Quantifying streamflow sources to improve water allocation management in a catchment undergoing agricultural intensification

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Abstract

Changes in streamflow contributing sources in semi-arid catchments undergoing agricultural intensification are often poorly understood. As a result, pathways to increase resilience to environmental change are not well established. Mixing model analysis using stable water isotopes and hydro-chemical tracers was applied to evaluate streamflow sources in the Kaleya Catchment, Zambia. Results showed that strong agricultural intensification signal influenced streamflow sources in time and space. In the rainy season, streamflow mainly originated from stormwater runoff from non-irrigated areas (43 ± 13%), the perennial spring (39 ± 21%) and stormwater runoff from irrigated areas (18 ± 17%). But in the dry season, the spring (65 ± 15%) and irrigation return flows (35 ± 15%) became the important upstream sources, while downstream sources were irrigation return flows (73 ± 15%) and wastewater containing vinasse (27 ± 15%), both associated with water originally transferred from the adjacent Kafue River. Given the current importance of irrigation return flows to downstream users including ecosystems, social cooperate responsibility and/or water markets must help to improve irrigation efficiency while simultaneously ensuring downstream flows are maintained.

Keywords: end member mixing analysis; intra-basin transfer water; Kaleya Catchment; stable water isotopes; wastewater; return flow

1 Introduction

Semi-arid areas such as most parts of southern Africa experience a climate characterised by distinct rainy and dry seasons. Climate change is increasing the frequency of extreme events (droughts and floods) and leading to higher rainfall intensities (Chisola et al., 2020; Nhemachena et al., 2020). Rainfall often falls during four to five months, so the dry season is relatively longer, placing pressure on water and food security. Irrigated agriculture intensification is often adopted in the region to increase agricultural productivity and grow export quality produce (Nhamo et al. 2019, Nhemachena et al. 2020, Hamududu and Ngoma 2020, Akayombokwa et al. 2017).

Given that most rivers and streams in meso-scale catchments are intermittent and ephemeral (Belemtougri et al., 2021; Fovet et al., 2021; Magand et al., 2020), irrigation often depends on groundwater abstractions, small dams, springs, and inter- and intra-basin water transfer schemes. Along with deforestation caused by the clearing of large tracts of land for agricultural expansion (German et al., 2020), these hydrological modifications alter the dominant runoff generation processes and streamflow sources. In many cases, this has left both water and food availability vulnerable to climatic variability and change (Misra 2014). Often there is a call to increase irrigation efficiency by reducing water ‘losses’, without properly understanding the fate of the return flows.

The water accounting concept recognises that while irrigation return flows may constitute water loss at the scale of water application, they are not necessarily losses at a river catchment scale as they may be recovered by downstream users and the riverine environment (Dumont et al., 2013; Perry, 2007; Perry et al., 2009). Case studies have highlighted the risk to downstream water availability that could arise with increased irrigation efficiency (Dumont et al., 2013; Loch and Adamson, 2015). The ‘rebound effect' can occur when initial water savings are used to expand irrigated areas at the expense of the environment and other downstream users. Addressing this issue does not justify excessive irrigation but provides a framework to ensure that the pursuit of water conservation does not create negative externalities on downstream flows.

Understanding streamflow sources in time and space can lead to improved management of catchments leading to increased resilience to environmental change (Uhlenbrook et al., 2004). Unfortunately, streamflow gauge networks needed to derive information on streamflow source dynamics tends to be sparse, especially in developing countries (Uhlenbrook et al., 2004). Tracer-based techniques such as the mixing models (Sklash et al., 1976) and End Member Mixing Analysis (EMMA) (Christophersen et al., 1990; Hooper, 2003; Hooper et al., 1990) are then essential to fill data gaps.

The application of mixing models and EMMA for process understanding in dry climates has gained momentum in recent years (Burns, 2002, Rahman et al., 2015). However, several research questions requiring the use of these tracer-based techniques in meso-scale catchments undergoing agricultural intensification remain. While rainfall-runoff processes are important in the rainy season, inter-basin water transfers and irrigation dynamics can play an important role in the dry season. Also, wastewater from urbanising areas often tends to be discharged into the same drainage systems meant for irrigation and storm water management, especially in developing countries (Tanji and Kielen 2002). Under these circumstances, the assumptions for tracer-based techniques, such as the need for tracer concentration to remain unchanged in space and time, may fail to be met (Sklash and Farvolden 1979, Hooper et al. 1990).

This study applied tracer-based techniques spatially and seasonally to investigate streamflow source dynamics in the water-stressed Kaleya Catchment in Zambia. The specific objectives were to (a) investigate the dominant streamflow sources in the catchment in both the rainy and dry season, and (b) assess the effects that the elimination of irrigation return flows could have on downstream flows.

2 Materials and Methods

2.1 Study area

The Kaleya Catchment is located between latitude 15^{o}40’S to 16^{o}20’S and longitude 27^{o}30’ E to 28^{o}10’ E (Figure 1) in southern Zambia. Originating from a slow discharging spring in the upper part of the catchment, the Kaleya River eventually drains into the Kafue River. The upper catchment is underlain by marble, metacarbonate and calc-silicate rocks, which form a productive aquifer due to their karstification and fracturing (Baumle et al., 2007). The lower catchment is low lying and underlain by alluvial deposits of the Kafue Flats (Baumle et al., 2007).

The study area experiences a semi-arid climate with distinct rainy and dry seasons. The rainy season is from November to March, with an average rainfall of about 750 mm per season. The dry season receives extremely little to no rainfall and covers the period April to October (Sichingabula et al., 2000). The potential evapotranspiration is about 2000 mm per year.

Irrigated agriculture has been practiced in the catchment since the beginning of the 1970s. Commercial sugarcane (*Saccharum officinarum L.*) estates in the downstream parts of the catchment were developed to increase sugar production for export to European markets (Akayombokwa et al. 2017). The irrigated area and the number of dams has continued to increase in response to unreliable rainfall and the need to increase income generation (Akayombokwa et al. 2017; Chisola et al. 2020).

While irrigation in the upper and middle Kaleya Catchment depends on water from within, the sugarcane estates in the downstream part are irrigated using intra-basin transfer water (IBTW) from the Kafue River. The Nakambala Sugar Estate (NSE) supplies the IBTW directly to their estates and those under their out-grower scheme called the Kaleya Smallholder Company Limited (KASCOL). The water is first stored in small night storage reservoirs within the estates from which it is later channelled to irrigation canals for flood irrigation by siphoning from the canals (Akayombokwa et al., 2017). Any return flows end up in the lower Kaleya River.

The vinasse from the brewing of local beer called *Kachasu* using sugarcane molasses in the neighbouring ‘Kaleya station’ township (an informal settlement) is dumped into some of the irrigation drainage canals and reservoirs/ponds. This vinasse mixes with water leaking/overflowing from the irrigation system forming wastewater. The wastewater eventually drains into the Kaleya River. Water for domestic use is often from a few boreholes in the area as well as shallow hand dug wells. Pit latrines are common due to the absence of a water supply and sewerage network within the settlement. Understanding the prevailing dominant streamflow contributing sources is required to inform integrated catchment management for increased resilience of the river system.

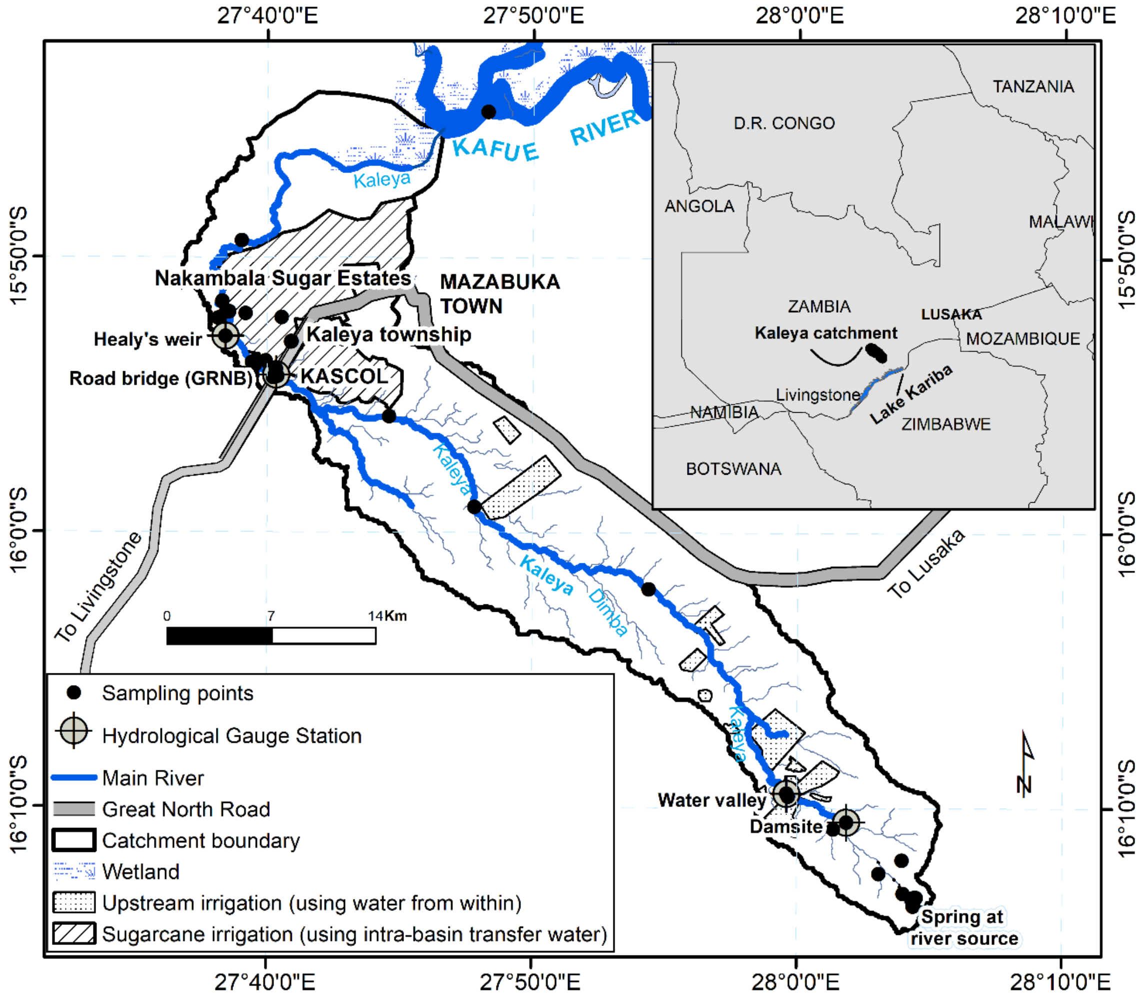

Figure 1. Kaleya Catchment in Zambia

2.2 Sampling

The water sampling strategy was guided by the spatial and temporal patterns of water use in the catchment. Rainfall, streamflow from the spring upstream, boreholes and shallow wells in the upstream and downstream catchments, and IBTW in the downstream part of the catchment provide water for various uses in the area. Other water use dynamics that could affect streamflow sources include, flood irrigation practices especially from gardening and commercial agriculture in the upper part of the catchment, and large-scale sugarcane cultivation downstream.

The concentration of naturally occurring stable water isotopes and dissolved ions in these potential sources of streamflow tends to be different. For example, irrigation return flows tends to have heavier stable water isotopes and higher concentration of ions than irrigation water. This is due to evaporation associated with irrigation as lighter isotopes are preferentially evaporated leaving behind heavier ones. In this regard, tracers involving stable water isotopes [deuterium ($\delta\ ^2H$) and oxygen-18 ($\delta\ ^{18}O$)] and ions [calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), chloride (Cl^{-1}), and sulphates ($SO4^{2-}$)] including Electrical conductivity (EC) which have commonly been used in areas facing agricultural intensification were adopted (Simpson and Herczeg 1991, Kattan 2008, Barros et al. 2012, Vallet-Coulomb et al. 2017).

Water samples were collected between August 2019 and March 2020, covering the middle and peak of the dry and rainy seasons, respectively. Grab samples were collected from flowing water of the Kaleya and Kafue rivers, and at strategic points within the Kaleya Catchment (Table 1). Samples for tritium (^3H) analysis were collected from the spring as well as a borehole located in the upper catchment, approximately 500 m downstream from the spring. Samples for stable water isotopes ($\delta\ ^2H$ and $\delta\ ^{18}O$) were sealed in 100 ml polythene bottles, while those for physical-chemical parameters (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^{-1}, and SO_4^{2-}) were sealed in 1000 ml polythene bottles. All samples were refrigerated for preservation. The EC, pH and temperature were measured *in situ* using the Hanna multi-parameter meter (model: HI 9829, Hanna Instruments, Woonsocket, USA).

For streamflow, some sampling sites were located at the existing gauge stations (‘Damsite’, ‘Water valley’, ‘Road bridge’ and ‘Healys estate weir’) to enable simultaneous recording of discharge during the time of sampling. Additionally, daily historical discharge data was obtained from 1975 – 2020 from the Water Resources Management Authority (WARMA) in Zambia. Two simple farm rain gauges were installed upstream and downstream in the catchment for rainwater sampling and measurement.

Table 1: Sampling sites and samples

Sampling sites	**Rainy season**	**Dry season**	**Total**
Upstream samples			
Perennial spring at river source	3	2	5
Boreholes irrigated areas	6	3	9
Boreholes non irrigated areas	4	5	9
Shallow wells	4	4	8
Kaleya River	11	9	20
Rain/Stormwater runoff from non-irrigated areas	6	0	6
Irrigation canals	2	3	5
Drainage with wastewater in the dry season	2	2	4
Kafue River at pumping site for intra-basin water transfer	2	2	4
Total	**40**	**30**	**70**

2.3 Laboratory analysis

Physical-chemical parameters were analysed at the Environmental Engineering Laboratory of the University of Zambia, in Lusaka, Zambia, using standard procedures for water quality analysis. Samples for $\delta\ ^{2}H$, $\delta\ ^{18}O$ and $\delta\ ^{3}H$ were analysed by the Environmental Isotope Laboratory at the iThemba LABS in Johannesburg, South Africa. For stable water isotopes, the samples were analysed using the Liquid Water Isotope Analyser [Model: LWIA-45-EP, Los Gatos Research (LGR), Mountain View, California, USA]. The isotope ratios were expressed in the delta-notation based on the formula:

$$\delta^{18}O(‰) = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \right] \times 1000 \qquad (1)$$

which also applies to δ ^{2}H (^{2}H/^{1}H). The delta values were expressed as per mil deviation relative to the standard mean ocean water (SMOW) for δ ^{18}O and δ ^{2}H. The analytical precision was 0.5‰ for δ ^{18}O and 1.5‰ for δ ^{2}H. The samples for δ ^{3}H were enriched by electrolysis and analysed on the Packard Tri-Carb 3170TR/SL Liquid Scintillation Counter. The detection limit for enriched samples was 0.2 Tritium Units (TU).

2.4 Data analysis

Both mixing model analysis (Phillips and Gregg, 2001; Sklash et al., 1976) and End Member Mixing Analysis (EMMA) (Christophersen and Hooper, 1992) were used in this study. The first step involved the determination of potential end members (streamflow sources) using EMMA. The EMMA used more tracers to generate mixing diagrams that were used to identify streamflow sources (referred to as end members) from the wide variety of potential streamflow sources that were sampled. Once the end members were identified by EMMA, the second step used the mixing model analysis (mass balance analysis) to estimate streamflow contributions of the identified end members.

The basis for considering uncertainties when computing mixing ratios is that the end members are usually not perfectly known. Even if the EMMA procedure identified the potential end members, their contributions to streamflow are highly variable in time and space especially in meso-scale semi-arid areas undergoing agricultural intensification (Carrera et al., 2004). Thus, the two approaches were used in a complementary way where EMMA identified the potential streamflow sources, while mixing model analysis quantified the mixing ratios of the streamflow sources and their uncertainties. The two approaches are further described in the following sections.

2.4.1 End Member Mixing Analysis (EMMA)

2.4.1.1 Bivariate and multivariate analysis of streamflow data

As a first step in EMMA, stable water isotopes ($\delta\ ^2$H and $\delta\ ^{18}$O) and solutes (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^{-1}, and $SO_4{}^{2-}$) were examined for conservative behaviour as conservative tracers are required for EMMA. Based on Hooper (2003), the simplest approach for identifying conservative tracers is by using bivariate scatter plots. Bivariate tracer versus tracer plots were thus constructed for all solutes and stable water isotopes (Figure 2). The solutes and isotopes that displayed the best linear fits ($p < 0.01$) were chosen as tracers for EMMA (Correa et al., 2017; Hooper, 2003; James and Roulet, 2006).

The second step in EMMA involved determination of the dimensionality of the hydrological system through Principal Component Analysis (PCA), using the observed streamflow data for all the conservative tracers ($\delta\ ^2$H, $\delta\ ^{18}$O, EC, Na^+, and Cl^-). This allowed for reducing the dimension of the data by determining the number of significant principal components to retain using eigenvalue analysis. As a requirement for EMMA, the number of principal components whose eigenvalues ≥ 1, and or the number of components which cumulatively explained at least 90% of the variability in the observed streamflow data ($\delta\ ^2$H, $\delta\ ^{18}$O, EC, Na^+, and Cl^-) were retained (Christophersen and Hooper, 1992; Correa et al., 2017). The number of significant components was then used to determine the number of end members (streamflow sources) needed to explain streamflow sources (Christophersen and Hooper, 1992; Correa et al., 2017). Thus, based on the Rule of One (Joreskog et al. 1976), the number of end members (streamflow sources) contributing to streamflow was determined as the number of principal components retained, plus one.

2.4.1.2 Mixing diagrams

Having determined the number of end members through the PCA process, the final step was to identify the relevant end members. When observed data for all tracers is projected in the mixing sub space formed by the two principal components, the extreme points of the observed data that enclose the rest of the data when connected by mixing lines is what is referred to as end members (Christophersen and Hooper, 1992). Theoretically, end members are considered as sources of water that could have mixed to contribute to the observed streamflow, and thus together explain 100% of the enclosed streamflow data in a mixing diagram (Correa et al., 2017). That is, end members and principal components (principal axes) are two different things.

Thus, the mixing diagrams were constructed using the *EMMA.xls* spreadsheet program (Hooper, 2015). The standardised streamflow data for $\delta\ ^{2}H$, $\delta\ ^{18}O$, EC, Na^{+} and Cl^{-} were projected into a U-mixing space (Christophersen and Hooper, 1992), a lower dimensional space defined by PCA that describes the variability of the data (Christophersen and Hooper, 1992). The medians of all the potential end members were then orthogonally projected into the mixing subspaces of stream water samples defined by PCA.

For a three-end model, streamflow data that plotted within the triangle formed by the three end members was attributed to those end members. The streamflow data that was not enclosed by the mixing triangle were taken as resulting from other sources not accounted for in the model (Christophersen and Hooper, 1992; Pelizardi et al., 2017). For the two-end member model, streamflow values that plotted on or close to the mixing line were attributed to the respective end-end members (streamflow sources) forming the mixing line (Christophersen and Hooper, 1992; Pelizardi et al., 2017).

2.4.2 Mixing model analysis for computation of mixing ratios

Having identified the members from the mixing diagrams, the proportion contributed by each end member and the associated uncertainties were determined using mass balance analysis. For this, the *IsoError.xls* spreadsheet program (Phillips and Gregg, 2001) was used. According to the mixing model theory, streamflow sample values are a linear mixture of the proportions of end members that form a convex polygon, where these proportions are not negative and sum up to 1. Therefore, for a three-end member mixing model, the following mass balance equations can be evaluated (Phillips and Gregg, 2001):

$$\delta J_M = f_A \delta J_A \ + \ f_B \delta J_B + f_c \delta J_C \tag{2}$$

$$\delta L_M = f_A \delta L_A \ + \ f_B \delta L_B + f_c \delta L_C \tag{3}$$

$$1 = f_A \ + \ f_B + f_c \tag{4}$$

where, $\delta J \ and \ \delta L$ are the mean concentrations of any two different tracers (isotopic or hydro-chemical) in the streamflow mixture *M*. The subscripts *A*, *B* and *C* are the respective streamflow sources and f is the mean proportion contributed by each end member (streamflow source) to the streamflow mixture. These proportions are quantified as follows:

$$f_A \ = \frac{(\delta L_C - \delta L_B)(\delta J_M - \delta J_B) - (\ \delta J_C - \delta J_B)\ (\ \delta L_M - \delta L_B)}{(\delta L_C - \delta L_B)(\delta J_A - \delta J_B) - (\ \delta J_C - \delta J_B)\ (\ \delta L_A - \delta L_B)} \tag{5}$$

$$f_B = \frac{(\delta J_M - \delta J_C) - (\delta J_A - \delta J_C)\, f_A}{\delta J_B - \delta J_C} \tag{6}$$

$$f_c = 1 - f_A - f_B \tag{7}$$

Similarly, a two-end member mixing model can be evaluated using the mass balance equation (Phillips and Gregg, 2001):

$$\delta K_M = f_A\, \delta K_A - f_B \delta K_B \tag{8}$$

$$1 = f_A + f_B \tag{9}$$

where, δK is the mean concentration of any tracer used, and the subscripts *A* and *B* are the respective streamflow sources. The f is the mean proportion contributed by an end member (streamflow source) to the streamflow mixture *M* and is computed as follows:

$$f_A = \frac{\delta K_M - \delta K_B}{\delta K_A - \delta K_B} \tag{10}$$

$$f_B = 1 - f_A \tag{11}$$

Details on how the variances and confidence intervals are calculated can be found in Phillips and Gregg (2001). Only those end member combinations that fulfilled the mixing model theory by not having negative contributions were accepted as being hydrologically plausible.

2.4.3 Inferring the volume of irrigation return flows from mixing model analysis

The mixing model analysis quantifies the contribution of each end member in terms of proportions. To obtain the volume of irrigation return flow in the lower Kaleya River, it was necessary to link discharge with the proportion of irrigation return flows in streamflow as determined by mixing model analysis (Equation 8-11), using Equation 12.

$$IRF \;\; = IRF\ proportion\ based\ on\ mixing\ model\ analysis\ x\ Q \qquad (12)$$

where, IRF is irrigation return flow and Q is the average estimate of dry season discharge of the downstream Kaleya River at Healy's estate weir gauge station based on Sichingabula et al. (2020).

Some of the IBTW bypasses irrigation through leakages and overflow from the system (reservoirs and canals). This water mixes with discharges from the factory and vinasse often dumped into the Kaleya drainage canal by the Kaleya community, thereby forming wastewater (Alsterhag and Petersson, 2004) as earlier discussed. The domestic waste from sewers is still negligible and difficult to account for as many households use pit latrines due to the absence of a formalised sewerage system in the area. Therefore, wastewater in this study refers to the IBTW water that bypasses irrigation through leakages and overflow from the irrigation transfer system (reservoirs and canals), mixing with water from the factory as it flows towards the Kaleya River, and carrying along with it the vinasse disposed into the canals by the Kaleya community. The proportion of this wastewater in streamflow of the downstream Kaleya, was estimated using equation 13.

$$Wastewater = Wastewater\ proportion\ from\ mixing\ model\ analysis\ x\ Q \qquad (13)$$

2.4.4 Inferring age of water discharging from the spring

Tritium (^3H) was used to infer whether the recharge from the upstream spring is from recent precipitation or old recharge. This would help to inform measures for sustained recharge. For this determination, water samples for ^3H analysis were collected from the spring, and a groundwater borehole about 500 m downstream from the spring was also sampled. The laboratory analysis followed the procedure explained under Section 2.3.

3 Results

3.1 Bivariate and multivariate analysis

Bivariate tracer versus tracer plots showed that there was a strong positive relationship between δ ^{2}H and δ ^{18}O (Figure 2) and between Na^{+} and Cl^{-}. Electrical conductivity also showed a relatively good relationship with stable water isotopes. Other ions such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} had weaker correlations (Figure 2) with other potential tracers, hence were taken to have failed the conservative behaviour criteria required for EMMA. The five tracers δ ^{2}H, δ ^{18}O, EC, Na^{+} and Cl^{-} were, therefore, retained for further analysis with EMMA and the mixing model as they showed linear patterns in the biplots, which suggested conservative behaviour. Additionally, these are among the elements most used as tracers in scholarly literature (Abiye et al., 2015; Camacho et al., 2015; Kattan, 2008; Koeniger et al., 2020), hence their conservative behaviour was not unique to this study.

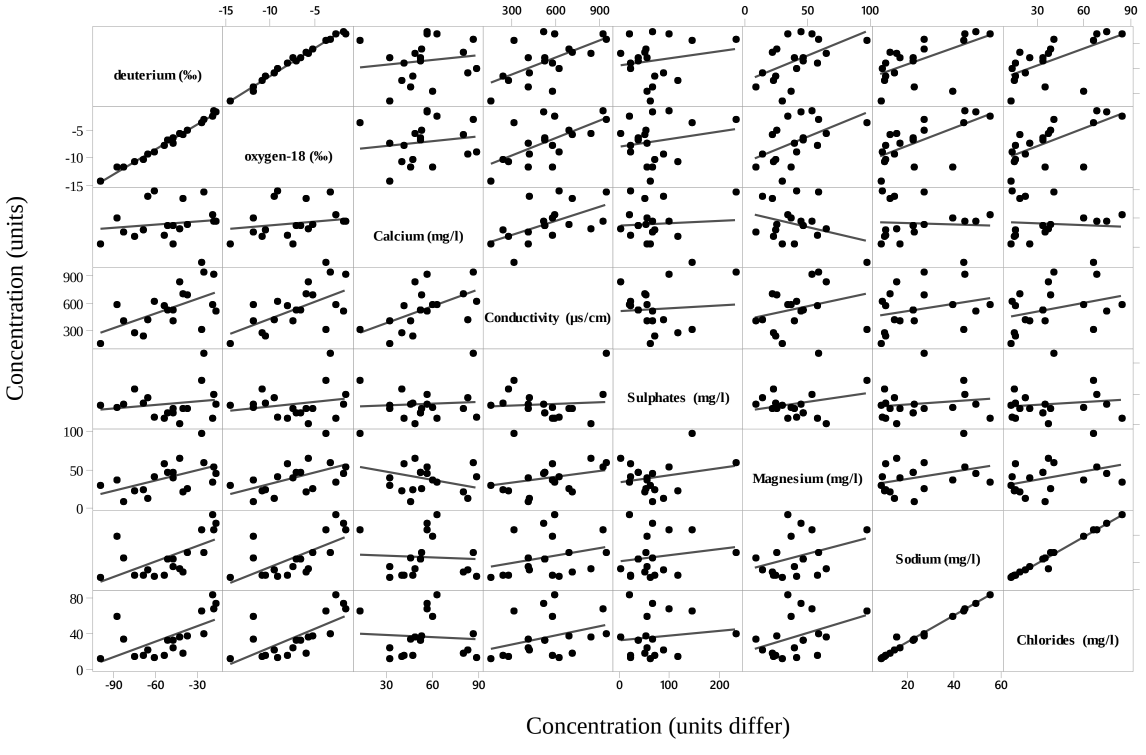

Figure 2: Bivariate solute plots of stream water chemistry in Kaleya catchment

The first two PCA components, together explained about 92% of the variance, with eigenvalues ≥ 1 (Table 2). The number of principal components whose eigenvalues ≥ 1, and or the number of components which cumulatively explain at least 90 % of the variability in the observed streamflow data are usually retained in EMMA (Christophersen and Hooper, 1992; Hooper, 2003). Based on this criteria, two principal components were retained for rainy season flows, while only one principal component was retained for dry season flows.

Table 2: Eigen analysis of the correlation matrix

	PC1	PC2	PC3	PC4	PC5
Eigenvalue	3.5960	0.9954	0.3972	0.0089	0.0026
Proportion	0.719	0.199	0.079	0.002	0.001
Cumulative	0.719	0.918	0.998	0.999	1.000

Table 3 shows that the first component was heavily weighted by stable water isotopes indicating a rainfall-runoff input, while the second component was heavily weighted by hydro-chemical tracers (EC, Na^+ and Cl^-) indicating an agricultural input (irrigation). Using the Rule of One (number of principal components retained plus one) (Joreskog et al. 1976), the results indicated that three end members (stream flows sources) would be needed to explain rainy season streamflow, while two end members would be required to account for dry season streamflow. The respective end members have been identified using mixing diagrams in Section 3.2.

Table 3: Factor loadings on the principal component analysis

Variable	Principal component 1	Principal component 2
deuterium	**0.560**	-0.439
oxygen-18	**0.579**	-0.398
Conductivity	0.420	**0.567**
Sodium	0.447	**0.510**
Chlorides	0.417	**0.572**

3.2 End member mixing diagrams

From the mixing diagram in Figure 3, stormwater runoff from non-irrigated and irrigated areas respectively and the spring were the dominant sources of streamflow in the rainy season. The stormwater runoff from non-irrigated areas was characterised by a lower EC value (6 ± 3 mS m^{-1}) compared to stormwater runoff from irrigated areas (EC of 99 ± 36 mS m^{-1}). The stormwater runoff from irrigated areas in the downstream part was a mixture of storm water from irrigated areas and wastewater. Hence, some rainy season upstream samples could not be enclosed in the mixing space of the three end members. Additionally, all the dry season flows upstream and downstream plotted outside the mixing space of the identified rainy season streamflow sources (Figure 3), indicating that these flows originate from different time and space variant sources in the catchment, which are identified in Figure 4.

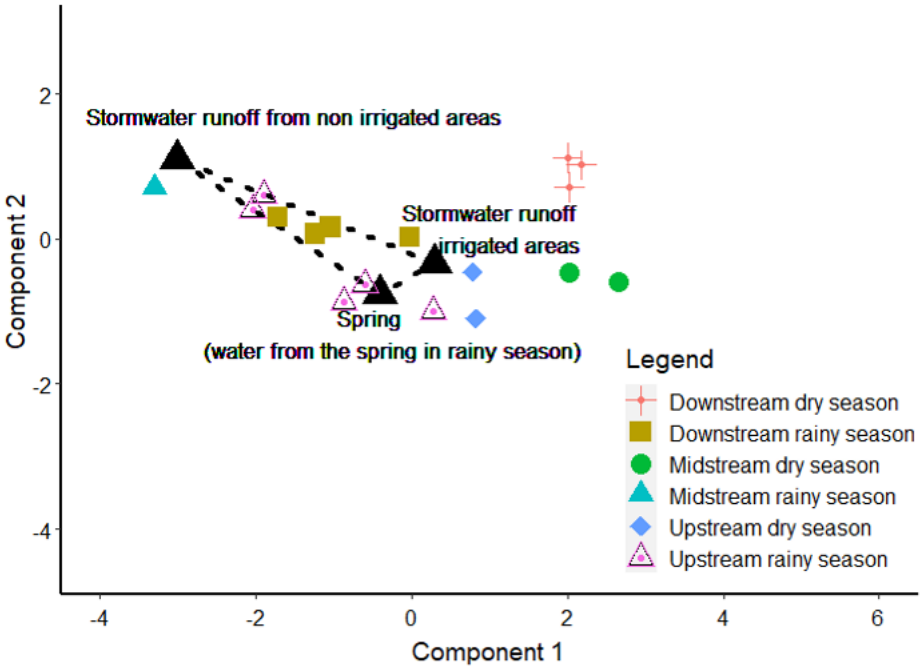

Figure 3: End member mixing diagram for rainy season flows (triangle) based on the first two principal components using all the conservative tracers.

Results showed that only two end members were needed to explain the dry season streamflow. Dry season flows upstream could be projected on the mixing line of the spring and the irrigation return flow end members (Figure 4). Hence, these were identified as upstream flow sources in the dry season. However, the downstream dry season streamflow was explained by completely different end members comprising of wastewater and irrigation return flows (Figure 4). The wastewater was the most enriched of all the end members in terms of the isotopic composition [δ ^{2}H (-16.3±0.5 ‰) and δ ^{18}O (-1.6±0.03 ‰)] and had a relatively high EC (79.9 ± 1.3). Additionally, the irrigation return flow in the downstream was associated with IBTW and thus differed in isotopic and hydro-chemical composition from the upstream irrigation return flow, where irrigation relied on water from within the catchment.

Compared to upstream, the IBTW associated return flow downstream, was more enriched in mean isotopic composition, δ ^{2}H (-18.99 ± 0.5 ‰) and δ ^{18}O (-2.34 ± 0.3

‰). This is characteristic of the Kafue River water that is enriched in δ ^{2}H (-19.7 ± 0.5 ‰) and δ ^{18}O (-2.63 ± 0.06 ‰). Hence, the similarity in isotopic composition was not surprising because irrigation water in the lower Kaleya River Catchment is obtained from the Kafue River through transfer using a 14 km earthen canal. However, there was a notable difference between the two in terms of other parameters, especially EC, which was about 44 ± 6.3 mS m^{-1} in return flows compared to 28.5 ± 2.5 mS m^{-1} in irrigation water.

Since return flow upstream is associated with water from within the catchment, it had a relatively lighter isotopic composition, δ ^{2}H (-24.90 ± 8.5 ‰) and δ ^{18}O (-3.0 ± 1.6 ‰) compared to the IBTW based return flow downstream. This upstream return flow was more enriched in isotopic composition compared to the spring, δ ^{2}H (-49.0 ± 0.5 ‰) and δ ^{18}O (-7.48 ± 1.6 ‰), which contributes streamflow used for irrigation. Apart from streamflow, some of the irrigation water upstream, especially around the commercial farms, could be coming from groundwater, which had a similar isotopic composition as the spring, as well as similar EC (66.8 ± 11.5 mS m^{-1} for groundwater and 54.6 ± 11.5 mS m^{-1} for the spring). The return flow upstream was both through the surface and shallow subsurface, possibly due to the limestone/karst geology in the upper catchment. Shallow subsurface flow was observed in the Kaleya River below the earthen dam wall on the irrigated area (left bank side) at ‘Water valley’ road bridge. This return flow had high EC of up to 151.1 mS m^{-1}.

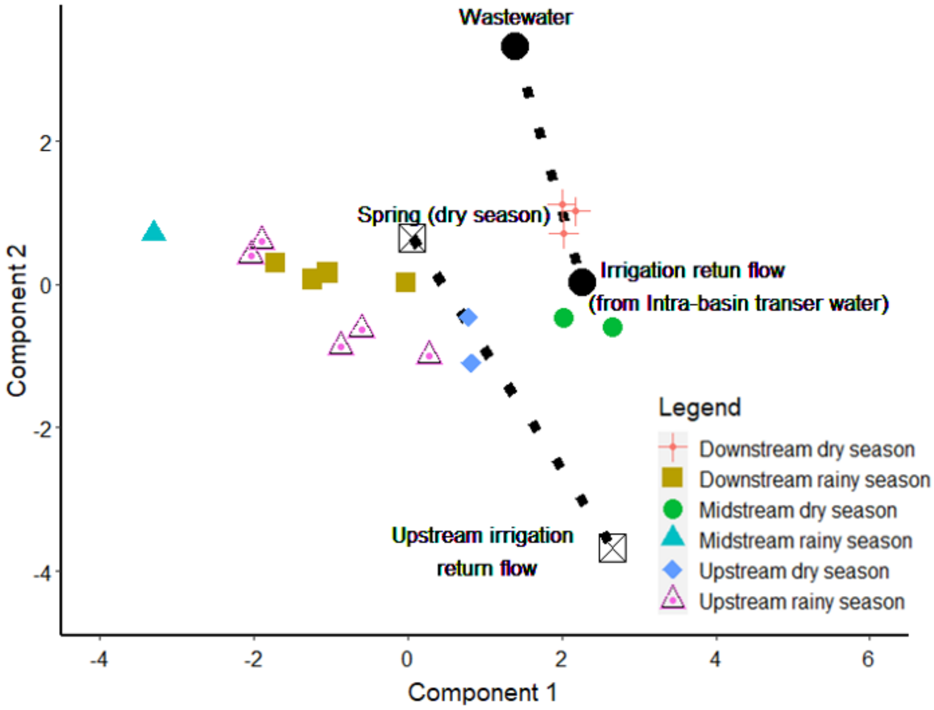

Figure 4: End member mixing diagrams for dry season flows (straight lines) based on the first two principal components using all the conservative tracers.

3.3 Quantification of mixing ratios for streamflow sources during the rainy season

The mass balance analysis based on the δ ^{18}O and EC tracers revealed that stormwater runoff from non-irrigated areas accounted for 43 ± 13% of the rainy season streamflow, the spring accounted for 39 ± 21%, while stormwater runoff from irrigated areas accounted for 18 ± 17%. The results were similar even when the δ ^{18}O and Cl^{-1} tracer combination was used, which estimated the contribution of stormwater runoff from non-irrigated areas at 48 ± 19%, the spring at 40 ± 18%, and stormwater runoff from irrigated areas at 12 ± 9% of rainy season streamflow.

The mixing diagram in Figure 5 shows that the stormwater runoff from irrigated areas end member plotted further away from the streamflow samples in the δ ^{18}O and EC mixing space. Hence this end member had the lowest contribution to streamflow compared to other endmembers. Additionally, most of the upstream streamflow samples plotted along the 'spring – stormwater runoff from non-irrigated areas' mixing line.

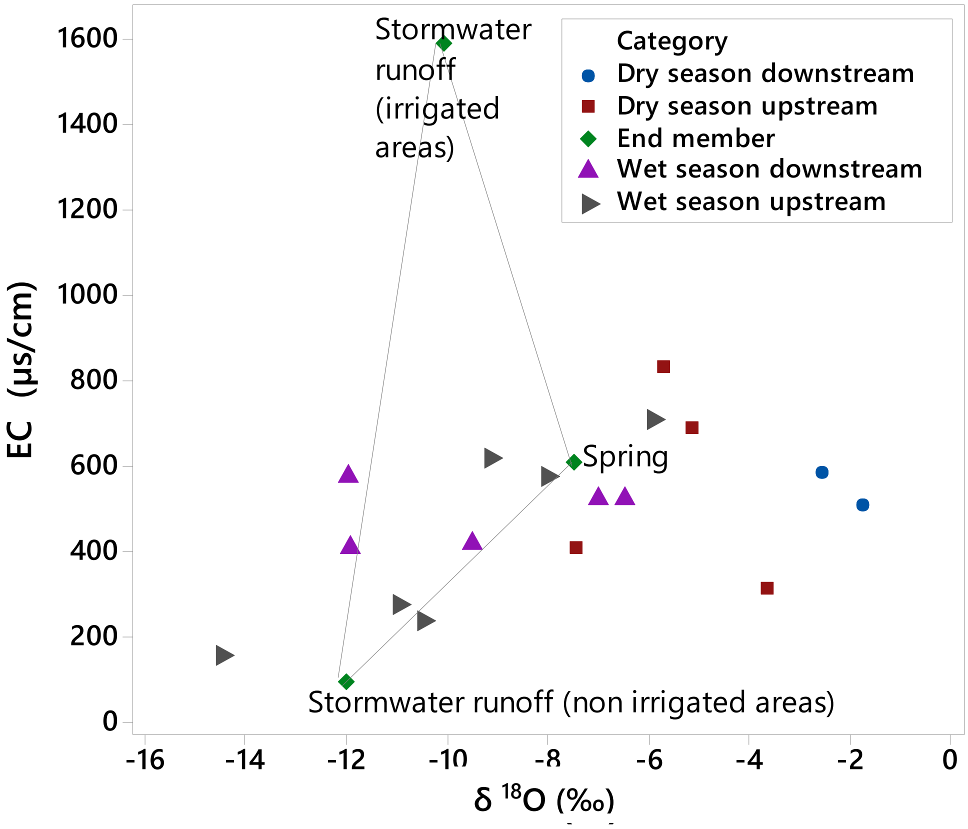

Figure 5: End member mixing diagram for rainy season flows based on the δ ^{18}O versus EC tracers

3.4 Quantification of mixing ratios of streamflow sources in the dry season

Mass balance analysis for the one end member model using EC as a tracer revealed that in the dry season, the spring directly accounted for 65 ± 15% of the upstream river flows, while 35 ± 15% was associated with irrigation return flows. The water from the spring is intercepted by run-on-the river dams in the upper-middle catchment, leaving downstream reaches of the river in the middle-lower catchment dry (Chisola et al., 2020; Sichingabula et al., 2020; WWF, 2018).

The mass balance analysis (based on EC as a tracer) revealed that the downstream dry season flows are accounted for by IBTW irrigation return flows, which contributes about 73 ± 15%, and wastewater, which contributes about 27 ± 15%. The mixing of these end members in the δ ^{18}O versus EC mixing space is indicated by the mixing line in Figure 6. The δ ^{18}O tracer was also tested in the mass balance equation and yielded similar results, albeit with slightly larger uncertainty ranges.

The average discharge in the lower Kaleya River as recorded at Healy's weir (Figure 1) was 0.66 m^3 s^{-1} or 57,100 m^3 day^{-1}. Based on the mixing ratio results for downstream dry season flows, the IBTW irrigation return flow contribution was estimated at about 41,683 ± 8,565 m^3 day^{-1}. The wastewater accounted for about 15,417 ± 8,565 m^3 day $^{-1}$.

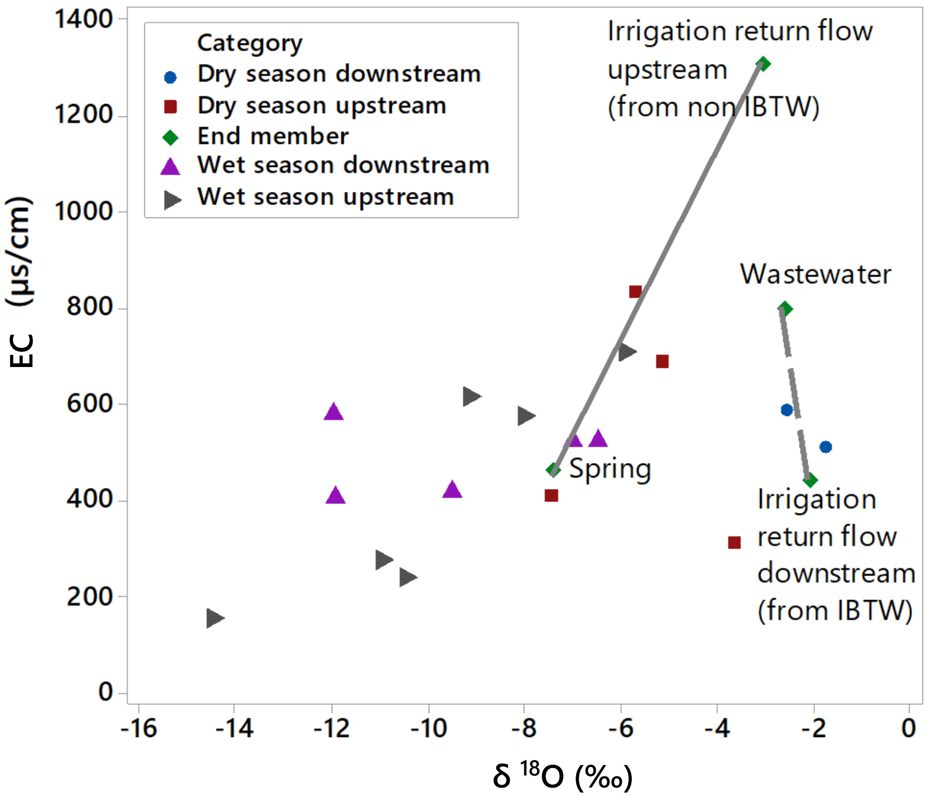

Figure 6: End member mixing diagrams for dry season flows based on the δ ^{18}O versus EC tracers

Due to limited time series data at the catchment outlet and at Healy's estate weir, discharge at the 'Road bridge' gauge station, upstream of Healy's estate weir (Figure 1) was used to illustrate the varying importance of the rainfall (runoff) and agricultural input (irrigation return flow). The results were derived using the recorded discharge data at the 'Road bridge' gauge station and the mixing ratios of end members (from the mass balance analysis) during the study period. Figure 7 shows that the rainfall input was almost the same in magnitude as the irrigation return flow. But the importance of various streamflow sources changed in the rainy and dry season, with rainfall contributing in the rainy season and irrigation return flow in the dry season. Sugarcane irrigation in the area mainly takes place in the dry season, hence there were no irrigation return flows in the rainy season.

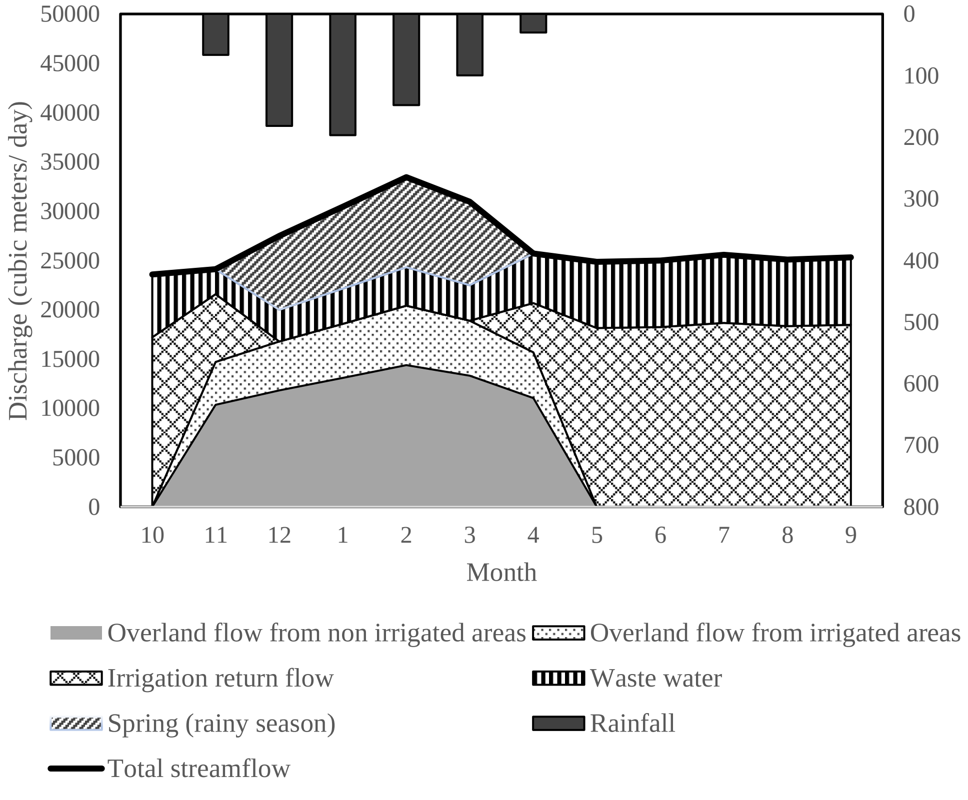

Figure 7: Estimated contribution of streamflow sources to mean monthly flows at Road bridge gauge station in Kaleya Catchment using mixing model analysis

3.5 Inferring the age of water from the spring in the upper catchment

Since the spring was an important source of streamflow upstream in the rainy and dry season, ensuring sustained recharge in the face of environmental change is needed. Hence it was important to gain insights into the age of water coming from the spring using tritium (^{3}H), to infer whether this water is from recent or old recharge. Results revealed that the spring had a ^{3}H value of 1.2 ± 0.3 TU, while the groundwater borehole located 500 m downstream from the spring recorded 0.4 ± 0.2 TU.

Based on Clark and Fritz (1997), water with less than 0.8 TU is considered pre-modern (at least 50 years old), while that with 0.8 - 4 TU could be considered as recent (from rainfall) mixed with old water. Based on this classification, it was determined that water from the spring is a mixture of recent and old recharge, while the groundwater downstream is predominantly old recharge. This was also corroborated by lower EC values for the spring (59.7 mS m^{-1}) compared to the groundwater (72.0) mS m^{-1}). This slightly lower EC for the spring could be due to constant dilution of old water with the relatively new water from rainfall. The results imply that the spring would be affected by climate and land use change effects much earlier than groundwater downstream. Measures are needed to ensure sustained recharge in the face of environmental change.

4 Discussion

4.1 Dominant streamflow sources

Given that most rivers and streams in meso-scale catchments are intermittent and ephemeral, the importance of direct runoff and the spring as natural sources of streamflow observed in this study corroborate those from other semi-arid areas in the southern African region (Camacho et al., 2015; Mokua et al., 2020). The results also highlighted the effects of increased human activities, particularly irrigation intensification, in creating spatial – temporal differences in streamflow sources in the catchment. As such, the spring is no longer an important streamflow source downstream during low flow conditions due to the diminished hydrological connectivity caused by dams on the main river channel in the middle catchment (Chisola et al., 2020; Sichingabula et al., 2020; WWF, 2018).

In the two years of monitoring in this study (2019 – 2020), sampling proved difficult in the middle catchment area as only pools of stagnant water in most parts of the rainy season and dry season could be observed. According to WWF (2018), the dry state of the middle catchment was reported by catchment managers from as far back as 2015. The findings by Chisola et al. (2020) suggest that this dryness started a little earlier than 2015 and could not have been spotted by stakeholders earlier on given that the river continues to flow throughout the year in the upstream and downstream part of the catchment.

From inception, the large-scale sugarcane estates in the lower Kaleya River Catchment have irrigated using IBTW from Kafue River. The study revealed that it is the return flows and wastewater from this IBTW that are currently helping to sustain dry season streamflow in the downstream part of the catchment. Although out of the scope of this work, it was observed that these return flows are playing a critical role both socio-economically and ecologically. Socio-economically, the return flows are sustaining local livelihoods along the lower Kaleya by supporting gardening and other income generating activities. Ecologically, they provide an ecological flow, which often tends to be difficult to secure in meso-scale arid and semi-arid areas in the face of increasing water demand and climate change (Qureshi et al., 2010).

4.2 Implications for management

In most IBTW schemes, water is delivered directly to the recipient river or reservoir on the recipient river (Purvis and Dinar, 2020; Snaddon, 1998). The unique characteristic of the Kaleya scheme is that it is the private commercial irrigators in the catchment who hold the permits (allocation) for IBTW instead of the catchment itself. As such, intra-basin transfer water is delivered to the sugarcane fields rather than directly to the Kaleya River. Any excess water from the irrigation activity ends up in the lower Kaleya River. Where water is not pumped directly to the recipient river, it is the sewer effluents forms of IBTW that have been reported to sustain dry season flows (Gupta and van der Zaag, 2008; Snaddon, 1998). In this regard, the findings on the important role played by the irrigation return flow associated with ‘indirect’ IBTW adds to the scholarly literature.

Over and above the socio-economic, and ecological importance, return flows associated with ‘indirect’ IBTW are often neglected in integrated water resources management, especially in meso-scale semi-arid catchments where they could be more critical. Apart from water quality concerns, return flows tend to be viewed as mere water losses, yet this is only true at field scale and may not apply at catchment scale. In this case, irrigation return flows are neither a loss at a recipient catchment scale (Kaleya) nor are they losses at the donor catchment scale (Kafue) as the Kaleya discharges back into the Kafue upstream of the IBTW pump station (Figure 1).

Therefore, strategies for improved water use efficiency at field application scale must be well conceived to avoid creating more negative externalities on the recipient Kaleya River Catchment. The negative externalities that could ensue include, accumulation of pollutants in the water, and/or the use of the ‘saved’ water for expansion of irrigated area or growing of other crops that consume a lot of water

(Berbel et al., 2018; Scott et al., 2014). Additionally, results have shown that if not well-planned, increasing irrigation system efficiency could result into the drying of the lower Kaleya River as well. This would have further negative consequences on the downstream users and the riverine environment. Since these enjoy priority of water allocation compared to commercial uses as espoused in the Zambian water policy and the Water Resources Management, Act No.21 of 2011 (GRZ, 2011), negative externalities need to be minimised in the interest of all.

This paper argues that there is need to improve irrigation system efficiency, but also ensure that any water ‘saved’ is not used for activities that ignore the downstream and ecosystem benefits of return flows. The ‘saved’ water from IBTW could be allowed to bypass irrigation and go straight to clean the environment and provide an environmental flow. Some of this water would still end up into the ‘donor’ Kafue River downstream, where it could get more diluted and re-transferred into the Kaleya through the existing IBTW, hence recycling. Even in the current state, some of the IBTW already bypasses irrigation, but this is unintended as it is through leakages and overflow from the irrigation systems (storage reservoirs). Hence, a more effective system where flow releases are planned and controlled is proposed. This could also benefit the sugarcane estates that are often under pressure from various stakeholders and regulators of water pollution and environmental degradation (German et al., 2020).

The pumping costs could be offset using funds sets aside for corporate social responsibility and environmental management given the current importance of return flows to downstream local communities and the aquatic ecosystem. Alternatively, water markets to buy off the ‘saved’ water after improving irrigation efficiency could be explored by government and stakeholders to support the continued delivery of the IBTW. Water market based initiatives are capable of addressing the current water scarcity challenges in southern Africa amid increasing and competing water demands (Matchaya et al., 2019). Elsewhere, studies have shown that such interventions can help obtain return flows for downstream uses from irrigators while promoting increased irrigation system efficiency (Grafton and Wheeler, 2018; Qureshi et al., 2010; Schwabe et al., 2020; Williams and Grafton, 2019).

For the upper catchment, ensuring sustained recharge to the perennial spring is the most sustainable way of keeping water in the catchment during the rainy season when there is surplus, for use in the dry season when there is a scarcity. This could be achieved through assisted natural regeneration of forests and other soil and water conservation practices (Chisola et al., 2020). The dams on the main river channel have impaired the downstream streamflow regime and ecology as indicated by the findings on the lack of flows in the middle catchment, and failure by the spring to contribute to downstream flows in the dry periods. These dams are also inefficient in conserving water since they are prone to siltation and high evaporation rates (Sichingabula, 1997; Sichingabula et al., 2015; Sichingabula et al., 2000; Walling et al., 2001). However, rather than demolish the dams as dictated by the public discourse in the area, a better option could be to construct minimum flow bypasses to always divert some flows downstream (Habets et al., 2018). This can also help to replace some of the irrigation return flows in lower Kaleya so that irrigation efficiency can be improved in the catchment.

4.5 Study limitations and future studies in the catchment

A more detailed study on groundwater, particularly the recharge dynamics, is recommended as only tritium, sampled over a short period was used in this study. Despite this, the results are suggestive of the important processes, allowing for the formulation of hypotheses upon which future studies could build. Thus, it is hypothesised here that the recharge zone for the spring could be the Siamakambo hills that are within 1 - 2 km upstream the spring. Given the karst environment observed in the area, water could be coming out to the surface through fractures/sink hole. The geological formation around the boreholes further downstream may not be the same as for the spring, hence the observed differences in ^{3}H.

In addition to the officially known spring (Kaleya source), there were other areas within the upper catchment where water was observed to come out of the subsurface to contribute to streamflow. This was partly tested from the point of view of irrigation return flows via the subsurface in the irrigated area upstream. But given that some streamflow samples fell outside the mixing spaces of the identified end members, it is highly likely that the subsurface discharges from the karst environment are vaster than earlier thought and are recommended for more intensive sampling in future studies. Thus, a more detailed assessment of the geology and subsurface flow pathways in the upper catchment, incorporating tracer-based techniques and groundwater modelling is thus recommended.

5 Conclusion

Tracer-based techniques proved useful in filling the gap of inadequate hydrological monitoring data towards improving water allocation decisions in a rapidly fragmenting landscape facing agricultural intensification. Based on the combination of EMMA and mixing model analysis, the major streamflow sources were found to reflect a strong human signal in time and space. Stormwater runoff and discharge from the spring were the important streamflow sources in the rainy season. In the absence of rainfall input in the dry season, the dams on the main river channel prevented the water from the spring higher up the catchment from reaching the lower Kaleya River. The downstream dry season flows were thus sustained by irrigation return flow and wastewater both associated with intra-basin transfer water. The results indicate that there is a need to improve hydrological connectivity and ensure that irrigation efficiency is improved in a way that will still maintain the downstream flows.

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Disclosure statement

We do not declare any potential conflict of interest.

References

Abiye, T., Mengistu, H., Masindi, K., Demlie, M., 2015. Surface water and groundwater interaction in the upper Crocodile River Basin, Johannesburg, South Africa: Environmental isotope approach. South African Journal of Geology 118, 109-118.

Akayombokwa, I., van Koppen, B., Matete, M., 2017. Trends and outlook: Agricultural water management in Southern Africa. Country Report Zambia. Colombo, Sri Lanka:

Southern Africa Regional Program of the International Water Management Institute (IWMI). Accessed on 15.

Alsterhag, E., Petersson, L., 2004. Nutrient loading in the Kafue River between Mazabuka and Kafue Town, Zambia. Uppsala University.

Baumle, R., Nkhoma, J., Silembo, O., Neukum, C., 2007. Groundwater Resources for Southern Province. Brief Description of Physiography, Climate, Hydrology, Geology and Groundwater Systems of the Southern Province.

Belemtougri, A.P., Ducharne, A., Tazen, F., Oudin, L., Karambiri, H., 2021. Understanding key factors controlling the duration of river flow intermittency: Case of Burkina Faso in West Africa. Journal of Hydrology: Regional Studies 37, 100908.

Berbel, J., Gutiérrez-Martín, C., Expósito, A., 2018. Impacts of irrigation efficiency improvement on water use, water consumption and response to water price at field level. Agricultural Water Management 203, 423-429.

Camacho, S.V., Saraiva, O.A., Wenninger, J., Uhlenbrook, S., 2015. Understanding runoff processes in a semi-arid environment through isotope and hydrochemical hydrograph separations. Hydrology and Earth System Sciences 19, 4183-4199.

Carrera, J., Vázquez-Suñé, E., Castillo, O., Sánchez-Vila, X., 2004. A methodology to compute mixing ratios with uncertain end-members. Water resources research 40.

Chisola, M.N., van der Laan, M., Bristow, K.L., 2020. A landscape hydrology approach to inform sustainable water resource management under a changing environment. A case study for the Kaleya River Catchment, Zambia. Journal of Hydrology: Regional Studies 32, 100762.

Christophersen, N., Hooper, R.P., 1992. Multivariate analysis of stream water chemical data: The use of principal components analysis for the end-member mixing problem. Water Resources Research 28, 99-107.

Christophersen, N., Neal, C., Hooper, R.P., Vogt, R.D., Andersen, S., 1990. Modelling streamwater chemistry as a mixture of soilwater end-members. A step towards second-generation acidification models. Journal of Hydrology(Amsterdam) 116, 307-320.

Clark, I.D., Fritz, P., 1997. Environmental isotopes in hydrogeology. CRC press.

Correa, A., Windhorst, D., Tetzlaff, D., Crespo, P., Célleri, R., Feyen, J., Breuer, L., 2017. Temporal dynamics in dominant runoff sources and flow paths in the A ndean P áramo. Water Resources Research 53, 5998-6017.

Dumont, A., Mayor, B., López-Gunn, E., 2013. Is the rebound effect or Jevons paradox a useful concept for better management of water resources? Insights from the irrigation modernisation process in Spain. Aquatic procedia 1, 64-76.

Fovet, O., Belemtougri, A., Boithias, L., Braud, I., Charlier, J.b., Cottet, M., Daudin, K., Dramais, G., Ducharne, A., Folton, N., 2021. Intermittent rivers and ephemeral streams: Perspectives for critical zone science and research on socio-ecosystems. Wiley Interdisciplinary Reviews: Water 8, e1523.

German, L.A., Hepinstall-Cymerman, J., Biggs, T., Parker, L., Salinas, M., 2020. The environmental effects of sugarcane expansion: A case study of changes in land and water use in southern Africa. Applied Geography 121, 102240.

Grafton, R.Q., Wheeler, S.A., 2018. Economics of water recovery in the Murray-Darling Basin, Australia. Annual Review of Resource Economics 10, 487-510.

GRZ, 2011. Government Republic of Zambia (GRZ), The Water Resources Management Act. No 21 of 2011 15th April, 2011 ed. Government Republic of Zambia (GRZ), Lusaka, Zambia, p. 114.

Gupta, J., van der Zaag, P., 2008. Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock. Physics and Chemistry of the Earth, Parts A/B/C 33, 28-40.

Habets, F., Molénat, J., Carluer, N., Douez, O., Leenhardt, D., 2018. The cumulative impacts of small reservoirs on hydrology: A review. Science of The Total Environment 643, 850-867.

Hooper, R.P., 2003. Diagnostic tools for mixing models of stream water chemistry. Water Resources Research 39.

Hooper, R.P., 2015. End Member Mixing Analysis.

Hooper, R.P., Christophersen, N., Peters, N.E., 1990. Modelling streamwater chemistry as a mixture of soilwater end-members—An application to the Panola Mountain catchment, Georgia, USA. Journal of Hydrology 116, 321-343.

James, A.L., Roulet, N.T., 2006. Investigating the applicability of end-member mixing analysis (EMMA) across scale: A study of eight small, nested catchments in a temperate forested watershed. Water Resources Research 42.

Kattan, Z., 2008. Estimation of evaporation and irrigation return flow in arid zones using stable isotope ratios and chloride mass-balance analysis: Case of the Euphrates River, Syria. Journal of Arid Environments 72, 730-747.

Koeniger, P., Hamutoko, J., Post, V.E.A., Beyer, M., Gaj, M., Himmelsbach, T., Wanke, H., 2020. Evaporation loss along the Calueque-Oshakati Canal in the Cuvelai-Etosha Basin (Northern Namibia): evidence from stable isotopes and hydrochemistry. Isotopes in Environmental and Health Studies, 1-14.

Loch, A., Adamson, D., 2015. Drought and the rebound effect: a Murray–Darling Basin example. Natural Hazards 79, 1429-1449.

Magand, C., Alves, M.H., Calleja, E., Datry, T., Dörflinger, G., England, J., Gallart, F., Gómez, R., Jorda-Capdevila, D., Martí, E., 2020. Intermittent rivers and ephemeral streams: what water managers need to know. Technical report – Cost ACTION CA 15113.

Matchaya, G., Nhamo, L., Nhlengethwa, S., Nhemachena, C., 2019. An Overview of Water Markets in Southern Africa: An Option for Water Management in Times of Scarcity. Water 11, 1006.

Mokua, R.A., Glenday, J., Nel, J., Butler, M., 2020. Combined use of stable isotopes and hydrochemical characteristics to determine streamflow sources in the Jonkershoek catchment, South Africa. Isotopes in Environmental and Health Studies 56, 238-259.

Nhemachena, C., Nhamo, L., Matchaya, G., Nhemachena, C.R., Muchara, B., Karuaihe, S.T., Mpandeli, S., 2020. Climate Change Impacts on Water and Agriculture Sectors in Southern Africa: Threats and Opportunities for Sustainable Development. Water 12, 2673.

Pelizardi, F., Bea, S.A., Carrera, J., Vives, L., 2017. Identifying geochemical processes using End Member Mixing Analysis to decouple chemical components for mixing ratio calculations. Journal of Hydrology 550, 144-156.

Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage 56, 367-378.

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. Agricultural Water Management 96, 1517-1524.

Phillips, D.L., Gregg, J.W., 2001. Uncertainty in source partitioning using stable isotopes. Oecologia 127, 171-179.

Purvis, L., Dinar, A., 2020. Are intra-and inter-basin water transfers a sustainable policy intervention for addressing water scarcity? Water Security 9, 100058.

Qureshi, M., Schwabe, K., Connor, J., Kirby, M., 2010. Environmental water incentive policy and return flows. Water Resources Research 46.

Schwabe, K., Nemati, M., Landry, C., Zimmerman, G., 2020. Water Markets in the Western United States: Trends and Opportunities. Water 12, 233.

Scott, C.A., Vicuña, S., Blanco-Gutiérrez, I., Meza, F., Varela-Ortega, C., 2014. Irrigation efficiency and water-policy implications for river basin resilience. Hydrol. Earth Syst. Sci. 18, 1339-1348.

Sichingabula, H.M., 1997. Problems of sedimentation in small dams in Zambia. IAHS Publication 245, 251-259.

Sichingabula, H.M., Chisola, M., Nyambe, I., Phiri, W., Kabika, J., Muchanga, M., Chomba, I., Sikazwe, H., Chinonge, M., 2015. Water Resources Management in Kaleya River Basin and Beyond, Consultative Stakeholders' Workshop on Water Resources Management, Held from 10-11th November, 2015 at Muko Lodge, Mazabuka Town, Zambia.

Sichingabula, H.M., Nyirenda, E., Banda, K.E., Lehner, B., 2020. Hydro-environmental documentation of selected candidate sites for gazetting of Water Resource Protection Areas (WRPAs) in Zambia. Report prepared for WWF-Zambia, Lusaka.

Sichingabula, H.M., Walling, D.E., Collins, A.L., 2000. Dynamics of Erosion, Sediment Transport and Sediment in Small Catchments. Proceedings of the International workshop on Dynamics, Erosion, Sediment Transport and Sedimentation in Small Catchments, River Motel, Kafue, Zambia, 5-6th July 2000. Zambia Education Publishing House, Lusaka, 165.

Sklash, M., Farvolden, R., Fritz, P., 1976. A conceptual model of watershed response to rainfall, developed through the use of oxygen-18 as a natural tracer. Canadian Journal of Earth Sciences 13, 271-283.

Snaddon, C.D., 1998. Some of the ecological effects of a small inter-basin water transfer on the receiving reaches of the upper Berg River, Western Cape. University of Cape Town.

Uhlenbrook, S., Roser, S., Tilch, N., 2004. Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. Journal of Hydrology 291, 278-296.

Walling, D., Collins, A., Sichingabula, H., Leeks, G., 2001. Integrated assessment of catchment suspended sediment budgets: A Zambian example.

Williams, J., Grafton, R.Q., 2019. Missing in action: possible effects of water recovery on stream and river flows in the Murray–Darling Basin, Australia. Australasian Journal of Water Resources 23, 78-87.

WWF, 2018. Integrated Flow Assessment for the Kafue River. Phase 1:Water Resources Developments. WWF Zambia, Lusaka, Zambia.