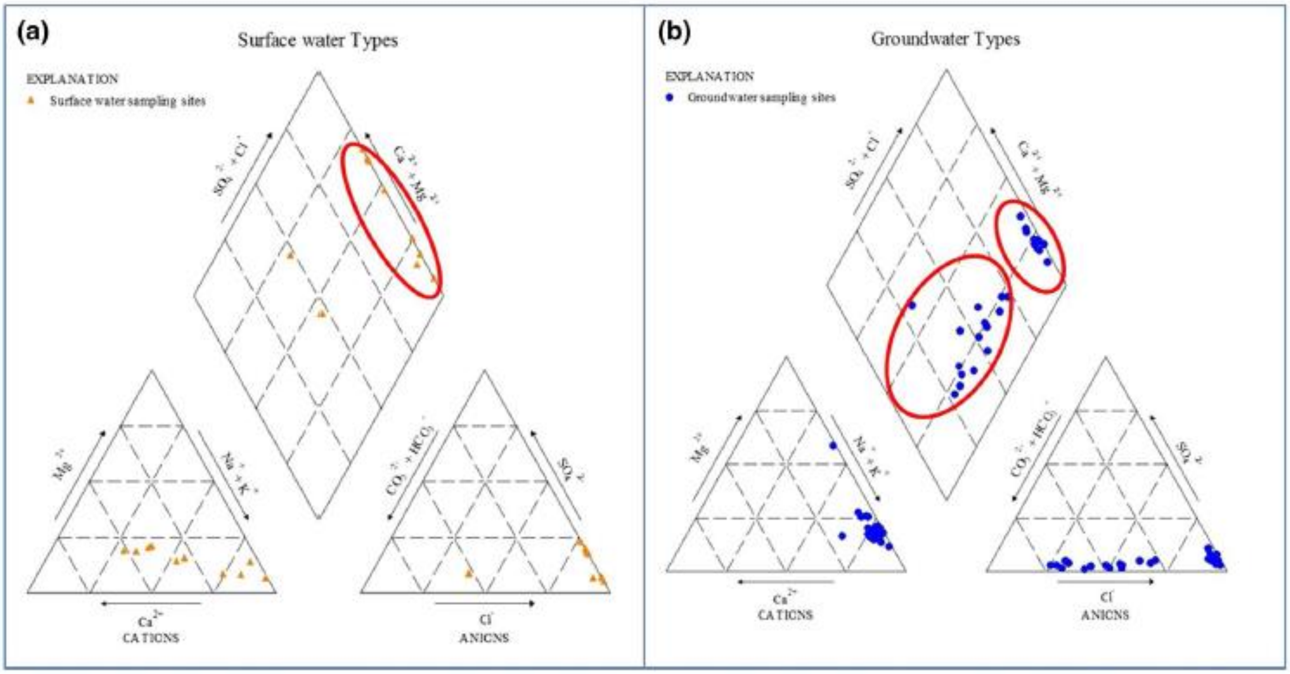

Fig. 10 Water types of **a** surface water and **b** groundwater in upper Berg River catchment

Table 3 Table listing the different water types found in groundwater and surface water in the upper Berg River catchment

G1H076 descriptive statistics	Chapman	Lyne and Hollick
Mean	0.214	0.203
SD	0.354	0.323
Maximum	3.186	2.454
Sum	150.108	79.992
G1H076 BFI descriptive statistics	Chapman BFI	Lyne and Hollick BFI
Mean	0.078	0.081
Maximum	0.233	0.242
Sum	59.217	31.989

The Chapman and Eckhardt algorithms modeled an identical annual mean percentage of discharge (Base flow Index) of 7.81% from subsurface drainage to the river compared to the Lynne and Hollick algorithm, which modeled an annual mean BFI of 8.1%. The Lynne and Hollick base flow filter algorithm modeled a 30% higher mean annual base flow (BFI) contribution to total stream flows than the Chapman filter algorithm. Considering the differences in maximum base flow contributions modeled using the two filter algorithms, the Chapman filter algorithm had a 87% higher maximum base flow value of 3.186 m^3/s than the 2.454 m^3/s modeled by the Lynne and Hollick filter algorithm.

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The upper catchment is bound by steep mountains that affect the spatial rainfall pattern in the area, by occasionally bringing rainfall during regionally dry periods (Clark and Ractliffe 2007), which reflect on the stream flow hydrograph. The base flows filtered with the various algorithms indicate that the upper stretch of the Berg River in this area relies on the discharge of subsurface water during periods of extended dry weather (November–March). The dependency of the river to subsurface water (groundwater and interflow) discharges during wet weather gradually becomes insignificant when compared to measured total flow, as the catchment area and its streams respond almost immediately to rainfall events. This factor is further exasperated by the presence of mountain face seeps (interflow) which flow though faults and fracture conduits in the underlying aquifer. Annual mean Base Flow Indices ranging between 7.81 and 8.1% indicated a relatively significant contribution of flow from subsurface storages (i.e., groundwater and interflows) during the dry season, compared to the insignificant contribution from subsurface water storages during the rainy season. The Chapman filter algorithm maintained the highest maximum base flow contribution of 3.186 m^3/day (Table 3) in August 2013.

Hydrochemical analysis

Water type

The chemistry of groundwater and surface water in a natural catchment is primarily influenced by the various type of geology through which it flows, rainfall chemistry and the land use activities occurring on the land surface. Water in contact with soluble rocks produces water with the chemical signature of the rocks. This occurs as the water weathers and dissolves the rock material (Younger 2007). However, there may be other external influences to this chemistry arising from a range of unnatural anthropogenic activities which transport chemicals into these resources. In high water yielding mountain catchments like the upper Berg River catchment, increased levels and type of anthropogenic activity pose a threat and may hinder the provision of sufficient amounts of water of usable quality to the various water users in the catchment. To understand the dominant factors contributing to groundwater and surface water quality, it is important to understand the levels of salinity in relation to the various kinds of salts dissolved (major cations and anions) in this water. In situ measurements of groundwater electrical conductivity (EC) and total dissolved solid (TDS) content revealed that the upper catchment contains relatively low content of dissolved solutes (i.e., 24.97 µS/ cm) due to the chemically inert geology through which it flows (Clark and Ractliffe 2007). Groundwater and surface water types in this catchment as presented in Fig. 11. Seven groundwater types exist in the upper Berg River catchment. These include Na–Ca–HCO_3–Cl (13.79%), Na–Cl–HCO_3 (6.90%), Na–Cl (37.93%), Na–Mg–Cl (6.90%), Ca–Na–HCO_3–Cl (10.34%) Mg–Na–HCO_3–Cl, (3.45%) and Na–Ca–Cl–HCO_3 (20.69%). The percentages represent the proportion of the groundwater sampling sites that have these water types. Regarding surface water types, three water types were found within the upper Berg River catchment, which include Na–Ca–HCO_3–Cl (20%), NaCl (10%) and Na–Ca–Cl (70%).

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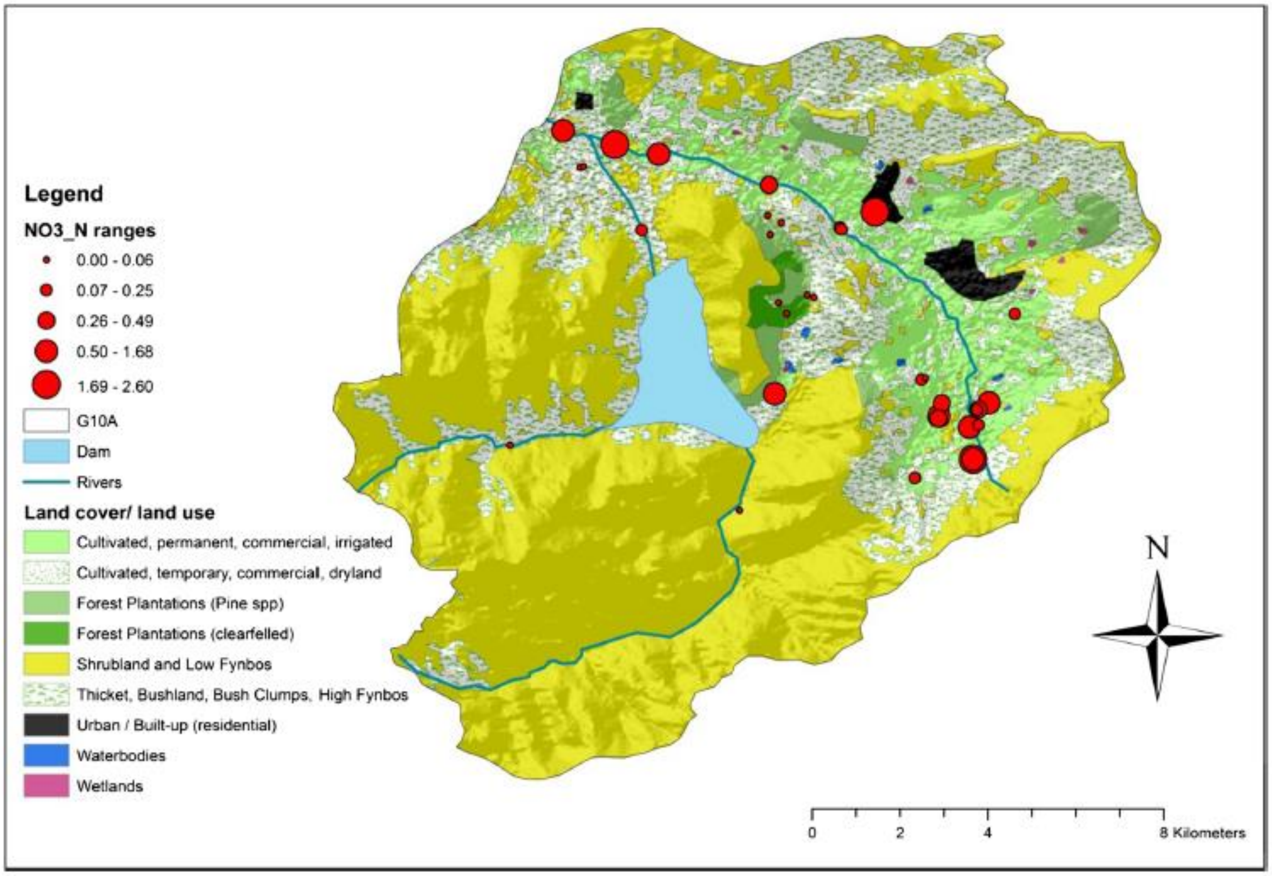

Fig. 11 Nitrate ranges in groundwater and surface water within the upper Berg River catchment

The dominance of Na–Cl-and Na–Ca–Cl-type water is generally indicative of the dominance of surface water, relatively short residence times of water in the underlying aquifer, rock–water interactions, saline seeps and minor atmospheric deposition of NaCl ions during rainfall events (Panno et al. 2002), while the presence of HCO_3 suggests microbial and bio-geochemical processes occurring at the groundwater–surface water interface.

The low salt content and mainly NaCl nature of the water indicate that the Berg River catchment in the upper catchment is dominated by low salt content flows through the year. These salinities increase in areas where the groundwater table was at shallow depths to the surface. In most of these areas, the activities occurring on the land surface exasperated the accumulation of dissolved solutes in the shallow groundwater and its interaction with surface water. Using multivariate statistical analysis of the principal components as well as cluster analysis, Madlala (2016) showed that groundwater and surface water were hydrochemistry and were controlled mainly by two factors, i.e., water–rock interactions (Na–Ca–Cl) and the recharge of atmospherically derived Na–Cl-type water. Furthermore, three distinct clusters of groundwater and surface water we determined. These were grouped into three groups and indicated that water sampled from the Franschhoek

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agricultural are fell into one group, those sampled along the Franschhoek River fell into one group and the sites located within the Robertsvlei and Berg River Dam areas fell into on group (Madlala 2016).

Nutrient concentrations

Groundwater chemistry is influenced by a variety of natural factors as well as the activities occurring on the land surface. Where the catchment comprises an important recharge area, these external influences may have detrimental effects on the quality of groundwater. As indicated in studies by Cao et al. (2012) and Yang et al. (2012), anthropogenic inputs of chemical constituents for various reasons, such as the application of fertilizers, eventually end up influencing the chemical characteristics of the water resources. This eventuality is attributed to the fact that surface water and groundwater are in hydraulic connectivity. As pointed out by Cao et al. (2012), the infiltration of agricultural fertilizers has been detected in the local groundwater in the form of elevated nitrate concentrations. To compare to this phenomenon, this study investigated the trend of nitrate concentration ranges in the groundwater of the upper Berg River catchment and further conducted additional groundwater and surface water sampling to assess whether this observed trend is escalating or remaining constant.

Figure 11 shows the ranges of nitrate concentration ranges in groundwater and surface water sampled in the upper Berg River catchment. It is clear that areas with substantial agricultural activity (areas with bigger sized circles) have elevated concentrations of mainly agriculturally derived nitrate in the groundwater. In these areas, groundwater levels area relatively shallow, within 4 m below the surface were detected (Mutoti 2016). The conceptual model depicted in Fig. 6 indicates that locally, as illustrated by Toth (1963) groundwater flows along the topographical gradient and regionally then flows in a northerly direction, where interactions between groundwater and surface water are dictated by the relative elevations of the water table with respect to the surface elevation. From this Fig. 11, it can be seen that nitrate concentrations are higher in surface water and groundwater near the Franschhoek River and in areas of extensive agricultural activity or human settlement (informal), than in the lower reaches of the Berg River and areas covered by natural land cover (Fig. 11). Groundwater nitrate levels were generally below 0.05 mg/L; however, as indicated in Fig. 11, these concentrations increase in groundwater near rivers along anthropogenically utilized land, thus alluding to the relative connectivity of the surface water to the groundwater aquifers. Such revelation prompts further research into the nitrate loading and fluxes between groundwater and surface water in these areas. Since after the completion of the construction of the Berg River Dam from 2005 to 2008 and the clearing of invasive alien plants species from the Berg River Dam catchment area (Albhaisi et al. 2013; Clark and Ractliffe 2007), no catchment disturbance has been reported. Therefore, the higher nitrate concentrations seem to be originating from the anthropogenic activities, such as the agriculture, the old Franschhoek wastewater treatment works (WWTW) along the Franschhoek River and the Langrug informal settlement within the largely agriculturally driven catchment.

These increases in nitrate concentrations are observed in boreholes located on land that is used for agricultural activity along the Franschhoek River and in the Robertsvei Saddle area (see Fig. 11). The presence of nitrate in the groundwater and surface water does not exceed the target water quality guidelines for all uses of water as set by the Department of Water Affairs (DWAF 1996). Considering that this area comprises a significant water source area, the increasing presence of nitrate in the groundwater suggests that although concentration levels were below water quality guidelines, anthropogenic inputs of nitrate were leaching to the important groundwater reserves and also affecting surface water. Further investigation is recommended to assess the nitrate capacity that the Berg River system can handle and assess this in relation to the ecological reserve to ensure sufficient quantities of water of suitable quality for ecological requirements.

The Berg River site (situated downstream of the Berg River Dam) indicated the lowest loading of nitrate, while the sites located along the Franschhoek River had the highest levels of nitrate (Fig. 11). The sites situated along the Franschhoek River are predominantly used for urban settlements. de Villiers (2007) and Jackson et al. (2013) reported that as observed in the current study, the nutrient concentrations of the Berg River increase with distance downstream. This indicates that anthropogenic activities in the study area negatively impact the water resources. It is clear that the stream reaches located along or around areas with intensive agricultural activity and human settlements were more prone to exhibiting elevated concentrations of plant nutrients derived from anthropogenic activities. Elevated nitrate levels found at the Franschhoek and Stiebeuel Rivers showed a substantial input of nitrate into the river system. Such high loading indicates the influence of the informal settlements (Langrug) and decommissioned wastewater treatment works along the Franschhoek River. Contrary to the fact that there is intensive agricultural land use activity that is contributing substantially to nitrate concentrations in surface water, the Stiebeuel River traverses through an informal settlement with poor sanitation. Nitrate is also derived from animal fecal matter, and at this informal settlement, the lack of sewage services and an overloaded old (decommissioned) wastewater treatment works exasperates this issue of nitrate deposition into water resources. However, following the convergence of the two rivers (Berg and Franschhoek), a reduction in the concentration ranges is observed (Fig. 11), where the ranges decrease from 0.50–1.68 to 0.26–0.49. The base flow contributions computed in this study for the area above the Berg River Dam plays a significant role in the regulation of contaminate concentration derived from the affected Franschhoek River arm of the catchment. However, quantification of the nitrate fluxes from agricultural and settlements as well as a computation of the self-purification capacity of these rivers is recommended to assess the influence that the dominant types of land uses have on water resources nitrate concentrations.

During the study period, nitrate levels in both groundwater and surface water in the upper Berg River catchment were below Department of Water and Sanitation (DWS) water quality guidelines for irrigation water. Through the application of agriculture-derived nitrate-containing fertilizers and other products for plant growth, the shallow depth to water level, migration of nitrate into groundwater through seasonal water table fluctuation is possible

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(Madlala 2016; Mutoti 2016). Groundwater in the upper Berg River catchment is partially secure from nitrate contamination in areas where the groundwater level is not close to the surface and where there are less nitrate contributing activities occurring on the land surface.

Conclusion

The current study demonstrates the applicability of base flow separation and hydrochemical analyses to assess the implications of groundwater–surface water interactions on river water quality, i.e., contamination or self-purification potential. This study shows that in the upper catchment, the Berg River is between 23 and 24% dependent on discharges from subsurface storages during extended periods of days of no rainfall. This percentage flow derived from subsurface water storages is important for maintaining water quality during these times, when there is less precipitation flushing contaminants downstream. However, during this study, the self-purification process was not studied and it is recommended that further investigation into the role that these subsurface water discharges play in the regulation of water quality during dry periods though the computation of a river self-purification potential.

The shallow depth to the groundwater table during the wet season indicates that groundwater in parts of this area is susceptible to contamination from surface land use activities when high recharge rates are reported during such periods. Groundwater and surface water in areas mainly utilized for agricultural and human purposes has indicated a connection between the presence of nutrients with the groundwater levels during the year. However, it is recommended that the influence of the declining water levels, evapotranspiration and antecedental soil moisture conditions is assessed for their influence on nutrient loading into groundwater.

The base flow separation filter parameter utilized in this study provides a good starting point for the quantification of the contributions of subsurface water discharges to total gauged streamflows. As such, conducting a hydrochemical or isotope base hydrograph separation is recommended to assess the applicability of the standard filter parameters used in this study. Additionally, assessing the sensitivity of the derived filter parameters will provide a basis for future research on the actual quantity of water derived from subsurface water storages to total gauged stream flows.

The findings of the current study indicate that there is a requirement for further investigation on the nitrate capacity of the Berg River system in handling increased concentrations of nitrate. Quantifying these fluxes from agricultural activities and human settlements is suggested to assess the influence on water resources quality that these types of land uses have. It is also recommended that research on the nutrient fluxes from surface land uses to water bodies is conducted to assess the effect of the quantity of such land use derived nutrients on the quality of groundwater and surface water.

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Table 2 Descriptive statistics of three filter algorithms and resultant Base Flow Index computed for gauging station G1H076 in the upper Berg River catchment

Source	Site	Water type	Group #
GW	3 streams	Na–Ca–HCO_3–Cl	1
GW	Holden Manz BH2		
GW	Holden Manz BH3		
GW	Lavenir-BHl		
SW	G1H03		
SW	Moreson		
GW	3 Streams-Fount	Na–Cl–HCO_3	2
GW	3 Streams-Salm		
GW	BG158	Na–Cl	3
GW	BG33		
GW	BG34		
GW	BG35		
GW	BG35.2		
GW GW	BG36 BG37		
GW	BG38		
GW	BG46		
GW	BG50		
GW	RV2		
SW	Stream @ BG51		
SW	Berg and Franschhoek	Na–Ca–Cl	4
SW	Berg River		
SW	Franschhoek Bridge		
SW	Franschhoek upstream WWTW		
SW	Wolvekloof		
SW	Stiebeuel-WWTW confluence		
SW	Stiebeuel River		
GW	BG21	Na–Mg–Cl	5
GW	BG44		
GW	Bordeaux	Ca–Na–HCO3–Cl	6
GW	Lacombie		
GW	Stonybrook		
GW	Cape Fruit Process	Mg–Na–HCO3–Cl	7
GW	Holden Manz-Produc	Na–Ca–Cl–HCO3	8
GW	Lavenir-BH2		
GW	Lavenir-BH3		
GW	Tsherigma		
GW	Burgundy-BH1		
GW	Burgundy-Fount		

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