Quantifying the contribution of riparian total evaporation to streamflow transmission losses: Preliminary investigations along the Groot Letaba river

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ARTICLE INFO

ABSTRACT

The Groot Letaba River, situated in the semi-arid north-eastern region of South Africa is an example of a river system in which the uncertainty associated with transmission losses (TL) has limited the effective management of environmental water requirement (EWR) flows. TL along the river significantly impacts EWR flows, as it is often the case that specified EWR releases are not adequately received further downstream. Due to the limited understanding of the magnitude of TL, as well as the dominant contributing processes to TL within the region, it remains a challenge to operate the river using downstream targets far from the source of operations. In an attempt to address this knowledge gap, detailed characterizations of hydrological processes were performed along the lower reaches of the river, which centred around the estimation of riparian total evaporation and quantifying the rapport between surface and subsurface water flow processes. Riparian total evaporation was estimated using the satellite-based surface energy balance system model, soil water evaporation measurements and open water evaporation estimates. Losses from the river to the adjacent aquifer were determined from the continuous monitoring of the groundwater phreatic surface and characterization of aquifer hydraulic properties. The results of these investigations indicated that present flows within the system are likely to be insufficient to satisfy gazetted median and extreme low flow targets. Overall, the study details key hydrological processes influencing TL along the river. It should, however, be noted that these observations only provide an understanding of the system over a limited observation period.

1. Introduction

Globally, water scarcity has been exacerbated by the effects of increasing population growth, socio-economic development and climate change (Molle et al., 2010; Pittock and Lankford, 2010). As a result, the availability of water to sustain the natural functioning of riverine ecosystems and the provision of ecosystem goods and services has fallen under threat (Pittock and Lankford, 2010). In a South African context, numerous perennial river systems have become severely constrained as water resources abstractions are close to exceeding or have exceeded the available supply and ecosystem resilience (Molle et al., 2010).

According to Pollard and du Toit (2011), the environmental water availability in various catchments of the South African Lowveld have been on the decline during the latter periods of the 20th century. This has been attributed to the compounded effects of land-use change, as well as the improper management of water resources within these catchments. Consequently, the natural ecological functioning of the riverine ecosystems and surrounding environments have begun to steadily decline (Vlok and Engelbrecht, 2000; Everson et al., 2001; Pollard and du Toit, 2011; Shenton et al., 2012; Grantham et al., 2014; Overton et al., 2014), despite the EWR possessing the only 'right' to water, in addition to the Basic Human Needs reserve under South Africa's National Water Act (NWA, Act 36 of 1998). Intensive management of the EWR flows is therefore required to ensure that all water users

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receive an acceptable quantity and quality of water, which can be supplied and sustained at an acceptable assurance level without impeding the ability to maintain the EWR (Riddell et al., 2017).

Presently, knowledge regarding precipitation inputs to a river system, releases from dams and permitted water abstractions from river systems, are used to manage the flows for river operations within these environments (Riddell et al., 2017). However, the lack of an adequate quantitative understanding with regards to the loss of water from the stream/aquifer through TL processes remains a constraint to the effective management of flows especially in arid and semi-arid environments (Hughes, 2008; Costa et al., 2013). TL are defined as a reduction in the volume of flow in a river system between upstream and downstream points, due to the loss of water through three natural processes i.e. (a) riparian evapotranspiration (ET), (b) infiltration or evaporation of flood waters stored in channel depressions or the flood plain and (c) the recharge of groundwater as water infiltrates the stream channel or open-water evaporation directly from the stream channel (Cataldo et al., 2010).

The significance of TL as a contributing process to the water balance of river systems particularly in arid and semi-arid environments has been well documented internationally (Hughes and Sami, 1992; Lange, 2005; Costelloe et al., 2003; Costa et al., 2013; Shanafield and Cook, 2014). However, there remains a paucity of studies of this process in southern Africa (Hughes, 2008; Tanner and Hughes, 2015). Whilst TL have not been adequately quantified through hydrological process definition for any South African river system (Riddell et al., 2017), the magnitude of these losses is estimated to be high, especially for perennial river systems flowing through arid and semi-arid environments. Boroto and Görgens (2003) predicted that up to 30% of the Limpopo rivers mass balance may be allocated to TL, as a result of riparian ET and aquifer storage. The Letaba River Reserve Determination study (Department of Water Affairs and Forestry (DWAF), 2006) estimated that TL may account for between 8 and 50% of channel inflows. According to Department of Water Affairs (DWA) (2011), a 10% loss of channel inflows to TL is used for flow management within the Olifants River.

In order, to ensure that EWR flows and water provisions are managed efficiently, it is essential that the hydrological processes contributing to TL in these environments are understood and quantified at various spatio-temporal scales (Gu and Deutschman, 2001). It is often the case that ET is inadequately represented during the estimation of TL (Everson et al., 2001; Hacker, 2005; Cataldo et al., 2010; Shanafield and Cook, 2014). This may potentially be due to TL in most ephemeral rivers occurring as a result of infiltration-based losses (Cataldo et al., 2010). However, ET is generally the second largest component of the water balance in semi-arid and arid environments and has been shown to contribute significantly to TL within the study region. For example, Everson et al. (2001) showed that the flow rate along the Sabie River during low flow periods would have been approximately 15% higher without the influence of riparian ET.

Considering the significant role which ET plays within semi-arid and arid environments, the aim of this study was to undertake detailed characterizations of hydrological processes along a reach of the Groot Letaba River to establish the contribution of riparian ET to TL. For this purpose, we propose a novel methodology to derive spatially explicit estimates of TL. This largely involved the determination of source contribution to ET using stable isotope analysis coupled with *in-situ* and satellite-based ET estimation procedures.

These investigations were then supplemented by a parallel study which focused on the continuous monitoring of the groundwater phreatic surface and hydraulic characterisation of aquifer properties using a multi-piezometer borehole network along the selected river reach, to determine the hydraulic gradients between the river and surrounding aquifer and thereby baseline estimates of losses and gains along the river (Riddell et al., 2017).

2. Site description

The Letaba River is a typical example of a river system in which poor water governance and infrastructural development have resulted in flows within the river no longer resembling the natural flow regime (Vlok and Engelbrecht, 2000; Katambara and Ndiritu, 2010; Pollard and du Toit, 2011). These circumstances have placed additional pressure on water resources managers in this region as they attempt to balance the demands of various water users within the catchment whilst attempting to maintain the mandated EWR flows. This situation improved to some extent after the establishment of the Letaba operating rules in 2006 by the Department of Water Affairs (Department of Water Affairs and Forestry (DWAF), 2006), which was facilitated by a real time EWR implementation model (Hughes et al., 2008; Sawunyama and Hughes, 2010; Pollard and du Toit, 2011; McLoughlin et al., 2011).

However, one of the major challenges to the successful application of the model to date has been the uncertainty regarding the magnitude and influence of TL on flows within the river system (Riddell et al., 2017). TL along the Groot Letaba are thought to significantly impact EWR flows, as it is often the case that specified EWR releases from the Tzaneen dam are not adequately met further downstream at the Letaba Ranch (B8H008) gauging weir close to the Kruger National Park (Sinha and Kumar, 2015). This (therefore) makes it challenging to operate the river using downstream targets far from the source of operations. The catchment generally experiences a semi-arid climate with hot and wet summer and mild and dry winter conditions. The mean annual precipitation within the catchment is approximately 612 mm, which predominantly occurs during the summer months (October to March). According to Katambara and Ndiritu (2010) 40–50% of this rainfall is received during January and February, with the majority (60%) of this rainfall being received in the mountainous western region ($\approx$6% of the total catchment area) (Water Research Commission (WRC), 2001). In general, temperatures vary across the catchment with cooler conditions in the mountainous western region ($\approx$18 °C) to hotter conditions in the eastern region ($\approx$28 °C).

Approximately three quarters of the catchment is underlain by granite and gneiss. The varied distribution of sediment along the Letaba River has resulted in the formation of varying channel types with distinctive vegetative compositions and morphological characteristics (Heritage et al., 2001). There are numerous land-use activities distributed throughout the Letaba catchment, amongst these the dominant land-uses include: intensive commercial afforestation and agriculture (predominantly citrus crops), densely-populated rural villages with informal dryland agriculture and conservation areas in the eastern regions of the catchment (Pollard and du Toit, 2011). The TL study site is situated along the lower reach of the Groot Letaba river between the now defunct Mahale weir (B8H007) and the Letaba Ranch gauging weir (B8H008) which is situated approximately 14 km further downstream, as illustrated in Fig. 1.

The rationale for this site selection was to employ a mass balance approach (Costa et al., 2012) with the aim of: i) verifying the losses measured in this study and ii) determining the contribution of riparian total evaporation to these losses. Between these two gauging weirs, there are no contributing tributaries. Agricultural areas are situated adjacent to the riparian zone in the west before the river traverses conservation areas further downstream. The section of river studied between these weirs is largely dominated by woody savanna vegetation such as: *Ficus sycomorus*, *Philenoptera violacea* and *Diospyros mespiliformis*, with *Phragmites mauritianus* dominant in the river microchannel. Detailed descriptions of the soils, lithology, stream networks and topography are provided in Riddell et al. (2017).
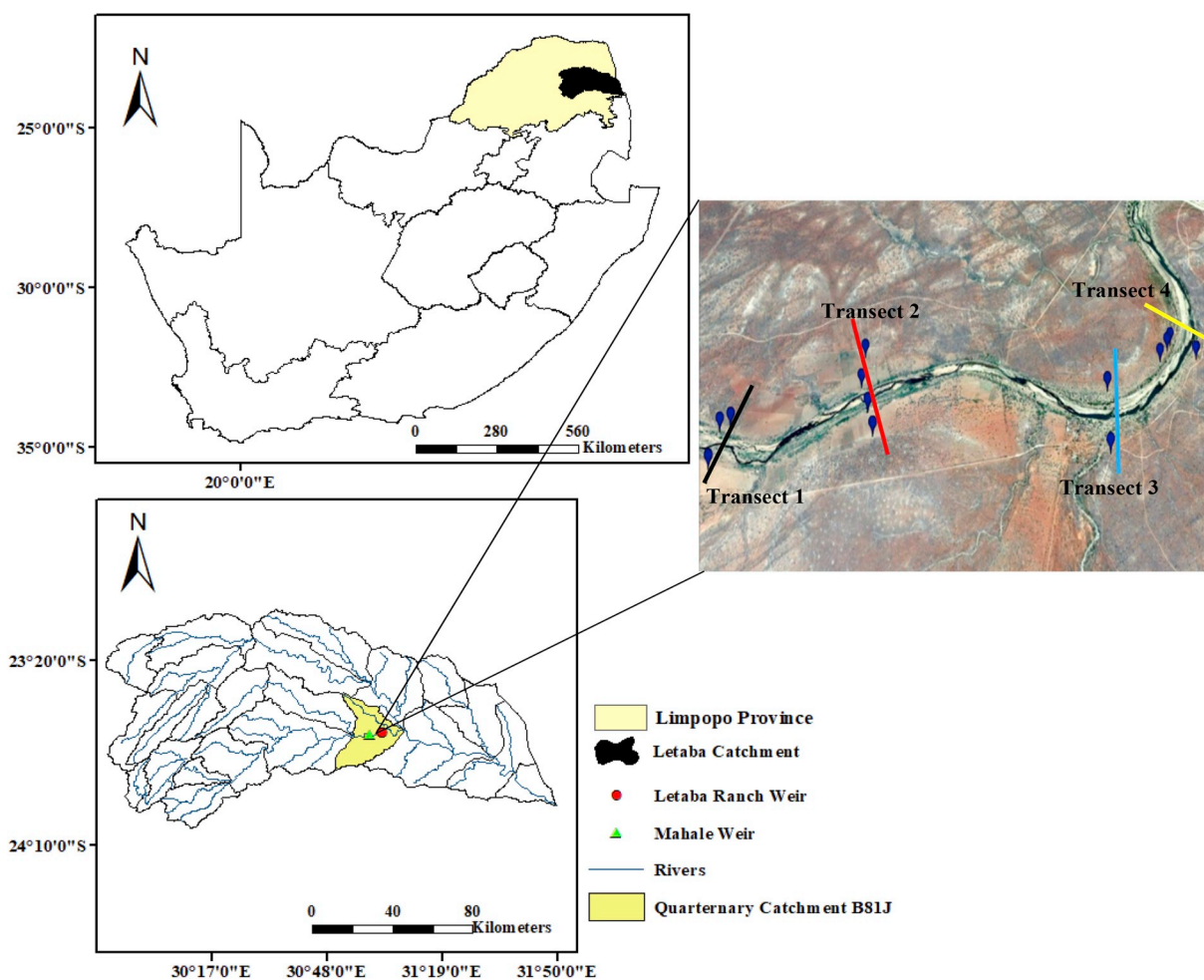
Fig. 1. Location of the study area and distribution of borehole sampling points (Google Earth™ image), situated along the lower reach of the Groot Letaba River within the Quaternary catchment B81J (adapted from Gokool et al., 2018).

3. Methodology

3.1. Data collection

3.1.1. Streamflow and artificial abstractions

Daily average flow data ($m^3 s^{-1}$) was acquired from B8H007 and B8H008, in order to verify the estimated losses along the length of river reach studied using a mass balance approach. Verified flow data for B8H008 was collected from the Department of Water and Sanitation (DWS) HYDSRTA database (http://www.dwa.gov.za/Hydrology/). In order to record the river stage height at B8H007 (now ungauged), a stilling pipe was bolted to the upstream side of the weir and fitted with a SolinstTM Levelogger Junior to record the river stage at a 5-min time step. A rating was then attempted for B8H007 to obtain the stage height discharge relationship. However, the unrefined structure of the weir wall prevented an accurate rating from being undertaken (Riddell et al., 2017). Therefore, when the level logger data (pressure head expressed as stream stage height in mm) showed a constant stage, it was assumed that there was no overtopping of the weir but rather a continuous discharge through two low flow scour sluices located at the base of the structure. This was determined as the product of the cross-sectional area of pipe and outflow rate measured using a Pasco™ 2000 flow meter (Table 1).

A hydro-census was undertaken within the surrounding areas of the study site, to determine the reliance of the local community on stream and groundwater resources for domestic use and small scale-irrigation. The results of this survey revealed that these artificial abstractions were relatively low and estimated to be in the magnitude of $52 m^3 d^{-1}$

Table 1
Low flow rating for Mahale weir.

	Flow (m s^{-1})	Pipe diameter (m)	Discharge (m^3 s^{-1})	Total Discharge (m^3 s^{-1})
Sluice 1	3.4	0.3	0.24	0.50
Sluice 2	3.7	0.3	0.26	

(Riddell et al., 2017).

3.1.2. Groundwater piezometric monitoring network

The rapport between stream water and groundwater interactions was established by performing a detailed hydraulic characterisation of the aquifer properties and through the continuous monitoring of groundwater levels (Riddell et al., 2017). In order to continuously monitor stream water and groundwater interactions, a piezometric borehole network was drilled by the Department of Water and Sanitation Limpopo Drilling Division along the northern and southern banks of the study site. This network consisted of paired piezometric boreholes which were drilled into both the shallow weathered material and deep fractured hard rock. The rationale for this network/arrangement was to determine gains/losses associated for both alluvial and hard rock material (Riddell et al., 2017). The groundwater piezometric network was divided into four geohydrological transects (Fig. 1) and the river reach length represented by the adjacent aquifers was estimated.

3.1.3. Riparian total evaporation

In this study, riparian total evaporation was defined as the combined contribution of transpiration, soil water evaporation and open water evaporation. Open water losses were determined using the Priestley-Taylor method (Priestley and Taylor, 1972). Average daily soil water evaporation from August to October was estimated as 0.15 mm d^{-1}, 0.47 mm d^{-1} and 0.45 mm d^{-1}, respectively, within the river channel.

These measurements were obtained using micro-lysimeters, which were installed at various points within and adjacent to the active river channel. The micro-lysimeters were made of 2 mm thick PVC pipe, were 100 mm deep and had an internal diameter of 50 mm. Each micro-lysimeter was equipped with one external cylinder made of 3 mm thick PVC pipe which was 80 mm in diameter and 145 mm deep. The external cylinders were placed at fixed positions, whilst the internal cylinders were filled with soil samples extracted from selected areas within the river channel.

The rate of soil water evaporation was calculated as:

$$Es = \frac{\Delta Mass * 10^{-3}}{A} \tag{1}$$

where $\Delta Mass$ is the mass of the soil sample (g) and A is the surface area of the microlysimeter (0.0196 m^2). Soil water evaporation along the banks of the riparian zone was not measured, as flow within the channel did not exceed bank full storage during this low flow period. Consequently, the probability of enhanced losses of stream water due to soil water evaporation along the river banks were low.

Transpiration was estimated indirectly by calculating the difference between soil water evaporation and daily evapotranspiration (ET) estimates acquired from a satellite-based evapotranspiration (ET) model. Satellite earth observation (SEO) data was used in this study to obtain spatially representative estimates of ET within the study area. The SEBS Model (Su, 2002) was applied in this study to estimate daily ET. SEBS computes all components of the shortened surface energy balance (Equation (2)), as well as the evaporative fraction (*EF*), using land surface parameters which are derived from meteorological and SEO sources, respectively.

$$Rn = Go + H + LE \tag{2}$$

where R_n is net radiation (W m^{-2}), G_0 is the soil heat flux (W m^{-2}), H is the sensible heat flux (W m^{-2}) and LE is the latent heat flux (W m^{-2}). SEBS has been extensively applied and shown to provide fairly accurate estimates of fluxes and ET (Ma et al., 2012, 2014; Szporak-Wasilewska et al., 2013; Matinfar and Soorghali, 2014; Shoko et al., 2014; Yang et al., 2015; Ferreira et al., 2016; Gokool et al., 2016; Mohammadian et al., 2017). However, it should be noted that the original model formulation is generally unable to adequately represent fluxes and ET during water stressed conditions (Gokmen et al., 2012). To address this limitation, empirically derived calibration factors were used to adjust the evaporative fraction previously determined in SEBS, in order to better represent the influence of stress on surface energy fluxes (Gokool et al., 2019). The ET estimates derived from the aforementioned approach were then used to develop a moderate spatial resolution (30 m) daily satellite-based ET time series (Gokool et al., 2017). Comparisons between this data set and *in-situ* ET observations were found to be in fairly good agreement (as shown in Fig. 2), yielding a Nash-Sutcliffe efficiency value of 0.60 with no significant difference between the observed and simulated values (*p-value* = 0.62).

3.2. Estimation of transmission losses

TL were estimated during the latter stages of the 2016 low flow period (August to October), which typically represents a critical period with regards to water scarcity. While TL during higher flow periods are equally important for the estimation of EWR flows, during the dry season soil water availability is substantially lower. Consequently, riparian
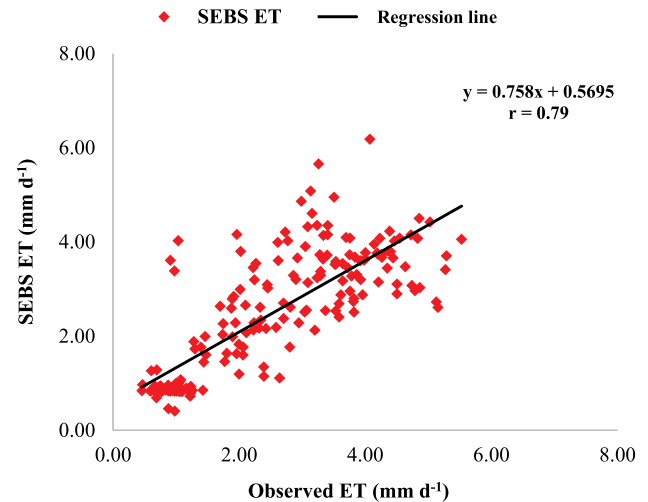

Fig. 2. A comparison between SEBS derived ET estimates and observed ET measurements during the period 21st June – 22nd October for 2015 and 2016.

vegetation may access alternate water sources (stream and groundwater) if available to fulfil a portion of their daily transpiration demands (Gribovski et al., 2008; Cadol et al., 2012). Therefore, estimating riparian total evaporation during this period provides the ideal scenario to quantify the contribution of this process to TL. It was initially envisaged that the losses estimated in this study would be verified using a mass balance approach. However, this was not possible as we were unable to obtain accurate inflow data from B8H007.

It was assumed that when the data showed a constant stage height, there was no overtopping of the weir and a continuous discharge of 0.5 m^3 s^{-1} was experienced. However, this was seldom the case. Consequently, the abovementioned discharge could not be used to perform the mass balance calculation. Instead, we computed the inflow as a residual of the mass balance (Equation (3)).

$$Inflow = Outflow + TL \tag{3}$$

It should be noted that while the magnitude of the estimated losses was compared relative to this estimated inflow, this inflow volume was not necessarily an accurate representation of the flow within the system. Following the groundwater hydraulic characterisation undertaken by Riddell et al. (2017), the interaction between the river and adjacent aquifers was quantified in terms of either gains or losses from the watercourse (Table 2). In this study, it was assumed that streamflow TL to the aquifer was due to seepage (steady state percolation) rather than some other mechanism. Streamflow TL to the aquifer was calculated as:

$$Loss\ to\ aquifer = TiL \tag{4}$$

where T is transmissivity, i is the hydraulic gradient between the river and the surrounding aquifer (dimensionless), L is the length of river reach (m).

Further details regarding the borehole drilling information, fluid logging and derivation of undisturbed *in-situ* borehole parameters used to obtain these baseline estimates are provided in Riddell et al. (2017). As shown in Table 2, there is a net loss from the river to the adjacent aquifer within the agricultural areas, with the highest loss occurring to the deep fractured hard rock aquifers adjacent to the river. Further downstream within the conservation areas, there is a net gain from the adjacent aquifer to the river, with the highest gains occurring from the shallow aquifer. In general, the length of river reach studied was shown to be a losing system, with a net loss of 253.98 m^3 d^{-1} to the adjacent aquifers within the riparian zone.

The daily transpiration estimated in this study represents the total

Table 2
Estimated gains and losses (emboldened values) from the watercourse to the adjacent aquifers within the riparian zone during the dry season.

			Section Length (m)	Storativity	Transmissivity (m² d⁻¹)	Hydraulic Gradient	Loss to Aquifer (m³ d⁻¹)
Deep Borehole Data (A)	Farms	LF002	2200.00	0.00	0.08	0.00	**−0.70**
		LF003	2180.00	0.01	0.05	0.02	2.18
		LF004	2200.00	0.00	0.87	0.01	15.31
		LF005	2180.00	0.00	1.18	−0.06	**−141.48**
	Total						**−124.69**
	Reserves	LR001	880.00	0.02	0.98	0.01	5.17
		LR002	1580.00	0.00	0.16	0.01	2.69
		LR004	1580.00	0.00	0.68	−0.01	**−11.82**
		LR005	880.00	0.05	3.83	0.01	26.96
	Total						23.01
Shallow Borehole Data (B)	Farms	LF002	2200.00	0.50	18.00	0.00	**−118.80**
		LF003	2180.00	0.04	1.00	−0.04	**−89.38**
		LF004	2200.00	0.00	0.67	0.02	26.46
		LF005	2180.00	0.00	0.06	−0.03	**−4.05**
	Total						**−185.76**
	Reserves	LR001	880.00		0.98	0.02	20.70
		LR002	1580.00		0.16	0.02	3.67
		LR004	1580.00	0.00	2.04	−0.02	**−51.57**
		LR005	880.00	0.14	3.83	0.02	60.67
	Total						33.47

water used by riparian vegetation from multiple sources such as: soil water, groundwater and streamflow. Although transpiration demands are generally met by available soil moisture (Gokool et al., 2017), in arid settings, riparian vegetation generally become increasingly reliant on groundwater and streamflow to fulfil a portion of their daily water requirements (Gribovski et al., 2008). TL due to transpiration may occur as a result of direct water uptake from the river/stream or indirectly from the uptake of groundwater. In the case of the latter, groundwater used during transpiration may potentially be replenished by river/stream water due to an inverse in the hydraulic gradient, ultimately resulting in a loss of streamflow (Gribovski et al., 2008; Tanner and Hughes, 2015).

Furthermore, riparian ET of waters stored within the river banks may enhance TL during high flow periods when flood waters exceed the bank full storage. During low flow periods, TL may comprise the proportion of water consumed by riparian vegetation from stream and groundwater. Therefore, in order to estimate the contribution of transpiration to TL, the proportional contribution from these sources needed to be quantified. For this purpose, Gokool et al. (2018) coupled stable isotope analysis of ²H and ¹⁸O contents of plant water, soil water, stream and groundwater with a Bayesian mixing model (Stable Isotope Mixing Model package available in R).

4. Results and discussion

According to Cadol et al. (2012), the volume of water lost from stream and groundwater to transpiration should equal the volume of water transpired over an area of influence within and adjacent to the stream. Therefore, the average proportion of surface and groundwater contributing to transpiration were used in conjunction with the satellite-derived daily ET estimates to determine the volume of water used from these sources.

Gokool et al. (2018), showed that the contribution of groundwater and stream water to transpiration during the latter stages of the 2016 dry season, was approximately 15%. However, this proportional contribution was only used to determine transpiration losses for vegetation situated on either side of the river channel (riparian forest). For riparian vegetation situated within the active river channel (*P. mauritianus*), it was assumed that daily transpiration demands are fulfilled by accessing water in the upper levels of the saturated zone (water table) and stream water (Everson et al., 2001), as *P. mauritianus* were predominantly located in areas in which the root zone was inundated by water. Using the areas from Table 3, the volume of riparian total evaporation was determined as the combined contribution of transpiration, soil and open

Table 3
Distribution of riparian vegetation along a 14 km reach of the lower Groot Letaba River (adapted from Riddell et al., 2017).

Land Cover Category					
	Riparian vegetation		Soils	Open Water	Total
	Banks	Within River channel			
Area (km²)	1.09	0.41	0.25	0.16	1.91
Relative area (%)	57.00	21.00	13.00	9.00	100.00

water evaporation. These losses were then combined with the baseline estimates of losses to the adjacent aquifer and artificial abstractions to determine the total volume lost in the system.

The estimated reduction in flow for 2016 for the length of river reach that was investigated, is shown in Fig. 3. The total volume of water loss for the 2016 study period ranged from approximately 986 m³ d⁻¹ to 4066 m³ d⁻¹, with a mean loss of 3209 m³ d⁻¹. In general, the inflow rate for August and September were fairly similar and the magnitude of flow reduction ranged between 5 and 10%, as shown in Table 4. During these months, the average inflow (0.57 m³ s⁻¹ and 0.50 m³ s⁻¹) was much higher than the loss of water due to natural processes (≈0.04 m³ s⁻¹). During this period, the flow would have been approximately 8% higher, without the influence of these losses.

However, during October there was an increase in the magnitude of streamflow reduction with losses generally ranging between 10 and 20% and in a few instances exceeding 20%. The inflow rates during this period were relatively lower (0.25 m³ s⁻¹). Consequently, there is a greater influence of these natural losses on streamflow. The average reduction in flow during this period increased to approximately 17%.

Comparisons of the different contributing processes to TL indicated that throughout the period of investigation, riparian total evaporation losses were found to be the chief contributing process to TL along this portion of river reach, as shown in Fig. 4.

The average contribution of riparian total evaporation was approximately 2871.72 m³ d⁻¹ or approximately 90% of daily TL, whereas the contribution of artificial abstractions and losses to the adjacent aquifer were only 2% and 8%, respectively. Riparian total evaporation losses were largely due to the proportion of water transpired from stream and groundwater, as shown in Fig. 5. The average loss due to transpiration from the river banks and within the river channel was approximately
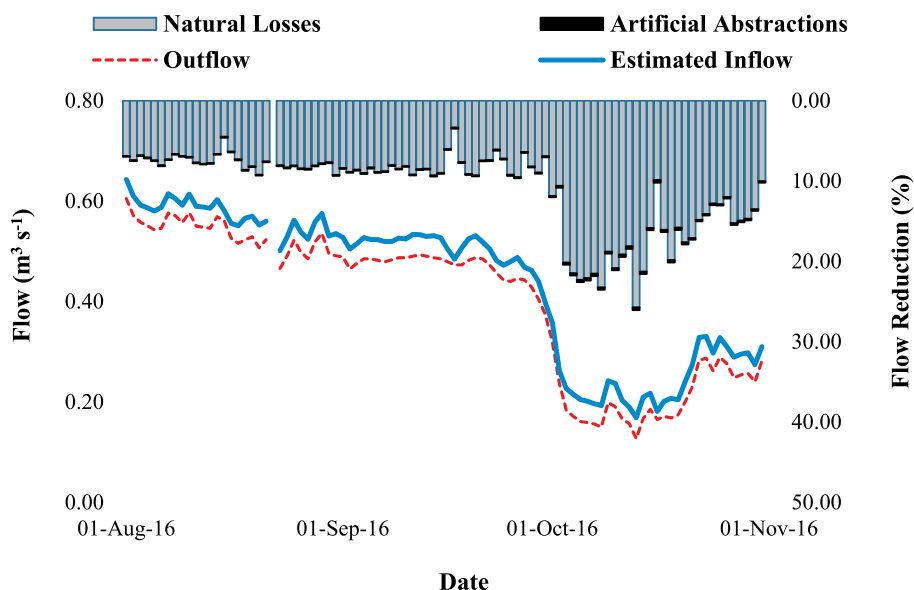
Fig. 3. Daily TL along a 14 km reach of the Groot Letaba River during the latter stages of the 2016 dry season.

Table 4
Frequency range of TL during the latter stages of the 2016 dry season.

Range	2016 Frequency (%)		
	Aug	Sep	Oct
0% < TL < 5%	3	3	
5% < TL < 10%	97	97	6
10% < TL < 15%			32
15% < TL < 20%			36
20% < TL			26

563.80 and 1263.64 $m^3 d^{-1}$, contributing a combined average of 56.00% of TL, whereas the combined contribution of open water and soil water evaporation losses were approximately 34% of TL.

In light of the recent gazetting of the Letaba Management Class and the mandatory implementation of EWR flows (RSA Government Gazette, 2016), the quantification of TL takes on added significance to ensure that EWR flows are adequately managed and maintained so that the natural functioning of the riparian ecosystem is not compromised. Table 5 depicts the low flow assurance rules for the median and ultra-low flows (90th percentile) at B8H008, respectively. These flow values have been gazetted for implementation prior to and proceeding the construction of the proposed Nwamitwa dam (RSA Government Gazette, 2016). Comparisons between the daily flows at B8H008 for 2016 against these target flows indicates that the daily flows at B8H008 are currently unable to meet the mandated target flows, as shown in Fig. 6.

Consequently, flows traversing B8H007 are required to be increased in order to satisfy both median and extreme low flow targets, whilst simultaneously accounting for TL. To facilitate this process, baseline estimates of the required increases to the flow emanating from B8H007 were determined (Table 6), using monthly averages of the estimated TL
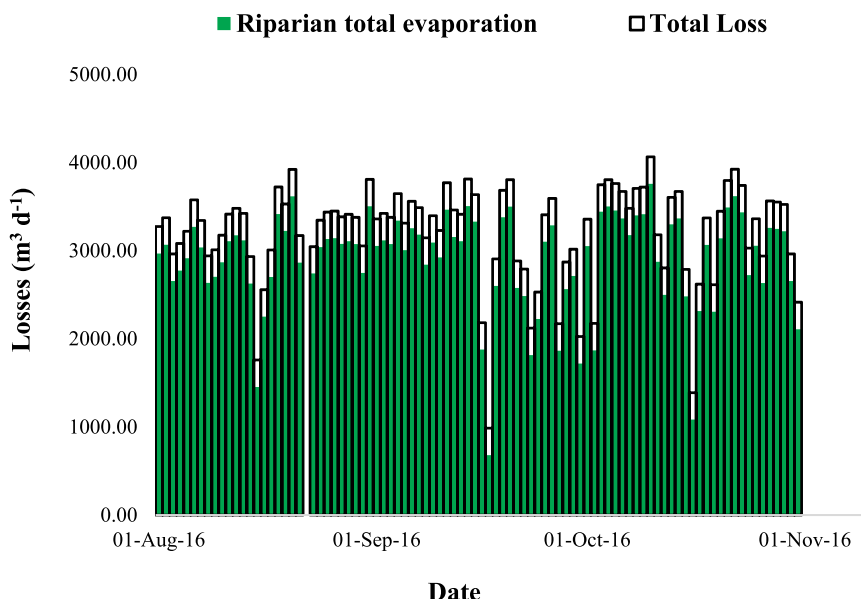

Fig. 4. Contribution of riparian total evaporation to daily TL during the latter stages of the 2016 dry season.
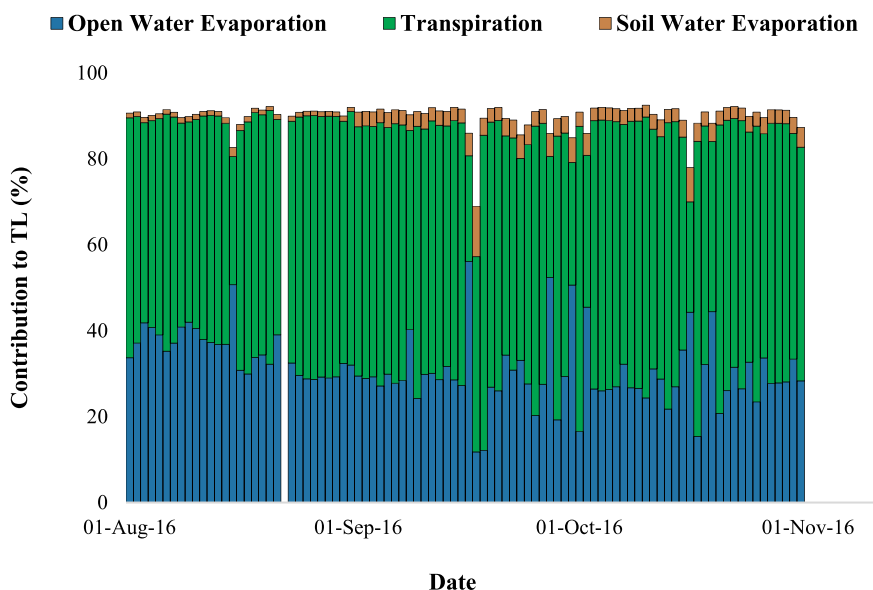
Fig. 5. Percentage contribution of riparian total evaporation processes to TL.

Table 5
Low flow assurance rules for median and extreme low flows (90th percentile).

Month	Target Flow at B8H008 ($m^3 s^{-1}$)			
	Prior to Construction		Post Construction	
	90%	50%	90%	50%
Aug	0.597	0.597	0.605	0.778
Sep	0.594	0.598	0.552	0.632
Oct	0.497	0.597	0.523	0.554

and inflow volumes. The magnitude of this increase in flow for B8H007 for 2016 ranges from: $0.07\,m^3\,s^{-1}$ (12%) to $0.45\,m^3\,s^{-1}$ (181%) prior to the construction of the dam; whereas post dam construction the magnitude of flow increase for B8H007 ranges from $0.08\,m^3\,s^{-1}$ (13%) to $0.40\,m^3\,s^{-1}$ (161%). The proposed increases in flow required to meet the gazetted target flows should be considered preliminary findings, as it was not possible to quantify the uncertainty in our estimated TL due to the lack of accurate inflow data.

Nevertheless, the temporal progression and magnitude of these losses in relation to streamflow are analogous to the losses reported by

Department of Water Affairs and Forestry (DWAF) (2006) (between 8 and 50%) and Everson et al. (2001) (approximately 15%) in similar environmental settings, lending some credibility to the TL estimated in this study. Based on the estimated current inflows from B8H007 and TL within this portion of river reach, the gazetted target flows will not be reached without additional increases to the flow passing B8H007 (Table 6). While this situation is particularly concerning, it may be further compounded by the effects of anthropogenic driven land use changes.

Everson et al. (2001) noted that the degradation of the riparian forests and increased sedimentation may result in a shift towards more reed-based communities within the riparian zone. Consequently, this may significantly alter the magnitude and temporal progression of TL within the system. For this purpose, Everson et al. (2001) simulated ET losses that would occur if riparian forests were completely replaced with reed communities and consequently determined how this would influence TL along the Sabie River.

Following the approach of Everson et al. (2001), we attempted to quantify how such a change in land use would affect the estimated TL in this study, as well as the implementation of the gazetted target flows. This scenario was simulated by assuming that there are no further
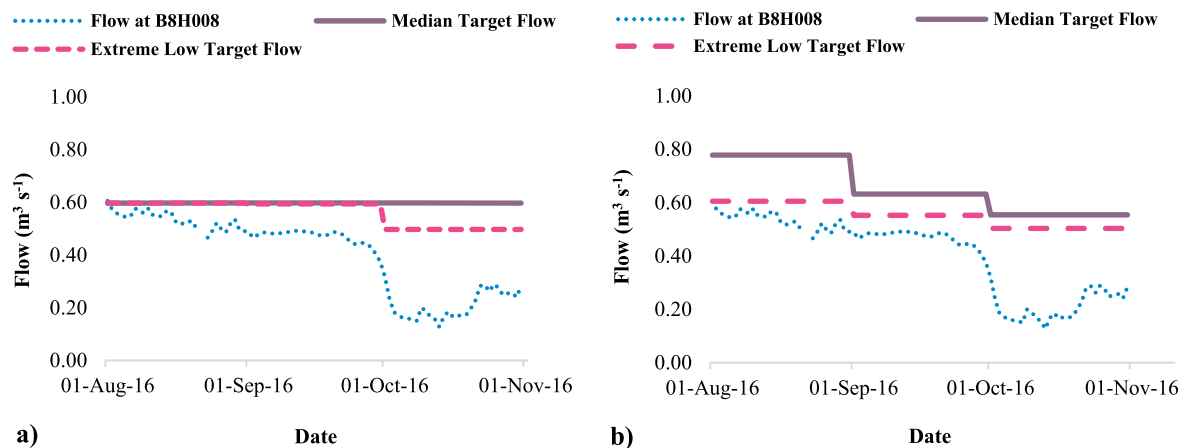

Fig. 6. A comparison of the flow at B8H008 against gazetted flows for implementation prior to and subsequent to the construction of the proposed Nwamitwa dam.

Table 6

Baseline estimates of the required increases to the flow emanating from B8H007 to meet the gazetted low flow assurance rules for the median and extreme low flows at B8H008.

			Target Flow (m^3 s^{-1})	B8H007 average Inflow (m^3 s^{-1})	TL (%)	Required increase to inflow (m^3 s^{-1})	Required increase to inflow (%)
2016	Prior to Construction (90%)	Aug	0.60	0.57	7.00	0.07	12
		Sep	0.59	0.50	8.00	0.14	27
		Oct	0.50	0.25	17.00	0.33	134
	Prior to Construction (60%)	Aug	0.60	0.57	7.00	0.07	12
		Sep	0.60	0.50	8.00	0.14	28
		Oct	0.60	0.25	17.00	0.45	181
	Post Construction (90%)	Aug	0.61	0.57	7.00	0.08	13
		Sep	0.55	0.50	8.00	0.09	18
		Oct	0.52	0.25	17.00	0.36	146
	Post Construction (60%)	Aug	0.78	0.57	7.00	0.26	50
		Sep	0.63	0.50	8.00	0.18	35
		Oct	0.55	0.25	17.00	0.40	161

changes in the losses of stream water to the aquifer or to artificial abstractions and the riparian zone consisted entirely of *P.mauritianus* with the root zone being inundated by stream water. Using the estimated inflows from B8H007, the estimated TL and the proposed increase to the flow are presented in Fig. 7 and Table 7, respectively. These results show that there would be a substantial increase in the magnitude of TL within this portion of river, with TL in the range of 10–25% occurring most frequently, if the aforementioned change in land use were to occur.

The magnitude of this increase in flow for B8H007 for the land use change scenario ranges from; $0.10\,m^3\,s^{-1}$ (17%) to $0.54\,m^3\,s^{-1}$ (219%) prior to the construction of the dam; whereas post dam construction the magnitude of flow increase for B8H007 ranges from $0.10\,m^3\,s^{-1}$ (17%) to $0.49\,m^3\,s^{-1}$ (196%).

Although this is a rudimentary approach at modelling the effect that the proposed land use change would have on TL, it clearly demonstrates how such changes can alter the flow dynamics within the river system and constrain the successful implementation of EWR flow targets if these changes are unaccounted for. While this scenario was used to provide further insights on the effects of land use changes on TL, this approach can be easily adapted to assess the effects that changing water uptake patterns (stream and groundwater uptake) during varying climatic conditions has on the magnitude of TL.

5. Conclusion

To ensure that water provisions and in particular EWR flows can be managed more effectively and efficiently in the future, it is imperative that the hydrological processes contributing to TL are quantified at various spatial and temporal scales. In this study, we aimed to reduce the uncertainty associated with TL by attempting to acquire an improved hydrological process understanding of the natural drivers of streamflow reduction along the lower reaches of the Groot Letaba river system. The findings presented in this study indicated that TL generally accounted for 5–15% of the flow in the river system.

Riparian total evaporation and transpiration (in particular) were found to be the most significant contributing processes to these losses. This finding is of particular relevance as riparian total evaporation has often been inadequately represented or excluded from TL estimation procedures. In general, it was shown that flows within the river system are unable to meet the gazetted low flow targets and are required to be increased in order to fulfil this requirement, whilst simultaneously accounting for TL. Furthermore, the results of the land use change simulations reaffirmed the importance of understanding and quantifying riparian water use requirements as it can assist in providing a more accurate estimate of the flows required to meet EWR flow targets under changing land use conditions.
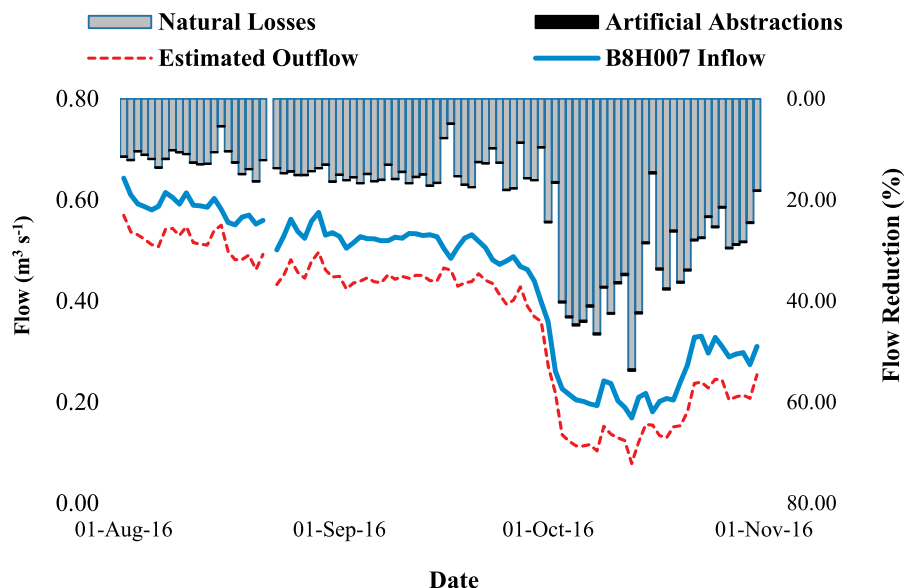

Fig. 7. Daily TL along a 14 km reach of the Groot Letaba River during the latter stages of the 2016 dry season for the land use change scenario.

Table 7
Baseline estimates of the required increases to the flow emanating from B8H007 to meet the gazetted low flow assurance rules for the median and extreme low flows at B8H008 for the land use change scenario.

			Target Flow (m³ s⁻¹)	B8H007 average Inflow (m³ s⁻¹)	TL (%)	Required increase to inflow (m³ s⁻¹)	Required increase to inflow (%)
2016	Prior to Construction (90%)	Aug	0.60	0.57	0.13	0.10	17
		Sep	0.59	0.50	0.14	0.17	35
		Oct	0.50	0.25	0.33	0.41	166
	Prior to Construction (60%)	Aug	0.60	0.57	0.13	0.10	17
		Sep	0.60	0.50	0.14	0.18	35
		Oct	0.60	0.25	0.33	0.54	219
	Post Construction (90%)	Aug	0.61	0.57	0.13	0.10	17
		Sep	0.55	0.50	0.14	0.13	25
		Oct	0.52	0.25	0.33	0.45	180
	Post Construction (60%)	Aug	0.78	0.57	0.13	0.30	53
		Sep	0.63	0.50	0.14	0.22	43
		Oct	0.55	0.25	0.33	0.49	196

Overall, the study has detailed key hydrological processes influencing TL along the Groot Letaba River. However, it should be noted that while the study site was extensively gauged, these observations only provide an understanding of the system for a limited period in time. Therefore, it would prove to be advantageous to continue long-term monitoring at the site, which may facilitate an improved understanding of the system under changing environmental conditions, as well as allowing for a reduction in the assumptions and related uncertainties that had to be factored into the analysis.

Declaration of competing interest

The authors do not have any competing interests to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2019.11.002.

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