Short communication

Isotopic tracing of stormwater in the urban Liesbeek River

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ABSTRACT

The ongoing drought in the Western Cape of South Africa (2014 to present) has called for an urgent need to improve our understanding of water resources in the area. Rivers within the Western Cape are known to surge rapidly after rainfall events. Such storm-flow in natural river catchments in the Jonkershoek mountains has previously been shown to be driven by displaced groundwater, with less than 5% of rainfall appearing in the storm-flow. However, the origin of storm-flow surges within urban rivers in the region remains unknown. In this study, we used stable isotopes in water to illustrate that at least 90% of water in the Liesbeek River during a storm event was rainwater. There was a strong correlation between storm-flow and rainfall rates ($P < 0.001$, Pearson's $r = 0.86$), as well as between the $\delta^{18}O$ and $\delta^{2}H$ values of river-water and rainwater ($\delta^{18}O$: Pearson's $r = 0.741$ (P = 0.001), $\delta^{2}H$: Pearson's r = 0.775 ($P < 0.001$)). Storm-flow within this urban river therefore appears to be driven by overland-flow over the hardened urban catchment, rather than piston-flow as seen in natural catchments. Our results support studies suggesting the Liesbeek River could be a target for stormwater harvesting to augment water resources in the city of Cape Town.

Keywords: stable isotopes, urban water management, water resources, urban rivers

INTRODUCTION

Water resources in the Western Cape of South Africa are scarce and are predicted to become increasingly so in the future (Otieno and Ochieng, 2004). At the time of this study the City of Cape Town was poised to become the first major city to run out of water (Du Toit, 2018). Currently, the cities within this predominately winter-rainfall region rely on surrounding dams for their water supply, which are generally replenished through winter streamflow. During drought years, streamflow recharge into dams is severely diminished (Mukheibir and Ziervogel, 2007). Extended below-average rainfall in the region since 2014 led to severe water shortages in the City of Cape Town and in 2017 threatened the potential collapse of the city's water infrastructure (so-called 'DayZero'). In order to secure future water supply, cities in the Western Cape will have to adapt to the likelihood of reduced rainfall in the future (New, 2002; Ziervogel et al., 2011), as well as augment their water supply from alternative sources such as aquifers and stormwater amongst others (New, 2002; Fisher-Jeffes et al., 2017). As such, understanding the storm-flow dynamics of rivers in this region and their relationship to rainfall is important, to properly manage the area's water resources.

Rivers in the Western Cape are known to rapidly increase in flow following rainfall. Midgley and Scott (1994) showed that streamflow in rivers in the Jonkershoek mountains surged within a few hours of the first rains. Using stable isotopes, they demonstrated that despite flow increasing by 400%, the storm-flow consisted of less than 5% of the rainfall event, leading to the conclusion that these rivers were fuelled mainly by piston-flow. Piston-flow occurs when rainwater seeps into the ground, displacing groundwater which then flows into the river (Sophocleous, 2002). Piston-flow is an important process for aquifer recharge, but may result in delayed storm-flow after extensive aquifer drawdown (McGuire et al., 2002). However, while piston-flow may generally be the predominant pathway for storm-flow in natural, fractured sandstone catchments (Midgley and Scott, 1994; Midgley et al., 2001), little is known about the dynamics of storm-flow from other rivers in this region, particularly urban areas where substrate permeability is low. In such areas, overland-flow should predominate, resulting in rainwater directly recharging streams without sinking into the ground to recharge aquifers (Burns et al., 2001). Unlike for piston-flow, overland-flow should result in rapid storm-flow surges even in the case where aquifers have been drawn down substantially during prolonged drought.

Additionally, unless overland-flow-driven streams are captured in dams or water storage schemes, usually not the case for low-elevation urban rivers, this water will eventually be lost to the sea without the benefit of aquifer recharge (Frazer, 2005; Saraswat et al., 2016). In June 2017, during a prolonged 3-year drought, a large storm hit Cape Town resulting in severe winds and precipitation across the city. We used this opportunity to determine whether overland or piston-flow predominated in the urban Liesbeek River and to assess the stormwater discharge occurring during a drought. The source of the increase in storm-flow was determined using stable isotopes of hydrogen ($\delta^{2}H$ (‰)) and oxygen ($\delta^{18}O$ (‰)) of river-water and rainfall (McGuire and McDonnel, 2007). We reasoned that a predominance of overland-flow would result in rainfall and storm-flow closely tracking each other throughout the storm event. However, if rainfall and storm-flow were isotopically dissimilar, or showed strong lags, then piston-flow was more likely to predominate.

We hypothesized that despite the mountain headwaters, this section of river flowing through the urban environment would be driven primarily by overland-flow, due to the extensive

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hardening of its urban catchment. If so, this would have implications for the effective future use of stormwater in this river to augment the City of Cape Town's scarce water resources.

METHODS

Study area

The Liesbeek River originates in the natural Table Mountain sandstone catchment above Kirstenbosch but then flows through the southern suburbs of Cape Town (Fig. 1), where approximately 40% of its channel has been canalised (River Health Programme, 2005; Brown and Magoda, 2009). It has a total catchment area of 327 km^2 and flows most strongly during the wet winter months. Flow is reduced during summer months, with the shallow upper and middle reaches often drying completely (Suri et al., 2017).

Sampling methods

Prior to the storm, rain gauges were placed at the river sampling point in Mowbray (33° 56′ 48.23″ S 18° 28′ 39.69″ E, 11 m amsl), at the University of Cape Town's Upper Campus (UCT, 33° 57′ 24.30″ S 18° 27′ 40.00″ E, 120 m amsl) and at the top of Skeleton Gorge on Table Mountain (the Liesbeek's headwaters, 33° 58′ 42.38″ S 18° 24′ 48.42″ E, 820 m amsl). Periodic measurement of accumulated rainfall amount and isotopic composition were recorded at the Mowbray gauge throughout the storm event. After recording rainfall amount, rainwater samples were decanted into 10 mL centrifuge vials, sealed with Parafilm (Bemis Flexible Packaging, Neenah, WI 54956, USA) and transported to the laboratory for analysis. The rain gauge was emptied and reset until the next collection.

For practical purposes, the UCT and Skeleton Gorge rain gauges were only assessed after the storm had passed. As such, these only reflect total rainfall and isotopic composition at those stations. No attempt was made to limit evaporative losses from the rain gauges during collection as these gauges were only exposed to the atmosphere during the storm, when evaporative losses would be minimal, and were sampled immediately thereafter. All isotope analyses were conducted within 24 hours of sample collection.

River-water was sampled from a weir in a canalised section of the Liesbeek River in Mowbray (33° 56′ 48.23″ S 18° 28′ 39.69″ E, 4 m amsl). Samples were taken prior to the storm event, at multiple intervals throughout the storm (in conjunction with Mowbray rainfall) and for 8 h after the storm had passed. River-water samples were collected from below the water's surface in a fast-flowing section mid-stream. Simultaneously, streamflow measurements were obtained by measuring the time (Δt) it took a nearly submerged floating object to travel a fixed distance (Δx) down the middle of the channel. We used small oranges as floating objects as they were visible at night and approximately the density of water and thus mostly submerged and unaffected by wind. The depth of the water in the canalized channel (d) and breadth of the channel (b) was also measured. From these measurements, streamflow rate (v) ($m^3 \cdot h^{-1}$) was calculated as:

$$v = d \times b \times \left(\frac{\Delta x}{\Delta t}\right) \quad (1)$$

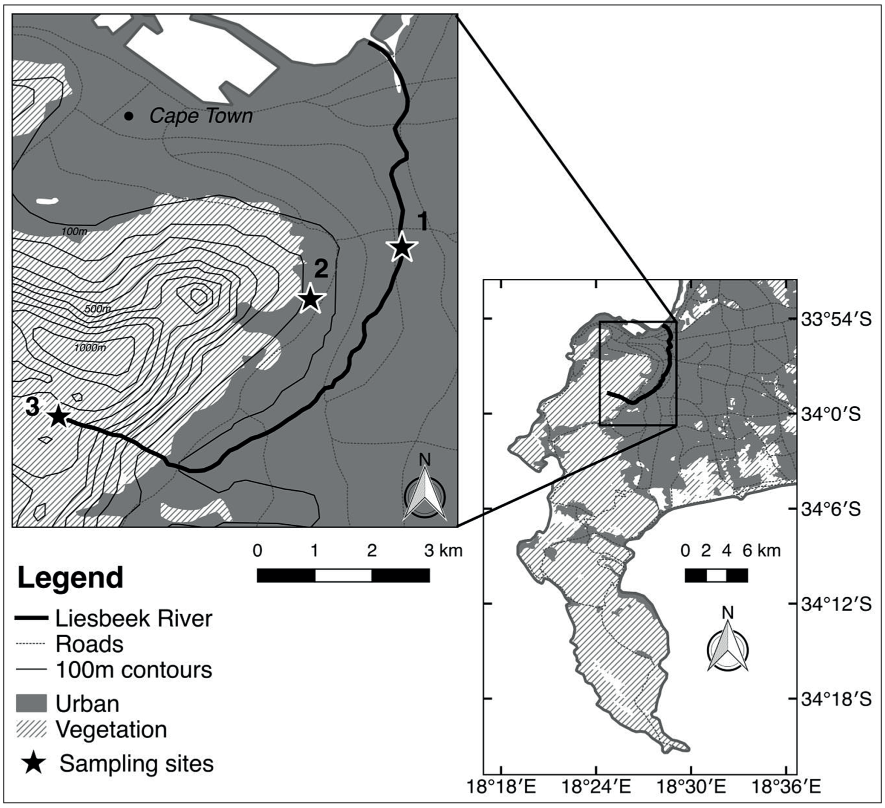

Figure 1
Map of the sampling sites along the Liesbeek River, Western Cape, South Africa (1: Mowbray site, 2: UCT Upper Campus site, 3: Skeleton Gorge site). The Cape Peninsula is shown, with the Liesbeek River inset.

As we did not measure $\Delta x/\Delta t$ across the entire breadth of the canal, notably near the edges where flow may be slower than midstream, our estimate of streamflow represents an upper limit of potential streamflow and most likely overestimates true streamflow.

Total storm-flow (T, m^3) was approximated as the sum of streamflow over the duration of the storm, assuming constant flow between measurements, from the beginning of the storm until the flow returned to base levels after the storm

$$T = \sum [v_i\,(t_{i+1} - t_i)] \tag{2}$$

where v_i is the streamflow ($m^3 \cdot hr^{-1}$) at time i and $t_{i+1} - t_i$ (h) is the interval between time i and the following measurement at time $i+1$.

Stable isotope analyses

Isotopic composition (δ^2H and $\delta^{18}O$) of water samples was analysed by wavelength-scanned cavity ring-down spectroscopy (WS-CRDS, Gupta et al., 2009) using a L2120-i (Picarro Inc., 480 Oakmean Parkway, Sunnyvale, California, 94085, USA; www.picarro.com) in the Department of Biological Sciences, UCT. Liquid water samples were filtered through a 20 µm filter into 2mL sample vials and analysed within 24 h of collection. Isotope ratios are expressed in ‰ as:

$$\delta^N E = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \tag{3}$$

where N is the atomic mass of the heavy isotope of element E and $R_{sample}/R_{standard}$ is the ratio of the heavy to light isotope ($^2H/H$ or $^{18}O/^{16}O$). Samples were corrected to Vienna Standard Mean Ocean Water (VSMOW) using a linear correction function based on two laboratory standards that spanned the range of values in our samples. Accuracy was determined using a quality control standard that was not used in standard corrections. Long-term precision and accuracy of this instrument were 0.2‰ and 1.5‰ for δ^2H and 0.07‰ and 0.13‰ for $\delta^{18}O$, respectively. We propagated these uncertainties appropriately (Genereux, 1998), conservatively treating total analytical uncertainty for isotope values as the combination of precision and accuracy. Due to the potential for organic contaminants to interfere with WS-CRDS measurements (West et al., 2010; Brand et al., 2009), all analyses were run through post-processing software (ChemCorrect version 1.2) to detect for possible organic contamination (West et al., 2011). No indications of contamination were seen for any of our river and rain samples.

Statistical analyses

All analyses were carried out in R (R Core Team, 2017) using the 'tidyverse' suite of packages (Wickham, 2017) for data exploration and visualisation. Simple linear regressions were performed for: streamflow rate against rainfall rate, $\delta^{18}O$ and δ^2H of stream-water against those of rainwater and $\delta^{18}O$ against δ^2H for stream-water and rainwater. Additionally, we assessed whether the residuals in these linear models depended on a measurement's timing within the sampling period, using regressions of those residual values against time, to ascertain whether the strength of coupling between stream- and rainwater isotope values changed during the course of the storm. We also constructed a local meteoric water line (LMWL) for Cape Town using previously published data (Harris et al., 2010) as the linear regression of rainwater $\delta^{18}O$ against δ^2H for Cape Town, across 4 years, from 2013 to 2016.

We calculated the proportion of storm-flow that was rainfall-derived using a mass-balance model, following the approach of Midgley and Scott (1994) and Midgley et al. (2001). We assumed only two inputs into the stream over the course of the storm: baseflow and rainfall. We used the isotope values of the stream before the storm as our estimate of baseflow ($\delta_{baseflow}$), the amount-weighted isotope values of the storm's cumulative rainfall (δ_{rain}) and the amount-weighted isotope values of the total river storm-flow ($\delta_{stormflow}$) to calculate p, the proportion of storm-flow that was derived from rainfall (Eq. 4). This was done for each isotopic tracer separately, and then averaged, with propagated uncertainties.

$$p_{rain} = \frac{\delta_{stormflow} - \delta_{baseflow}}{\delta_{rain} - \delta_{baseflow}} \tag{4}$$

RESULTS

A total of 53 mm of rainfall fell during the 52 h of the study period at the Mowbray study site (Fig. 2A). The flow rate of the Liesbeek River increased 100-fold during the storm, from 61 $m^3 \cdot h^{-1}$ (0.017 $m^3 \cdot s^{-1}$) before the storm, to a peak of 6 661 $m^3 \cdot h^{-1}$ (1.850 $m^3 \cdot s^{-1}$) during the storm, before dropping back to 68 $m^3 \cdot h^{-1}$ (0.019 $m^3 \cdot s^{-1}$) approximately 10 h after the last rain fell. Approximately 41 375.8 m^3 flowed down the river during the storm event (total storm-flow, T). There was a strong correlation between streamflow and rainfall rates ($P < 0.001$, Pearson's r = 0.86, Figs 2B, 2C, 3A).

There was also a strong correlation between the isotopic composition of the rainwater and stormwater (Pearson's r = 0.741 and 0.775 for $\delta^{18}O$ and δ^2H, respectively, $P < 0.001$ in both cases) (Figs 2D, 2E). The $\delta^{18}O$ and δ^2H values of rainwater were more variable than those of the stream-water (Fig. 2D, 2E). $\delta^{18}O$ ranged from −2.02‰ to −6.06‰ in stream-water and −2.95‰ to −7.75‰ in rainwater and δ^2H ranged from −5.34‰ to −28.37‰ in stream-water and −8.60‰ to −40.06‰ in rainwater. We found no significant relationship between stream- versus rainwater residuals (Fig. 3) and time, suggesting that the strength of the relationship between stream- and rainwater isotope values (Fig. 3B, 3C) (and indeed streamflow and rainfall amounts (Fig. 3A)) was relatively uniform during the course of the storm event.

The isotopic composition of the rain and stream measured during this storm was indistinguishable from the LMWL for the Cape Town area (derived from long-term data from Harris et al. (2010)), suggesting that rainfall is the principal source of water to streamflow within the section of river studied (Fig. 4). Notably, the amount-weighted isotope values for the Mowbray and UCT rainfall ($\delta^{18}O$ = −4.79‰, δ^2H = −20.09‰ and $\delta^{18}O$ = −5.08‰, δ^2H = −20.50‰, respectively, Fig. 4) were similar, and both markedly isotopically heavier in both δ^2H and $\delta^{18}O$ than that from Skeleton Gorge ($\delta^{18}O$ = −5.99‰, δ^2H = −22.48‰, Fig. 4).

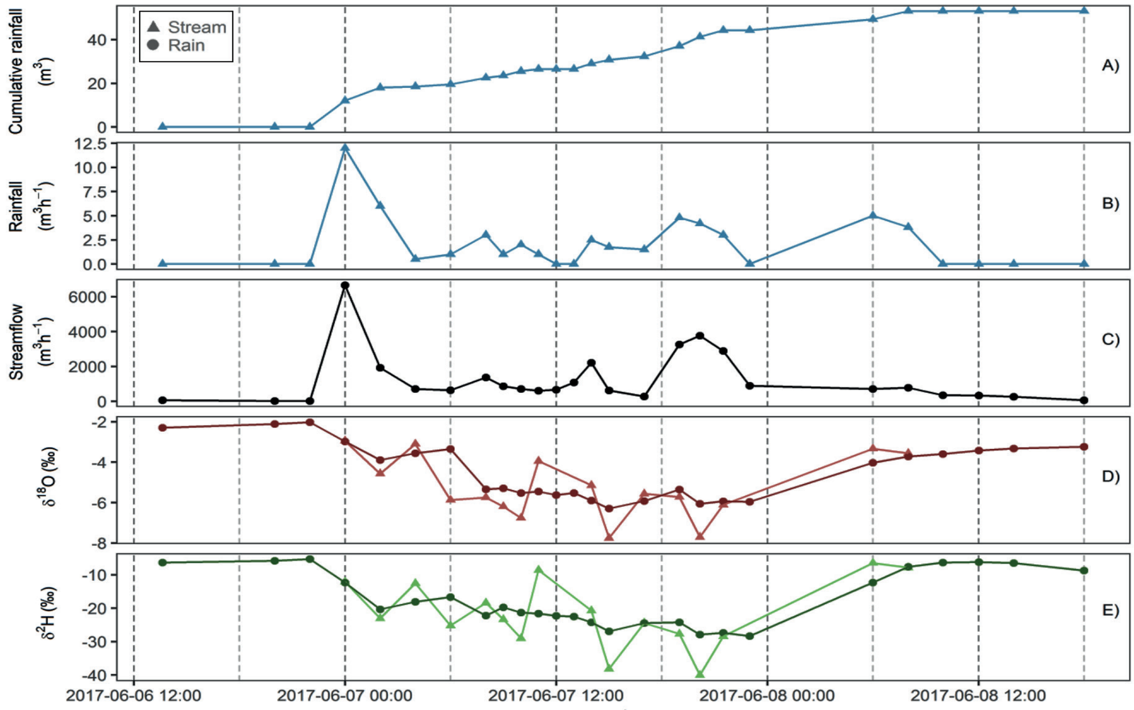

Figure 2

Timeline of isotopic and hydrological values throughout the winter storm event during which sampling was carried out (ca. 54 h range of sampling): A) cumulative and B) each measurement's rainfall rate ($m^3 \cdot h^{-1}$), C) streamflow rate ($m^3 \cdot h^{-1}$) of the Liesbeek River, and D) $\delta^{18}O$ (‰) and E) δ^2H (‰) values for both the rain and stream-water.

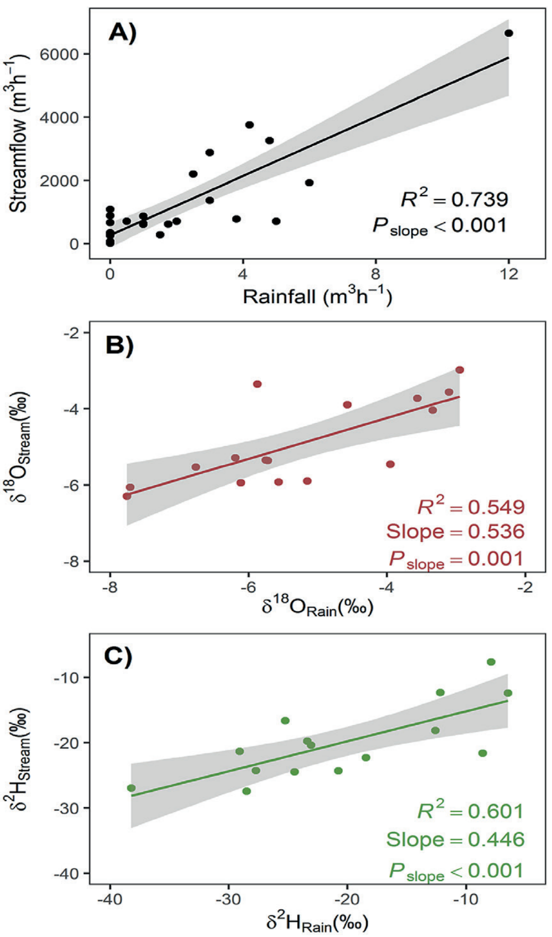

Figure 3

Scatter-plots of rain- versus stream-water A) amounts ($m^3 \cdot h^{-1}$), B) $\delta^{18}O$ (‰) and C) δ^2H (‰) values, where there were rainfall measurements contemporaneous with stream-water measurements (i.e. excluding those stream-water measurements when there was no rainfall for isotope analyses). The trend-lines represent the simple linear regressions of stream-water values against rainwater values, with 95% confidence intervals in grey. The R^2-values, slopes, and P-values of the slope-terms are inset for the linear regressions in each case. None of these models' residuals were found to depend on when measurements were taken during sampling (all $R^2 < 0.15$, all slopes ≈ 0, all $P >> 0.05$), following linear regressions of residual values against time.

Following the mass-balance model (Eq. 4), we calculated the contribution of rainfall to the storm-flow in the Liesbeek River. Using the amount-weighted values for streamflow, rainfall and storm-flow (Table 1), we calculated that 101.1% (± 10.7%) of storm-flow was derived from rainfall. This suggests that stream-water was almost entirely (> 90%) derived from recent rainwater.

DISCUSSION

Here we have presented the isotopic similarity of river and rainwater throughout the storm event, a strong correlation between streamflow and rainfall rates and a large proportion (> 90%) of rainwater making up the streamflow during the storm event. We therefore conclude that overland-flow is the predominant driver of the river's flow rate during this rainfall event. The isotopic similarity between stream- and rainwater, and the degree to which these values track each other during the storm event, suggest that recent rainfall is indeed the majority contributor to storm-flow. This directly contrasts

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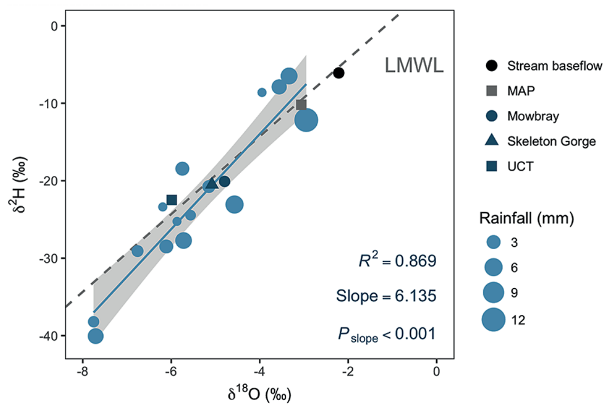

Figure 4

Scatter plot of δ^2H (‰) versus δ^{18}O (‰) for storm rainwater (blue circles), and other points of interest. The sample LMWL (grey dashes) (Harris et al., 2010) has the form $\delta^2H = 5.015 \times \delta^{18}O + 5.777$. The black point represents baseflow (i.e. the amount-weighted mean isotope values for the three pre-storm stream-water samples). The grey square (MAP) represents the amount-weighted mean annual rainfall isotope value (Harris et al., 2010). The dark blue points represent the amount-weighted mean isotope values for cumulative storm rainwater from near the urban stream in the suburb of Mowbray, from the slightly elevated Upper Campus of the University of Cape Town (UCT), and from the mountainous Skeleton Gorge. The solid blue trend-line represents the simple linear regression of δ^2H against δ^{18}O with 95% confidence intervals in grey. The R^2-values, slopes, and P-values of the slope-terms are inset.

TABLE 1
Input data and results from the mass-balance model (Eq. 4). Means presented here are amount-weighted. Proportions are unitless.

	δ^{18}O (‰)	δ^2H (‰)
Baseflow ($\delta_{baseflow}$)	−2.21	−6.08
Rainfall (δ_{rain})	−4.79	−20.09
Storm-flow ($\delta_{stormflow}$)	−4.79	−20.46
Uncertainty in isotope values	0.15	1.51
Mass-balance rainfall proportion (p_{rain})	0.997	1.026
Uncertainty	0.159	0.141
Average (p_{rain}) (± uncertainty)	1.011 (± 0.107)	

with the finding of piston-flow in the natural catchments of the nearby Cape rivers in the Jonkershoek Valley and on Table Mountain (Midgley and Scott, 1994; Midgley et al., 2001) and is most likely due to the hardening of the urban catchment around the Liesbeek River decreasing the infiltration capacity of the substrate and resulting in high overland-flow.

While factors such as soil type and rock cover cause a natural variation in the porosity of the land surface (Graniel et al., 1999), changes in surface porosity in urban areas have serious effects on the hydrological cycle (Sharp, 2010). Groundwater recharge rates are affected by impervious cover, which causes them to become less dependent on rainfall and more dependent on artificial forms of recharge, such as leakages and irrigation (Sharp, 2010). Increases in impervious cover and overland-flow can cause rainwater to run directly into rivers and out to sea, without recharging soil reservoirs or aquifers, thereby increasing an area's susceptibility to water shortages (Bruijnzeel, 2004).

A key implication of our study is that a potentially valuable source of water for the over-extended City of Cape Town's water supply is being lost directly to the sea, without influencing aquifer recharge. Considering the dire water crisis that the City currently finds itself in, any additional water sources that could augment its supply merit investigation.

When performed correctly, stormwater harvesting has been identified as beneficial for ecological, environmental and social reasons (Fletcher et al., 2007; Mitchell et al., 2007; Inamdar et al., 2013). While the City of Cape Town has already begun emergency development of aquifer extraction for municipal water use (Evans, 2018), recharge of these aquifers must be considered. Our study supports previous work suggesting that artificial recharge, as well as domestic water use, could include stormwater harvested from the Liesbeek River (Inamdar et al., 2013; Fisher-Jeffers et al., 2017).

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SUPPORTING INFORMATION

Data-sets and analyses in the form of R-scripts are available online at https://github.com/rvanmazijk/Liesbeek-River-isotopics.

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