



Focused groundwater recharge in a tropical dryland: Empirical evidence from central, semi-arid Tanzania

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ABSTRACT

Study region: Little Kinyasungwe Catchment within the River Wami Basin of central, semi-arid Tanzania.

Study focus: Groundwater and its replenishment via recharge are critical to sustaining livelihoods and poverty alleviation in tropical drylands yet the processes by which groundwater is replenished remain inadequately observed and resolved. Detailed observations are examined from central Tanzania, where the Makutupora Wellfield supplies freshwater to the rapidly growing, capital city of Dodoma.

New hydrological insights for the region: The prominence of focused recharge from ephemeral stream discharges is shown from: (1) groundwater recharge correlates more strongly with the seasonal duration of ephemeral stream stage exceeding a threshold than seasonal rainfall; (2) hourly monitoring of groundwater-levels and stream stage shows that sustained groundwater-level rises, indicative of groundwater recharge, correspond better to observed pulses of stream discharge from intensive rainfall observed upstream of the wellfield than rainfall recorded proximate to piezometers; and (3) stable isotope ratios of O and H indicate similar compositions of groundwater and ephemeral streamflow; both have undergone evaporative enrichment and are linked to intensive (90th percentile) daily rainfall. This characterisation of focused groundwater recharge from intensive rainfall in this tropical dryland highlights the potential resilience of groundwater resources to climate change amplifying precipitation extremes and informs strategies to augment replenishment of groundwater supplying the city of Dodoma.

1. Introduction

African climate is characterised by erratic precipitation (UNEP, 2010), which is markedly variable at intra-annual (Peel et al., 2001), annual (Nicholson, 1998), and decadal to millennial (Nicholson, 2000; Olago et al., 2009) timescales. Regionally, tropical

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Africa has the world's most variable surface water discharges (McMahon et al., 2007) and lowest per capita reservoir storage (White et al., 2010). From rural areas to large cities, groundwater is often the only viable, perennial source of water (Gaye and Tindimugaya, 2019; Murray et al., 2018; Pavelic, 2012) because of its widespread distribution (Shiklomanov and Rodda, 2004) and relative resilience to climate variability (Calow et al., 2010; Cuthbert et al., 2019; Olago et al., 2009). Groundwater supports livelihoods and poverty alleviation throughout sub-Saharan Africa (Braune and Xu, 2010; Cobbing and Hiller, 2019; Gaye and Tindimugaya, 2019), particularly in semi-arid regions (Xu and Beekman, 2019) where surface water resources are intermittent and non-linearly related to precipitation (De Wit and Stankiewicz, 2006). Groundwater use is increasing in rural (Carter et al., 2017) and especially in urban areas (Grönwall, 2016; Okotto et al., 2015; Thompson et al., 2000). These trends are anticipated to continue due to population growth (UN, 2017), urbanisation (UN, 2014), increased agricultural use (Carter and Parker, 2009; Villholth, 2013), changes to agricultural activity

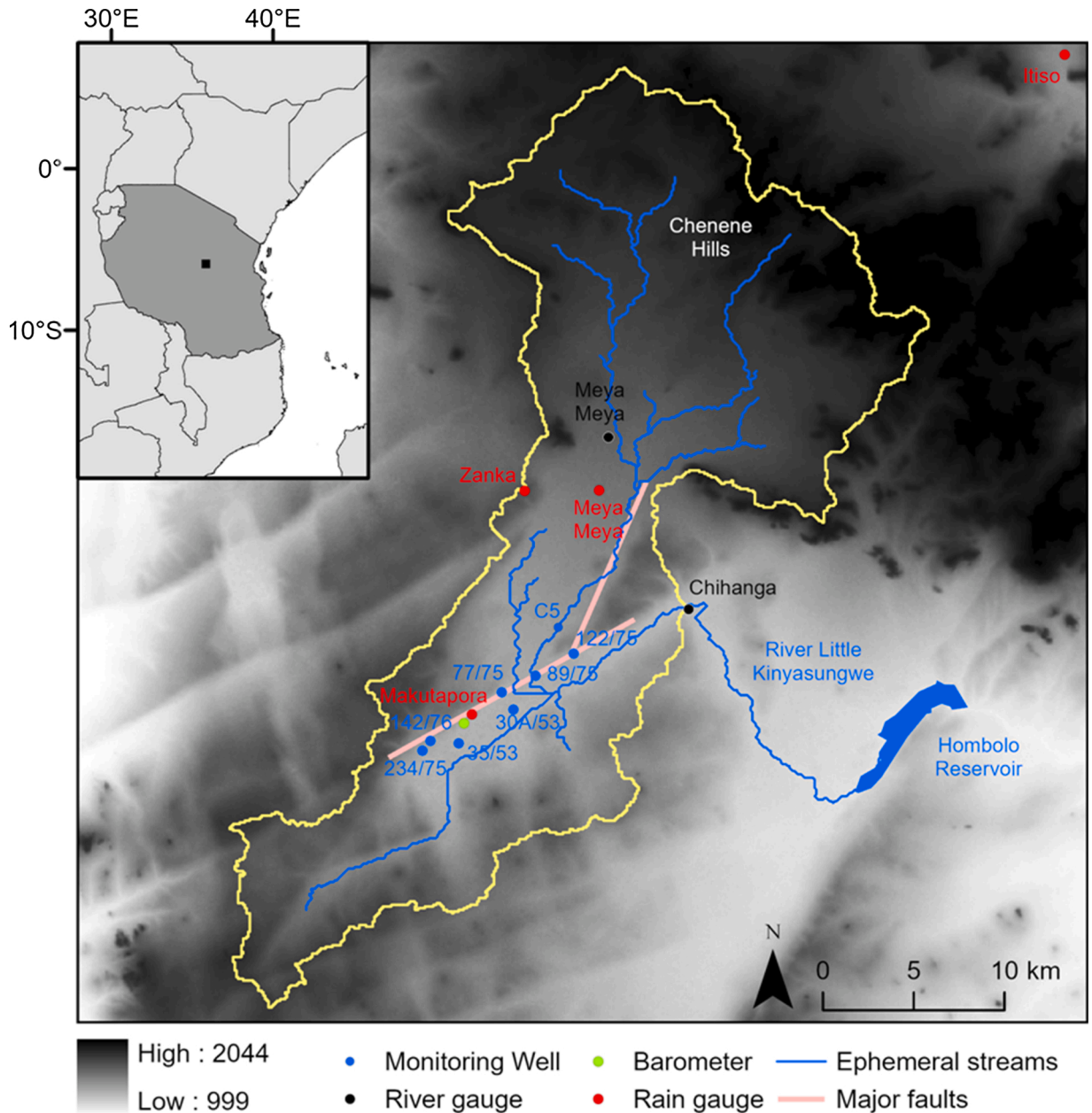


Fig. 1. Inset – location of the Little Kinyasungwe Catchment in East Africa. Main - Map of the Little Kinyasungwe Catchment delineated using NASA Shuttle Radar Topography Mission (SRTM) data (90 m resolution) with ArcSWAT. Location of surface water, comprising the ephemeral River Little Kinyasungwe and its main tributaries, and the perennial Hombolo Reservoir. Locations of major faults in the Little Kinyasungwe Catchment are also shown. Locations of high-resolution groundwater monitoring wells (blue dots: 89/75, 122/75, C5), rain gauges (red dots), barometric pressure datalogger (green dot), and the Meya Meya and Chihanga stream gauges (black dots).

(MacDonald et al., 2013), and climate change (Niang et al., 2014).

Africa is endowed with substantial groundwater storage (MacDonald et al., 2012). The sustainable use and optimal management of groundwater require knowledge of long-term groundwater recharge and discharge rates, and potential changes to these rates due to climate change and freshwater withdrawals. Understanding this balance and how it may change are predicated on knowledge of the mechanisms by which meteoric water replenishes aquifers as well as the conditions and pathways which generate groundwater recharge. Current understanding of groundwater recharge processes in semi-arid areas is constrained by a lack of observational data. Recent continental to global scale analyses (MacDonald et al., 2021; Moeck et al., 2020; Mohan et al., 2018) have highlighted broad associations between groundwater recharge and both climate and land-cover characteristics but little insight to the processes that transmit precipitation to groundwater systems (Jasechko and Taylor, 2015; MacDonald et al., 2021). Knowledge gaps are most acute in drylands (Cuthbert et al., 2019; Somaratne and Smettem, 2014).

Groundwater recharge can broadly be considered to derive from processes that are *diffuse*, taking place throughout a landscape from the direct or near-direct infiltration of precipitation, or *focused*, occurring from the leakage of ephemeral or perennial surface water at specific locations such as a drainage channel or depression within a landscape. Diffuse and focused recharge processes occur in most groundwater systems; the prevalence of focused recharge is generally considered to increase with aridity (Alley, 2009; Cuthbert et al., 2019). Limited research has shown groundwater recharge in semi-arid areas commonly occurs via leakage from ephemeral streams (Acworth et al., 2021; Cuthbert et al., 2016; Dahan et al., 2008; Villeneuve et al., 2015) or ponds (Favreau et al., 2009). However, studies throughout tropical Africa have shown considerable variation in predominant groundwater recharge processes (Carter and Alkali, 1996; Favreau et al., 2009; Faye et al., 2019; Goni et al., 2021). This variation is attributed to the wide range of geological, climatological and terrestrial environments (Cuthbert et al., 2019; Scanlon et al., 2006; Taylor et al., 2013a) that characterise this region.

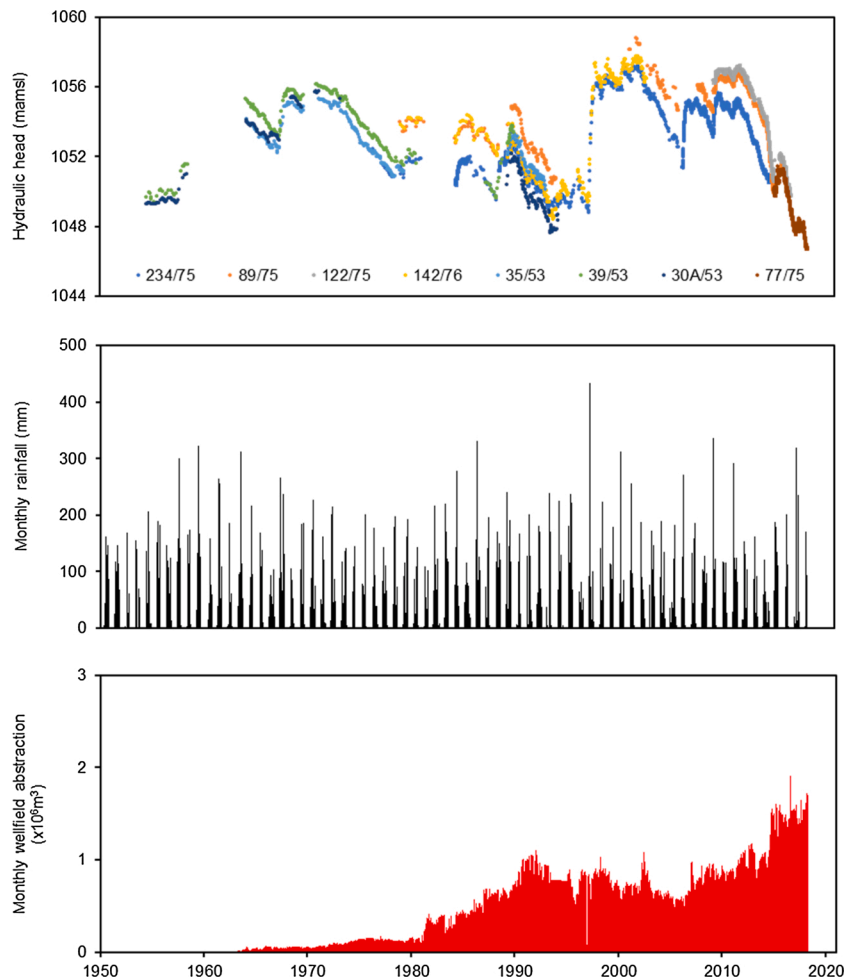


Fig. 2. 63-year observational record of groundwater-levels, rainfall and groundwater abstraction from the Makutapora Wellfield in Little Kinyasungwe Catchment of central Tanzania: (a) time series of groundwater-level observations from 8 monitoring wells (Fig. 1); (b) monthly rainfall at Dodoma Airport ($6^{\circ}10.182'S$, $35^{\circ}44.964'E$), ~ 25 km south of Makutapora (Fig. 1); and (c) monthly groundwater abstraction recorded at the Makutapora Pump House from 1954 to 2017.

The Makutapora Wellfield within the Little Kinyasungwe Catchment of central Tanzania (Fig. 1) features one of the longest near-continuous time series of groundwater-level observation in tropical Africa (Fig. 2). The record is characterised by episodic groundwater-level rises that interrupt multiannual recessionary trends whose magnitude has increased in response to sustained rises in wellfield abstraction. Perceptions regarding the predominant process by which groundwater recharge to the Makutapora Wellfield occurs have changed over time. Groundwater recharge was initially considered to be primarily diffuse (Nkotagu, 1996a; Shindo et al., 1989) with soil macropores transmitting the majority of infiltrating water through the unsaturated zone (Shindo et al., 1989). More recently, Taylor et al. (2013b) hypothesised that focused recharge via leakage from ephemeral streams features centrally in highly episodic recharge events often associated with extreme seasonal rainfall during El Niño events (e.g. 1997/1998); this latter assertion has, however, remained untested by limitations in observational datasets. Here, we seek to examine the processes by which heavy rainfall generates groundwater recharge. This analysis examines: (1) statistical relationships between groundwater recharge and both daily records of rainfall and ephemeral stream stage over hydrological years (i.e., 1st October to 30th September) from 2006/2007 to 2016/2017; (2) temporal relationships between hourly observations of groundwater-levels and stream stage together with daily rainfall from 2015/2016 to 2017/2018; and (3) associations among stable-isotope ratios of O and H in rainfall, surface waters, and groundwater. High-frequency monitoring of groundwater-levels and stream stage was initiated in advance of the 2015/2016 wet season as it was predicted to coincide with one of the strongest El Niño events on record.

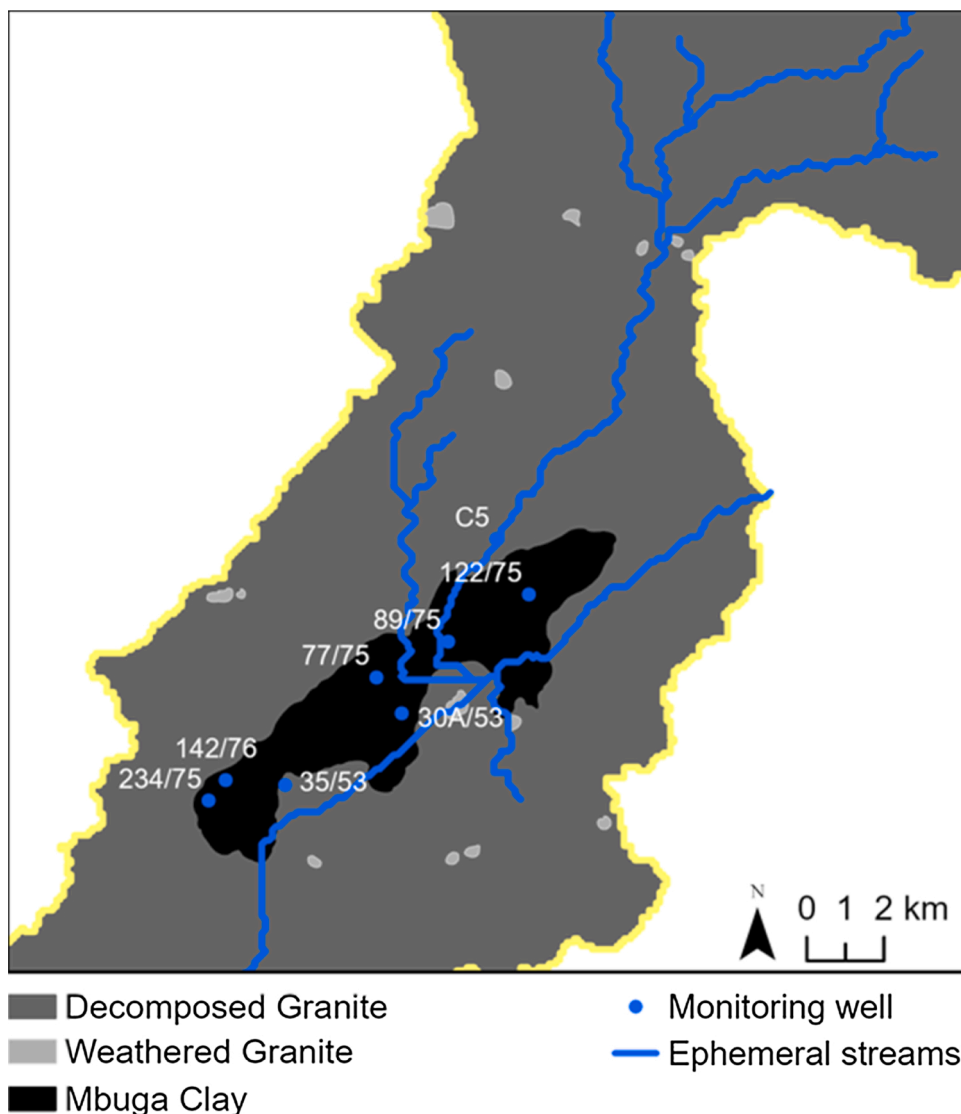


Fig. 3. Simplified map of surface geology in the Little Kinyasungwe Catchment, after Geological Survey of Tanganyika quarter degree sheet 143 (GST, 1953); locations of monitoring wells are also indicated.

2. Study area

The Makutapora Wellfield and Little Kinyasungwe Catchment are located on the East African Plateau of central Tanzania. They are located at the southern end of the Eastern branch of the East African Rift System (EARS), approximately 20 km north of Tanzania's capital city, Dodoma (Fig. 1). Surface drainage occupies an area of 698 km² upstream of the Chihanga stream gauge, the outlet of the River Little Kinyasungwe. Tectonic activity associated with the EARS has strongly influenced the basin and surrounding areas. Linear drainage features including lakes, rivers and swamps generally trend NE-SW and NW-SE and reflect extensive, tectonically induced faulting (Nkotagu, 1996a). Major lineaments include the Mlemu and Kitope faults, which follow a NE-SW trend (Fig. 1).

The Makutapora Wellfield experiences a 'hot semi-arid' climate that is characterised by distinct wet and dry seasons and perennially high temperatures (mean of 27 °C from in situ observations: 2017–2019). Mean annual rainfall of 527 mm (2006–2018) falls during a unimodal wet season between November and April; mean annual potential evapotranspiration is estimated to be 2120 mm. Lowland land cover is dominated by grassland and dwarf shrubs (Taylor et al., 2013b) whereas catchment uplands are mostly covered by thick shrubland and forest (De Pauw et al., 1983). Agriculture is restricted due to the importance of the wellfield, a nearby military base, and a soil preservation policy (Kangalawe, 2009). There is consequently little evidence of substantial changes in land-use (Taylor et al., 2013b).

Water-bearing formations comprise the regolith and weathered (and fractured) crystalline bedrock of the Dodoma System (Fawley, 1955; Shindo et al., 1989). The crystalline basement comprises migmatite granite and disconnected fragments of older, more basic basement rocks such as amphibolites, schists and gneisses (De Pauw et al., 1983). Younger intrusions are also present in the form of basic and ultrabasic dykes. In the seasonally inundated lowland depression in the vicinity of the wellfield, the regolith is covered by a generally thick (> 10 m) layer of Mbuga clay, a black clay-like deposit (Fawley, 1955) (Fig. 3). This surface clay layer restricts diffuse recharge and promotes ponding of ephemeral stream discharges leading to transmission losses not only to the atmosphere but also conceivably to the subsurface as recharge through slow piston flow or preferential pathways such as vertical fractures (Zarate et al., 2021). Depths to groundwater in the wellfield in range from 25 to 35 m below ground level and are considered largely to reside below the Mbuga clay, though locally confining conditions can occur (Seddon, 2019). Further details of the layering and geometry of the superficial geology in this area are outlined by Zarate et al. (2021).

Regolith thickness varies between 50 m and 100 m (Fawley, 1955). Anomalously high transmissivities found in the Makutapora Wellfield are thought to result from enhanced weathering associated with the network of faults present in the saturated zone (Maurice et al., 2019; Taylor et al., 2013b). Pumping tests indicate that transmissivities range from 400 to 4000 m²·d⁻¹ (Maurice et al., 2019), which are greater than typically observed in deeply weathered crystalline rock aquifer systems (Taylor and Howard, 2000; Bianchi et al., 2020). High-yielding wells are proximate to major faults. The wellfield currently comprises 24 production wells (DUWASA, 2017) and is the sole source of the public, piped water supply to Dodoma, the capital city of Tanzania. In 2016, the Makutapora Wellfield supplied water at an average rate of ~50 000 m³ per day to Dodoma. Groundwater abstraction from the wellfield has increased since the resources were first developed in the 1940s.

Drainage within the Little Kinyasungwe Catchment is strongly influenced by faulting (Taylor et al., 2013b; Zarate et al., 2021). There are no perennial streams in the catchment; surface drainage is ephemeral and can vary spatially from year to year. The largest ephemeral stream channel, River Little Kinyasungwe, drains part of the upland catchment and flows in the direction of the major faults into the wellfield (Fig. 1). Surface water exits the catchment at Chihanga and into a controlled reservoir (Hombolo), the closest perennial surface water to the wellfield (Shindo et al., 1989).

3. Data and methods

3.1. Hydrometric observations from 2006/2007 to 2017/2018

Statistical relationships were examined between groundwater recharge, derived from piezometry, and hydrological observations, compiled by the Ministry of Water and Irrigation (Wami/Ruvu Basin Water Board), comprising (1) daily rainfall representing a local source of groundwater recharge in the vicinity of monitoring wells within the Makutapora Wellfield; and (2) daily stream stage at Meya Meya (drainage area: 167 km²) and Chihanga (drainage area: 698 km²) representing a potential source of focused groundwater recharge (Fig. 1). Gauging stations at Meya Meya (upstream of the wellfield) and Chihanga (downstream of the wellfield) were established by Shindo et al. (1989) with daily records available since January 2006 (Fig. 1). Daily precipitation has been recorded at the Makutapora Meteorological Station (elevation: 1081 m above mean sea level (mamsl)), which is proximate to the wellfield in the lowland, since January 2007. Daily precipitation has also been collected at upland rain gauges: Meya Meya (1121 mamsl) and Zanka (1159 mamsl) since June 2008, and Itiso (1103 mamsl) since November 2007 (Fig. 1). Unlike the other 3 rain gauges, Itiso is situated ~10 km outside of the catchment (Fig. 1). Groundwater-levels have been monitored since 1954 at various locations throughout the wellfield (Fig. 2).

The strength of the statistical relationships between groundwater recharge and variables of both local rainfall and stream stage over hydrological years were tested using correlation analyses employing both non-parametric (i.e. Spearman's rank correlation coefficient, r_s ; Kendall tau-b correlation coefficient, τ_b) and parametric (i.e. Pearson correlation coefficient, r) measures. p -values are reported where the statistical significance of correlation coefficients is at a confidence level of 95 % ($p < 0.05$). Two rainfall variables, from both Makutapora Meteorological Station (lowland) and Zanka (upland) rain gauges, were chosen for correlation with corresponding groundwater recharge values: (1) the number of rain days in a hydrological year in which at least 1 mm of rainfall was recorded as the minimum non-zero value in the dataset, and (2) total rainfall over the duration of a hydrological year (mm). Additionally, three

streamflow variables derived from stage data recorded at Meya Meya and one derived from Chihanga data were chosen and comprised: (1) duration of streamflow, the number of days in a hydrological year where stream stage exceeded 0.1 m (i.e., minimum value) at Meya Meya; (2) cumulative stream stage at Meya Meya (i.e., sum of the daily stream stage values over the duration of a hydrological year in m); and (3) duration of streamflow in a hydrological year when stream stage exceeded a threshold determined iteratively (i.e. systematically varying threshold values by 0.01 m) to reach a best-fit linear regression model (0.25 m at Meya Meya, 0.77 m at Chihanga). The rationale for the analysis of variable stage thresholds derived from allied research employing surface geophysics, which suggested potential groundwater recharge pathways in association with overbank flood discharges that access permeable pathways through the regolith to enable rapid groundwater recharge (Zarate et al., 2021).

In the Little Kinyasungwe Catchment, a substantial proportion of the groundwater outflow is the result of groundwater abstraction. Hence, values of groundwater recharge were derived from piezometric data by employing a modified water table fluctuation (WTF) method in which changes in groundwater-levels through time are assumed to result from the balance between recharge and groundwater discharge that accounts for transience in pumped systems (Supplementary Material A). Groundwater recharge is reported in terms of q/S_y values in metres wherein recharge (q) values are normalised to specific yield (S_y) due to uncertainty in S_y .

3.2. High-frequency hydrometric observations from 2015/2016 to 2017/2018

Temporal relationships were examined between hourly observations of groundwater-levels at three locations (C5, 89/75, 122/75), the only monitoring wells for which data were available; hourly stream stage at both Meya Meya and Chihanga, and daily rainfall observed in the vicinity of the monitoring wells, in the lowland, at Makutapora and in upland locations remote from monitoring wells at Zanka, Meya Meya, and Itiso. The purpose of these comparisons was to move beyond simple empirical associations (Section 3.1) and draw insight from high-frequency observations into the hydrological dynamics that generate groundwater recharge. The analysis focused on a series of three groundwater recharge events that are marked by distinct rises in groundwater-levels (Fig. 4); two events (1 st to 16th February and 30th March to 8th April) occur during the 2015/2016 El Niño event and one event (1 st to 20th January 2018) is from the 2017/2018 wet season. Comparisons with rainfall time series and stream stage sought to examine associations between localised rainfall as a potential source of diffuse groundwater recharge and remote upland rainfall generating ephemeral stream discharge as a potential source of focused recharge. Daily records of wellfield abstraction were also considered to evaluate the influence of pumping on observed piezometric responses.

Automated hourly monitoring infrastructure for groundwater-levels, stream stage, and barometric pressure was installed in November 2015 prior to the wet season associated with the 2015/2016 El Niño event. Monitoring wells C5, 89/75 and 122/75 were equipped with unvented InSitu RuggedTROLL 100™ dataloggers and are located 110 m, 200 m, and 1430 m, respectively from the drainage channel of the River Little Kinyasungwe. Details of well screen depths are not available but are expected to occur at depths of 30 m below ground or more within the base of the weathered granite and underlying fractured bedrock. Stream stage was also monitored by suspending InSitu RuggedTROLL 100™ dataloggers inside a 2-inch perforated PVC piping, screened with wire mesh, and

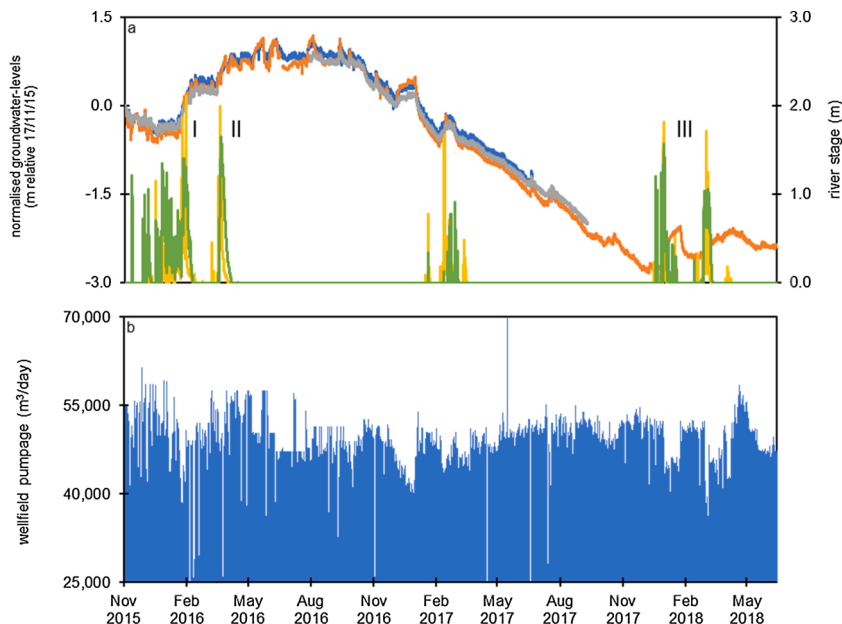


Fig. 4. (a) Hourly groundwater-levels (122/75 - blue, 89/75 - orange, C5 - grey) and stream stage (Meya Meya – yellow, Chihanga –green) together with daily wellfield abstraction from 17th November 2015 to 30th June 2018; specific recharge events I, II, and III examined in Section 4.2 are denoted. Note that recorded wellfield pumpage of 83,439 m³ on 1 June 2017 is disputed by Dodoma Urban Water Supply and Sanitation Authority (DUWASA).

sealed at the top using a torque-locking well plug (Supplementary Information B) allowing water to flow freely through the screened section and base. At each established stream-gauging stations on the River Little Kinyasungwe at Meya Meya and Chihanga, the datalogger was attached to an existing staff gauge and buried beneath the streambed. Groundwater-level data were compensated for variations in atmospheric pressure using data collected on site (Fig. 1).

3.3. Stable-isotope ratios of O and H

The origin of groundwater, sampled from production wells in the Makutapora Wellfield, was investigated using stable-isotope

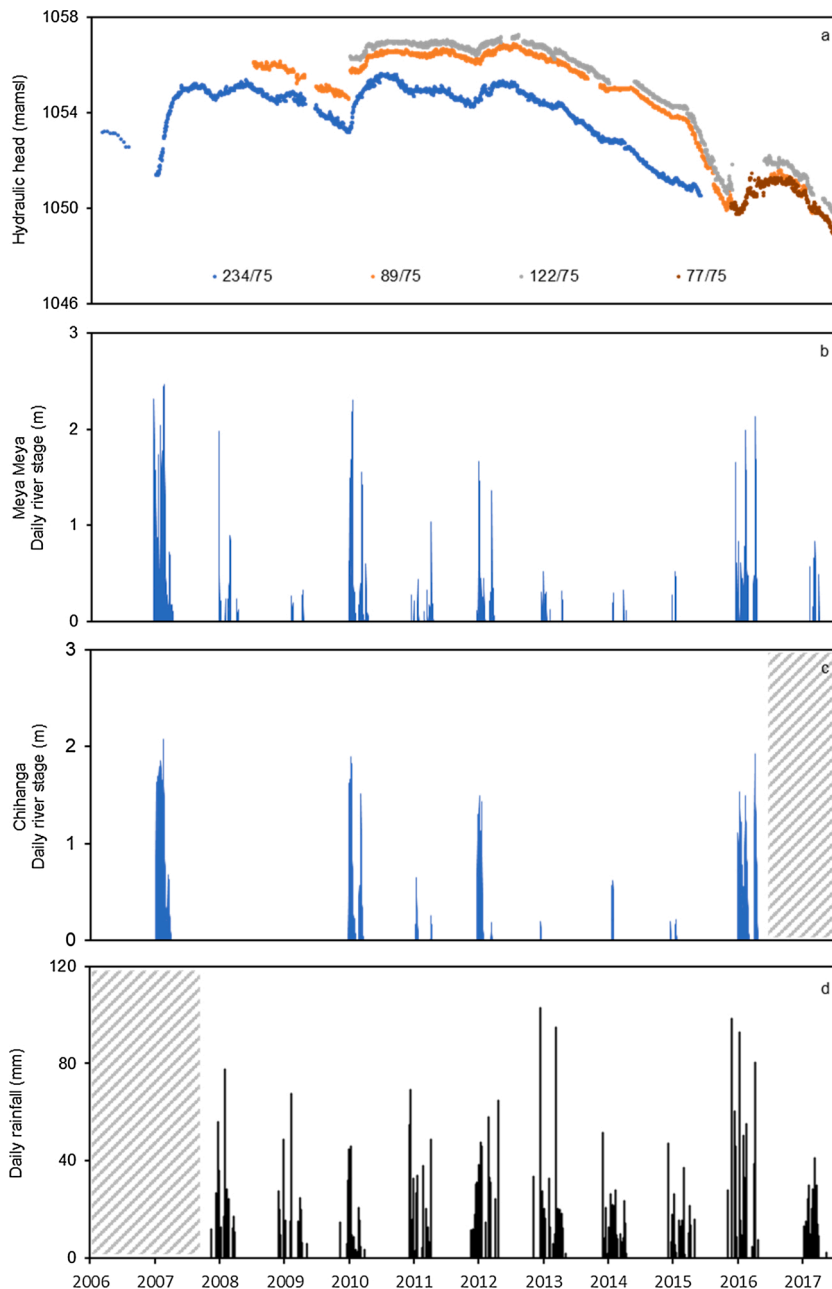


Fig. 5. Observations from July 2006 to June 2017 of: (a) hydraulic head values in metres above mean sea level (mamsl) observed in monitoring wells 234/75, 122/75, 89/75 and 77/75; (b) daily stream stage at the Meya Meya gauge on the River Little Kinyasungwe (drainage area: 167 km²); (c) daily stream stage at the Chihanga gauge on the River Little Kinyasungwe (drainage area: 698 km²); and (d) daily rainfall recorded at the Makutapora Meteorological Station; rainfall data collection commenced on 1 st January 2007 so all rainfall for the 2006/2007 hydrological year have been removed from the plot.

ratios of O and H in precipitation, groundwater, and perennial and ephemeral surface water. Daily rainfall samples ($N = 17$) were collected at the Makutapora Meteorological Station over 3 wet seasons (2015/2016 – 2017/2018) in accordance with IAEA (2014) precipitation sampling guidelines for event-based sampling using a buried sampler. The analysis of stable-isotope ratios of O ($^{18}\text{O}:^{16}\text{O}$) and H ($^2\text{H}:^1\text{H}$) was undertaken using a Los Gatos LGR100 water isotope analyser by Element Limited (Callington, UK). Supplementary data from the late 1980s and early 1990s for precipitation ($N = 60$), groundwater ($N = 120$), and perennial and ephemeral surface water ($N = 17$) were compiled from previously published studies (Nkotagu, 1996b; Onodera et al., 1995; Shindo et al., 1990) and the IAEA TWIN database (IAEA/WMO, 2018). Daily precipitation samples conducted through this research and from past studies, were all collected at the Makutapora Meteorological Station. Perennial surface water samples were taken from Lake Hombolo whereas ephemeral surface water samples were collected from River Little Kinyasungwe and River Madihi, the latter is just west of Makutapora Meteorological Station (Shindo et al., 1990). Herein, stable isotope ratios of O and H are described using delta notation ($\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively) in units of per mille (‰) where $\delta = ((R_{\text{sample}}/R_{\text{VSMOW}}) - 1) \cdot 1000$ and R is the ratio of $^{18}\text{O}:^{16}\text{O}$ or $^2\text{H}:^1\text{H}$ in Vienna standard mean ocean water (“VSMOW”) and the sample (“sample”). Reported analytical uncertainty was ± 0.1 ‰ and ± 0.3 ‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively.

The analysis sought to resolve the relationships between groundwater, rainfall, and surface waters on a cross-plot of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ including adherence of groundwater and surface waters to the meteoric water line and the influence of evaporative enrichment. This examination also explicitly traced the intensities of rainfall that generate groundwater recharge and surface waters as stable-isotope ratios in rainfall within the tropics are strongly determined by site-scale precipitation intensities through a process known as the “Amount Effect” (Jasechko and Taylor, 2015; Jasechko, 2019). Due to differences in the upwind distillation of light versus heavy storm clouds, low-intensity rainfalls are relatively enriched in heavy isotopes (^{18}O , ^2H) whereas high-intensity rainfalls are comparatively depleted in heavy isotopes. Comparisons of the amount-weighted mean rainfall composition (i.e., mean is normalised for rainfall amount) with groundwater isotope compositions that record recharge-generating rainfall, can trace rainfall intensities that produce groundwater recharge (Jasechko and Taylor, 2015; Goni et al., 2021).

4. Results

4.1. Hydrometric observations from 2006/2007 to 2016/2017

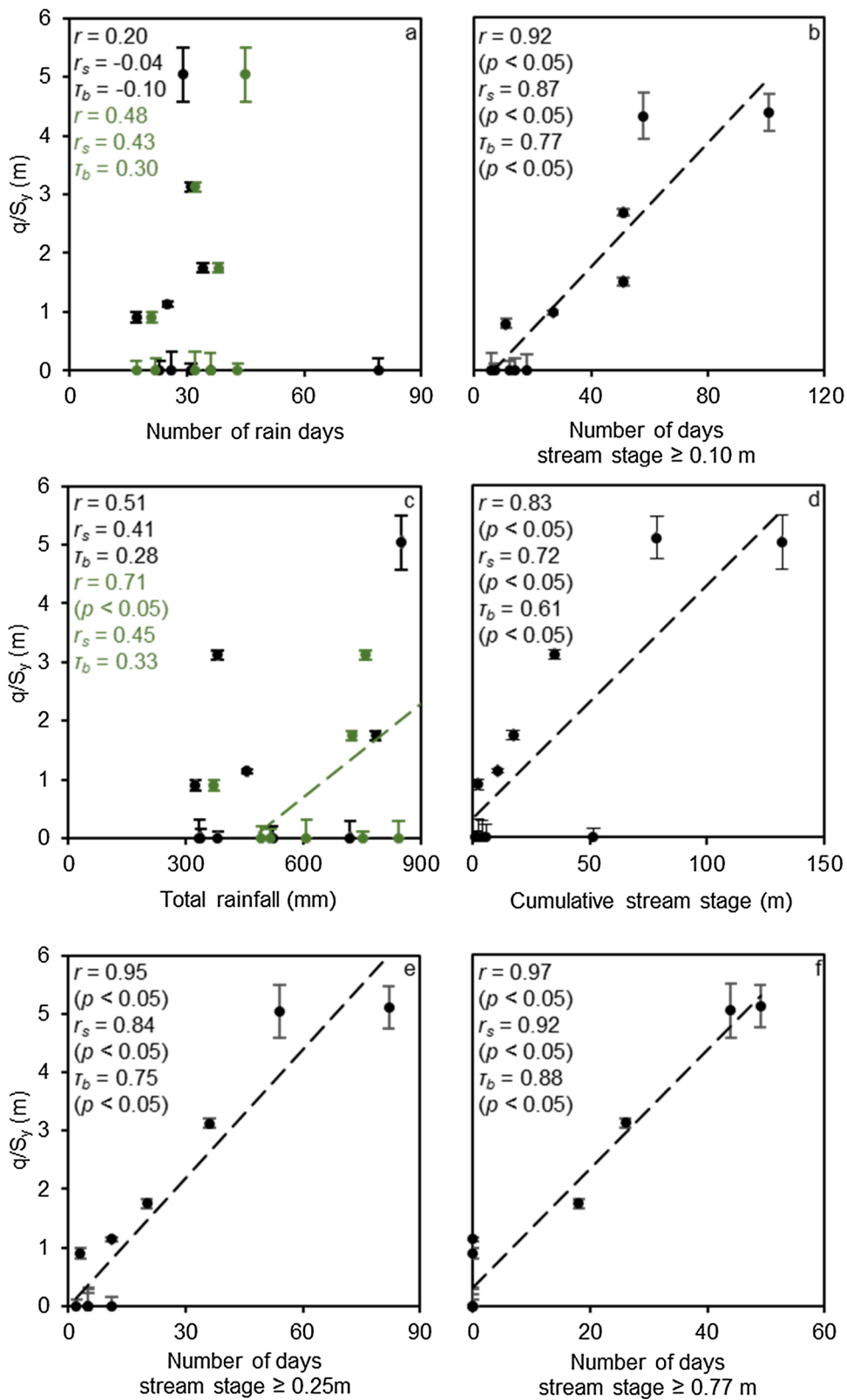
Observations of daily rainfall, stream stage, and groundwater-levels from the Little Kinyasungwe Catchment over the period of 2006–2017 are presented in Fig. 5; groundwater recharge and observed lowland (Makutapora) and upland (Zanka) rainfall for each hydrological year are listed in Table 1. Evident from these time series data are considerable inter-annual variations in rainfall and stream discharge (observed as stream stage). An association between El Niño events (2006/2007, 2009/2010, 2015/2016) and hydrological years exhibiting greater stream discharge and positive deflections in groundwater-levels indicative of groundwater recharge is observable and consistent with earlier analyses (Taylor et al., 2013b).

Relationships between groundwater recharge and a variety of parameters representing lowland (Makutapora) and upland (Zanka) rainfall as well as stream discharge of the River Little Kinyasungwe (Meya Meya, Chihanga) are shown in Fig. 6. The correlation between groundwater recharge and the duration of streamflow (i.e. number of days when stream stage exceeds 0.1 m) is stronger ($r = 0.92$, $p < 0.05$; $r_s = 0.87$, $p < 0.05$; $\tau_b = 0.77$, $p < 0.05$) than the correlation between groundwater recharge and the number of rain days (i.e. number of days when rainfall exceeded 1 mm) at the lowland ($r = 0.20$, $r_s = -0.04$, $\tau_b = -0.10$) and upland rain gauges ($r = 0.48$, $r_s = 0.43$, $\tau_b = 0.30$) (Fig. 4a–b). Further, the correlation between groundwater recharge and cumulative stream stage is stronger ($r = 0.83$, $p < 0.05$; $r_s = 0.72$, $p < 0.05$; $\tau_b = 0.61$, $p < 0.05$) than the correlation between groundwater recharge and total lowland rainfall (i.e., hydrological year) ($r = 0.51$, $r_s = 0.41$, $\tau_b = 0.28$). Relative to lowland rainfall, correlations between both total

Table 1

Rainfall and groundwater recharge recorded from the hydrological years (1st October to 30th September) 2006/2007 to 2016/2017; ground elevations of the rain gauges at Zanka and Makutapora are 1159 and 1081 mamsl, respectively; hydrological years 2006/2007, 2009/2010, and 2015/2016 were El Niño events. Note: quantified groundwater recharge is represented as an equivalent groundwater-level change, normalised with respect to specific yield (S_y) given uncertainty in its estimation.

Year	rainfall (mm)						Groundwater recharge (q/S_y) (m)
	Zanka			Makutapora			
	annual	maximum month	90 th percentile month	annual	maximum month	90 th percentile month	
06/07							5.11
07/08				456	163	115	1.14
08/09	371	176	52	323	68	65	0.91
09/10	758	254	200	380	148	129	3.13
10/11	492	191	98	521	194	102	0.00
11/12	723	217	172	784	223	195	1.75
12/13	843	293	185	719	332	146	0.00
13/14	751	285	167	381	110	67	0.00
14/15	607	241	142	334	114	59	0.00
15/16	1194	316	304	849	202	187	5.04
16/17	516	180	150	338	148	104	0.00



(caption on next page)

Fig. 6. Cross-plots of annual (by hydrological years) groundwater recharge estimates (error bars denote uncertainty in the computation using the modified Water-Table Fluctuation method), normalised for S_y , versus: (a) number of rain days in lowland (Makutapora) (black) and upland (Zanka) (green), (b) annual duration of ephemeral flow (stream stage ≥ 10 cm) of the River Little Kinyasungwe at the Meya Meya gauge, (c) annual total precipitation in lowland (Makutapora) (black) and upland (Zanka) (green), (d) annual cumulative daily stream stage of the River Little Kinyasungwe at the Meya Meya gauge, (e) annual duration of ephemeral flow of the River Little Kinyasungwe at the Meya Meya gauge above a stream stage threshold of 0.25 m, and (f) annual duration of ephemeral flow of the River Little Kinyasungwe at the Chihanga gauge above a stream stage threshold of 0.77 m. Plots a and c comprise data from hydrological years 2007/2008 – 2016/2017, plots b, d and e comprise data from hydrological years 2006/2007 – 2016/2017, and plot f comprise data from hydrological years 2006/2007 – 2015/2016. Correlation co-efficients (r , r_s , τ_b) for each relationship are given and p -values are noted if the values are statistically significant. Quantified groundwater recharge is represented as an equivalent groundwater-level change, normalised with respect to specific yield (S_y) given uncertainty in its estimation.

rainfall ($r = 0.71$, $p < 0.05$; $r_s = 0.45$, $\tau_b = 0.33$) and intensive (90th percentile monthly) rainfall ($r = 0.85$, $p < 0.05$; $r_s = 0.57$, $\tau_b = 0.46$, $p < 0.05$) in the uplands and groundwater recharge are stronger and statistically significant (parametric analysis). None of the independent predictors derived from stream stage data (duration of streamflow, cumulative stream stage) are significantly correlated with any of the independent predictors derived from upland or lowland precipitation data (number of rain days, total rainfall). The strong relationship between groundwater recharge and the duration of streamflow was investigated further to explore whether higher thresholds of stream stage may yield stronger relationships. Strongest correlations were found between groundwater

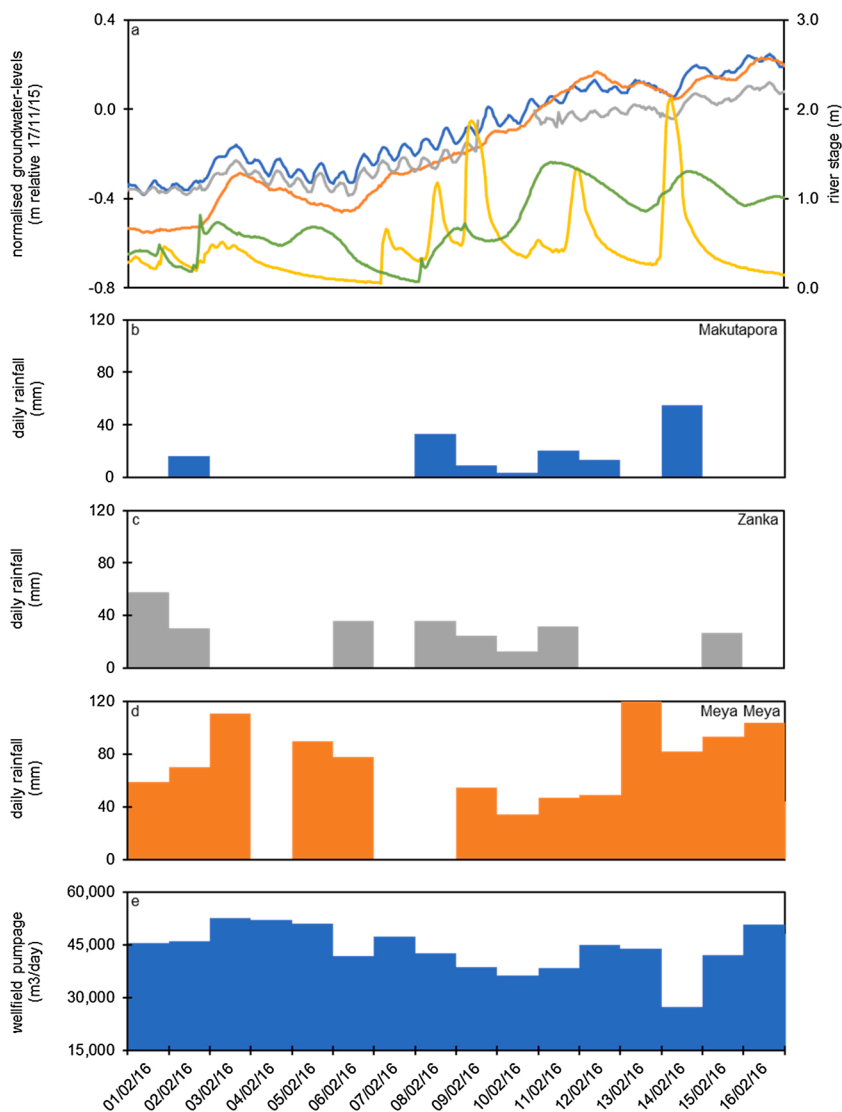


Fig. 7. (a) Hourly groundwater-levels (122/75 - blue, 89/75 - orange, C5 - grey) and stream stage (Meya Meya – yellow, Chihanga –green) together with daily rainfall from (b) Makutapora (lowland) and (c) Zanka (upland) and (d) Meya Meya (upland) as well as daily wellfield pumpage (e) from 1st to 16th February 2016.

recharge and the duration of streamflow exceeding a stage threshold of 0.25 m at the upstream gauge at Meya Meya ($r = 0.95, p < 0.05; r_s = 0.84, p < 0.05; \tau_b = 0.75, p < 0.05$) and 0.77 m at the downstream gauge at Chihanga ($r = 0.97, p < 0.05; r_s = 0.92, p < 0.05; \tau_b = 0.88, p < 0.05$) (Fig. 6e-f).

4.2. High-resolution hydrometric monitoring

Temporal associations among observed rainfall, ephemeral streamflow, and groundwater recharge events, indicated by sustained groundwater-level rises (I, II, III in Fig. 4a), were examined for three discrete events during the 2015/2016 El Niño event (Figs. 7 and 8) and the wet season encompassing January 2018 (Fig. 9). The influence of groundwater abstraction was explicitly considered as evidence from groundwater-level oscillations in the absence of rainfall and stream discharge during the dry season (e.g., June to July 2016 in Fig. 4) shows that brief and small-scale (generally < 20 cm) deflections in groundwater-levels can occur in response to sharp (50 %), episodic (e.g., one-day) variations in pumpage. Larger (up to 0.5 m) and longer changes in groundwater-levels required sustained (e.g., weekly) changes (>20 %) in pumping (Fig. 4b; Supplementary Materials C) and were considered here in the comparison of the timing of rainfall events and ephemeral streamflow as potential sources of groundwater recharge.

4.2.1. Groundwater recharge event I: 1 st to 16th February 2016

Fig. 7 presents hourly groundwater-levels at 3 piezometers (122/75, 89/75, C5), daily rainfall at 3 sites (Makutapora, Zanka, Meya

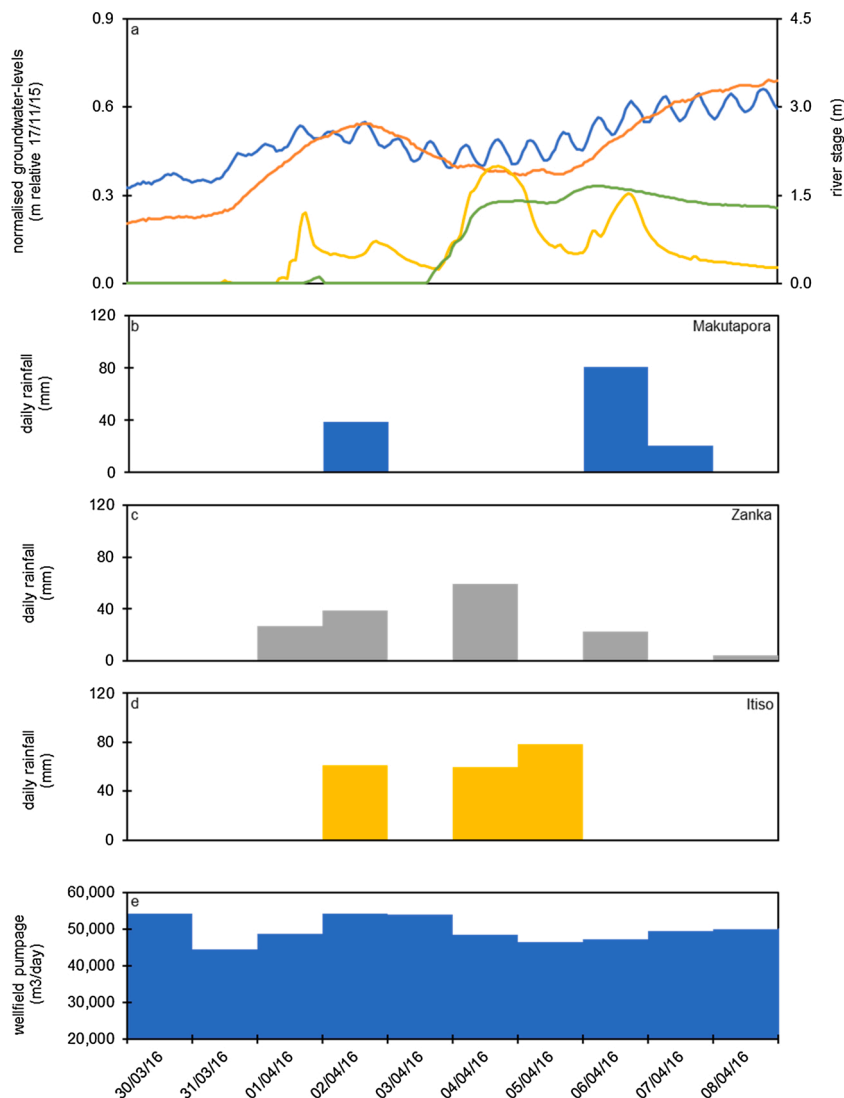


Fig. 8. (a) Hourly groundwater-levels (122/75 - blue, 89/75 - orange) and stream stage (Meya Meya – yellow, Chihanga –green) together with daily rainfall from (b) Makutapora (lowland) and (c) Zanka (upland) and (d) Itiso (upland) as well as daily wellfield pumpage (e) from 30th March to 8th April 2016.

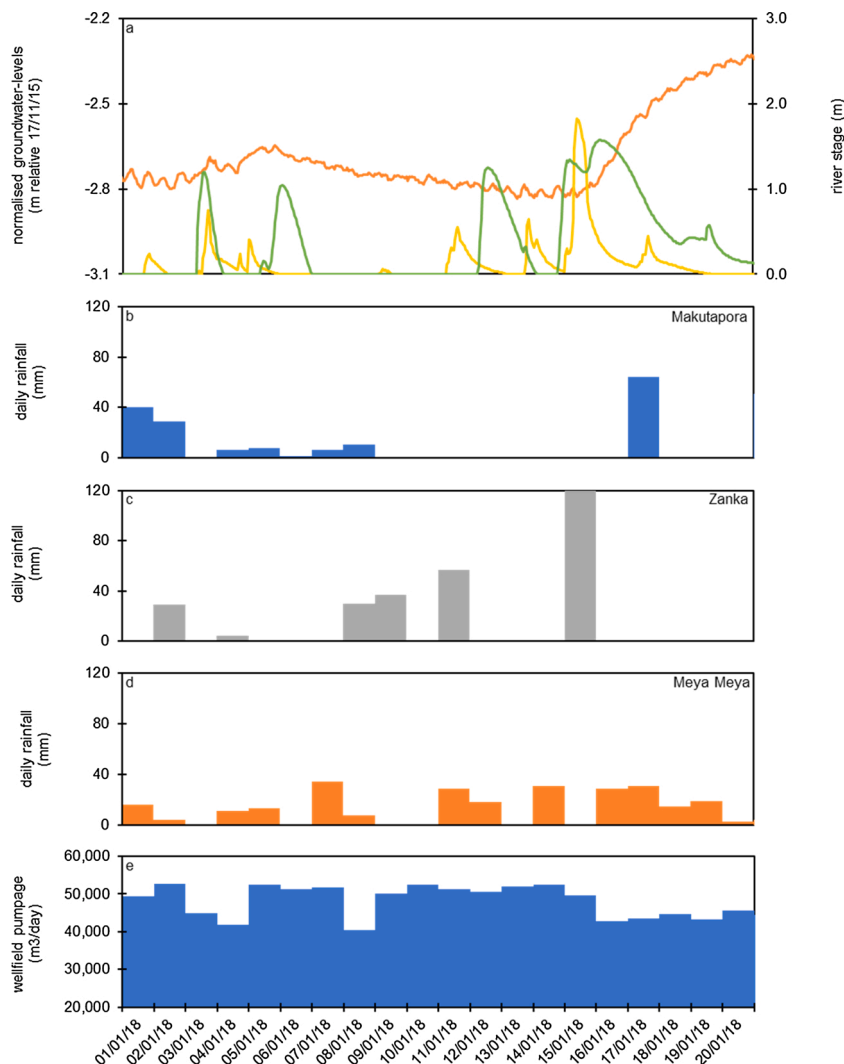


Fig. 9. (a) Hourly groundwater-levels (89/75 - orange) and stream stage (Meya Meya – yellow, Chihanga – green) together with daily rainfall from (b) Makutapora (lowland), and (c) Zanka (upland) and (d) Meya Meya (upland) as well as daily wellfield pumpage (e) from 1st to 20th January 2018.

Meya), hourly stream stage at 2 sites (Meya Meya, Chihanga), and daily wellfield pumpage from 1st to 16th February 2016. Following the cessation of groundwater-level decline in January 2016, groundwater-levels in all 3 piezometers showed distinct rises beginning on 3rd and 6th February that coincided with rises in stream stage observed at both Meya Meya and Chihanga on the 2nd and 3rd of February 2016 as well as at Chihanga on 5th February and Meya Meya on 7th February. On 2nd and 3rd February, both rises in groundwater-levels and stream discharge (stage) showed a stronger association with rainfall upstream of the wellfield on 1st and 2nd February at Zanka (50, 30 mm) and Meya Meya (59, 70 mm) than that observed near the wellfield at Makutapora (0, 17 mm). The brief decline in groundwater-levels (0.15 to 0.20 m) observed from 3rd to 6th February was likely influenced by an increase of 14 % in wellfield pumpage from 2nd to 3rd February (Fig. 7e). Subsequently on 6th and 7th February, rises in groundwater-levels and stream discharge observed at Chihanga (5th to 6th Feb) and then Meya Meya (7th Feb) occurred in the absence of rainfall observed at Makutapora and in response to rainfall observed on 6th February at Zanka (36 mm) and on 5th and 6th February at Meya Meya (90, 78 mm). Peak stream discharge responses at Meya Meya less than 20 h after upland rainfall events have been observed previously (Fig. 3.29 in Shindo et al., 1990). A series of pulses in stream stage exceeding 0.5 m at both Meya Meya and Chihanga were observed from 8th to 15th February; these showed an association with peaks in both upland and lowland rainfall and led to a sustained overall rise in groundwater-levels of ~0.5 m in all three monitoring wells. An 18 % decline in pumpage from 6th to 11th February was also expected to account for some of the noted rise in groundwater-levels over this period. Nevertheless, pumpage returned to a sustained rate in excess of 50 000 m³ per day on 16th February but groundwater-levels did not revert to values observed prior to the reduction in pumpage (Fig. 4), which is observed in the absence of groundwater recharge during the dry season (see Supplementary Information C).

4.2.2. Groundwater recharge event II: 30th March to 8th April 2016

Fig. 8 presents hourly groundwater-levels at 2 piezometers (122/75, 89/75), daily rainfall at 3 sites (Makutapora, Zanka, Itiso), hourly stream stage at 2 sites (Meya Meya, Chihanga), and daily wellfield pumpage from 30th March to 8th April 2016. A rise in groundwater-levels was initially observed on 31st March and, in the absence of observed rainfall, appeared to have been triggered by an 18 % reduction in daily pumpage from 54 282 to 44 442 m³. Within two days, daily pumpage returned to roughly the rate prior to the reduction (54 385 m³) yet groundwater-levels remained 10–15 cm higher than they were on 30th March and continued to rise, a trend that continued until the end of April 2016 (Fig. 4a). Similar to Groundwater recharge event I, groundwater-level rises coincided with a series of pulses in stream discharge. A rise in stream stage to 1.2 m at Meya Meya (and marginally at Chihanga) corresponded to rainfall recorded on 1st April at Zanka (27 mm). Rainfall recorded in the vicinity of the wellfield at Makutapora, upstream of the wellfield at Zanka and Itiso in the adjacent catchment on 2nd April corresponded to a peak in stream stage at Meya Meya of ~0.7 m. In the absence of rainfall recorded at Makutapora, substantial rises in stream stage exceeding 1.0 m were observed on 4th and 5th April at both Meya Meya and Chihanga in response to daily rainfall recorded upstream of wellfield at Zanka (59 mm) on 4th April as well as the upland site at Itiso on 4th (60 mm) and 5th (78 mm) April. On 6th April, rainfall events of 81 mm and 23 mm were recorded at Makutapora and Zanka, respectfully, and associated with a stream stage exceeding 1.5 m at Meya Meya and Chihanga. A stream stage exceeding 0.5 m was recorded at the downstream Chihanga gauge (catchment outlet) until 13th April. Over this period (4th to 8th April), wellfield pumpage remain steady ($\sigma = 3\%$) though slightly rising (Fig. 8e).

4.2.3. Groundwater recharge event III: 1st to 20th January 2018

Fig. 9 presents hourly groundwater-levels at 1 piezometer (122/75), daily rainfall at 3 sites (Makutapora, Zanka, Meya Meya), hourly stream stage at 2 sites (Meya Meya, Chihanga), and daily wellfield pumpage from the 1st to 20th January 2018. The cessation of the annual dry-season recession in groundwater-level was observed on 3rd January and corresponded to the observation of stream discharge at Meya Meya and Chihanga on the same day. Curiously, rainfall was not observed on 3rd January but rainfall of 29 mm was recorded on 2nd January in the vicinity of the wellfield at Makutapora and upstream of the wellfield at Zanka. A 21 % decline in wellfield pumpage was observed from 2nd to 4th January and may explain, in part, the cessation of groundwater-level decline. The continued recession from 6th January in groundwater-levels suggested that groundwater recharge over this period was minimal if it occurred at all. A sharp rise in groundwater-levels began on 15th January and was preceded by substantial rainfall upstream of the wellfield at Zanka and Meya Meya starting on 11th January; this included an extreme event of 120 mm recorded at Zanka. This extreme rainfall coincided with the generation of substantial streamflow indicated by stream stage observations exceeding 1 m at both Meya Meya and Chihanga on 15th January. Although a 13 % reduction in wellfield pumpage observed on 16th January could initially have contributed to the observed rise in groundwater-level, wellfield pumpage then began to increase slowly from 17th January while the observed groundwater-level continued to rise 0.75 m until 9th February (Fig. 4).

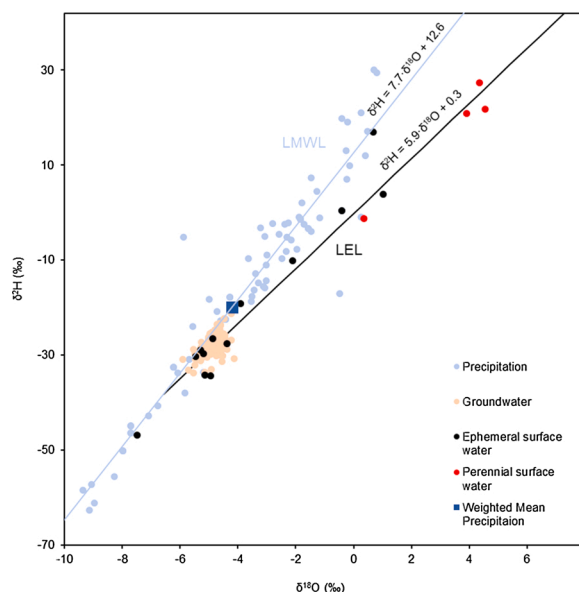


Fig. 10. Cross plot of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ in precipitation ($N = 77$), groundwater ($N = 120$) and surface waters ($N = 17$); the latter comprises both ephemeral surface waters from River Little Kinyasungwe and River Madihi, and perennial surface waters from Lake Hombolo; the weighted mean composition of rainfall at Makutapora ($\delta^{18}\text{O} = -4.2\%$, $\delta^2\text{H} = -20\%$; based on 70 samples with recorded rainfall) is shown by a large dark blue square; LMWL: Local Meteoric Water Line; LEL: Local Evaporation Line.

4.3. Tracing the origin of groundwater using stable-isotope ratios of O and H

Stable-isotope ratios of O and H in daily rainfall regress along a Local Meteoric Water Line (LMWL), $\delta^2\text{H} = (7.7 \pm 0.3) \cdot \delta^{18}\text{O} + 12.6 \pm 1.2\text{‰}$ ($R^2 = 0.92$, $p < 0.05$), which is similar to the Global Meteoric Water Line (Craig, 1961), $\delta^2\text{H} = 8 \cdot \delta^{18}\text{O} + 10\text{‰}$ (Fig. 10). The weighted mean $\delta^{18}\text{O}$ in sampled rainfall is 4.2‰ ($\sigma = 2.8\text{‰}$) based on 74 samples (Supplementary Materials D) for which rainfall amount was recorded. Perennial surface waters ($N = 4$) sampled from Lake Hombolo (Fig. 1) downstream of the Chihanga outlet (gauge) reflect substantial evaporative enrichment in heavy isotopes (^{18}O , ^2H) with a mean $\delta^{18}\text{O}$ of $+3.3\text{‰}$ ($\sigma = 2.0\text{‰}$) that greatly exceeds the mean $\delta^{18}\text{O}$ composition of sampled ephemeral surface waters from the Rivers Little Kinyasungwe and Madihi (west of Makutapora in Fig. 1) of $\delta^{18}\text{O} = -3.7\text{‰}$ ($\sigma = 2.6\text{‰}$, $N = 13$); stable isotope ratios of O and H in surface waters regress along a Local Evaporation Line (LEL): $\delta^2\text{H} = (5.9 \pm 0.3) \cdot \delta^{18}\text{O} + 0.3 \pm 1.3\text{‰}$ ($R^2 = 0.97$, $p < 0.05$). Groundwater samples ($N = 120$) have a mean $\delta^{18}\text{O}$ of -4.9‰ ($\sigma = 0.3\text{‰}$) and cluster around a line of linear regression, $\delta^2\text{H} = (4.1 \pm 0.6) \cdot \delta^{18}\text{O} - 7.5 \pm 2.7\text{‰}$ ($R^2 = 0.32$, $p < 0.05$), that is consistent with evaporative enrichment (Jasechko, 2019) and within error of the LEL.

Rainfall $\delta^{18}\text{O}$ decreases at Makutapora as precipitation intensity increases in a manner that is consistent with the ‘‘Amount Effect’’ (Fig. 11). The blue line in Fig. 11 represents the amount-weighted $\delta^{18}\text{O}$ composition of sampled rainfall exceeding a given intensity threshold (e.g., amount-weighted $\delta^{18}\text{O}$ value using for all rainfall events exceeding the 10th percentile is indicated as ‘>10th’). Rainfall $\delta^{18}\text{O}$ progressively decreases as precipitation intensity increases. As the LMWL and LEL intersect at a $\delta^{18}\text{O}$ value of -5.5‰ with an uncertainty ranging from -5.0‰ to -6.8‰ (based on computed at 95 % confidence bands for the linear regression of both LMWL and LEL), this isotopically depleted (in the heavy isotope) $\delta^{18}\text{O}$ value relative to the weighted mean average composition of rainfall ($\delta^{18}\text{O} = -4.2\text{‰}$; $\sigma = 2.8\text{‰}$) suggests that the origin of sampled surface waters is consistent with daily rainfalls exceeding the 80th percentile (Fig. 11). Groundwaters similarly regress to a stable-isotope composition on the LMWL that is isotopically depleted in the heavy isotope ($\delta^{18}\text{O} = -5.5\text{‰}$ with an uncertainty range from -4.8‰ to -6.9‰ , Fig. 10) relative the weighted mean average composition of rainfall ($\delta^{18}\text{O} = -4.2\text{‰}$). Groundwater is also consistent with the amount-weighted mean composition of 90th percentile daily rainfall (Fig. 11) or $\sim 40 \text{ mm} \cdot \text{day}^{-1}$ that shows evidence of slight evaporative enrichment.

5. Discussion

5.1. Evidence of focused groundwater recharge

Over a decade of hydrometric observations from hydrological years 2006–2007 to 2017–2018, stronger correlations exist between groundwater recharge and ephemeral streamflow than rainfall. Both the duration of observed streamflow (i.e., number of days stream stage $\geq 10 \text{ cm}$) and cumulative stream stage are better correlated to groundwater recharge than the number of rain events, total rainfall, and intensive (90th percentile monthly) rainfall recorded proximate to the wellfield at Makutapora and in the uplands at Zanka (Fig. 1). Stronger and statistically significant linear correlation are observed between total and intensive upland rainfall at Zanka and groundwater recharge, compared to Makutapora. Of further note is that the correlation between the duration of streamflow and groundwater recharge improved significantly by restricting the correlation to stream stage exceeding a threshold value (i.e., 0.25 m at Meya Meya, 0.77 m at Chihanga). This criterion is consistent with a proposed recharge pathway derived from the characterisation of the superficial geology in the Little Kinyasungwe Catchment by Electrical Resistivity Tomography (ERT) (Zarate et al., 2021). The identification of permeable pathways alongside ephemeral stream channels, accessed by flood overbank discharges (pathway ‘‘C’’), provided a clear rationale for comparing flood discharges exceeding a threshold to groundwater recharge derived from piezometric data. The lower threshold for flood discharges at the upstream gauging station at Meya Meya (i.e., stream stage of 0.25 m), relative to the catchment outlet at Chihanga (i.e., stream stage of 0.77 m), is consistent with the occurrence of flood discharges generating overbank flows downstream of the Meya Meya gauge (Fig. 1). As exceedance of stream stage thresholds could conceivably denote the timing and magnitude of effective precipitation (*Precipitation - Evapotranspiration*), correspondence among observed rainfall, stream discharge, and groundwater recharge events is discussed further below.

High-frequency (hourly) observations of groundwater-levels and stream stage from hydrological years 2015–2016 to 2017–2018, together with daily rainfall and wellfield pumpage, show that sustained groundwater-level rises, indicative of groundwater recharge events, correspond better to the timing and magnitude of rainfall observed in areas upstream of the wellfield and in association with observed pulses of stream discharge. Stable isotope ratios of O and H also suggest that groundwater in the wellfield is recharged by intensive (90th percentile) daily rainfalls that have undergone slight evaporative enrichment in the heavy isotope (^2H , ^{18}O). Similarities in the regressed isotopic compositions of groundwater and ephemeral surface waters in the Little Kinyasungwe Catchment provide additional evidence to hydrometric observations of the contribution of focused groundwater recharge to the Makutapora Wellfield.

The presented analysis focuses on observations of stream stage at gauging stations on the River Little Kinyasungwe. We recognise, however, that leakage can potentially occur along or adjacent to other ephemeral stream channels (e.g., River Madihi). Similar to Shindo et al. (1990), one of the authors (Taylor) observed surface flows not represented in the mapped drainage of the River Little Kinyasungwe in Fig. 1 during Groundwater recharge event II on 4th April 2016. Presented evidence linking focused groundwater recharge to ephemeral streamflow does not preclude the possibility of additional pathways recently identified from the characterisation of superficial geology around the Makutapora Wellfield from ERT surveys including diffuse groundwater recharge (Zarate et al., 2021). These include the contribution of diffuse recharge more widely within the catchment, possibly aided in its transmission by extensions of fault and fracture networks. Simple water balance calculations (see Supplementary Materials E) show, however, that despite the variable and ephemeral nature of streamflow in the Little Kinyasungwe Catchment, the volumes of water transmitted

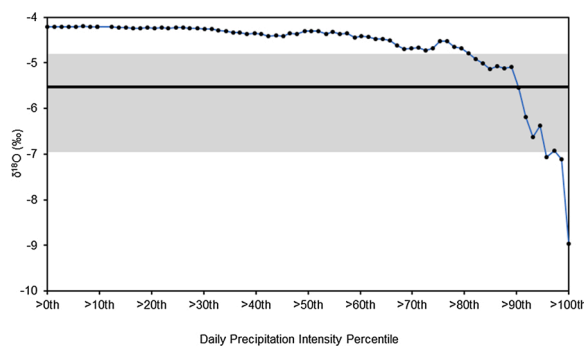


Fig. 11. Amount-weighted $\delta^{18}\text{O}$ composition of daily rainfall plotted as a function of the value exceeding a given intensity threshold (e.g., amount-weighted precipitation $\delta^{18}\text{O}$ using all precipitation events exceeding the 10th percentile shown as '>10th') as per Jasechko and Taylor (2015); the decrease in rainfall $\delta^{18}\text{O}$ as precipitation intensity increases, reflects the "Amount Effect" in which low-intensity rainfalls are relatively enriched in heavy isotopes (^{18}O , ^2H) whereas high-intensity rainfalls are comparatively depleted in heavy isotopes; the blackline and area shaded in grey represent respectively the regressed estimate and uncertainty therein of the $\delta^{18}\text{O}$ composition of rainfall generating both groundwater recharge and ephemeral streamflow.

episodically, especially during El Niño events, have been of a magnitude that may be capable of sustaining both intensive groundwater abstraction recorded from the Makutapora Wellfield via focused recharge and discharges from the catchment outlet at Chihanga. These rough computations do not challenge the possibility of contributions from both diffuse recharge and even inter-basin water transfers along fault systems to the Makutapora Wellfield but suggest that such dynamics are not intrinsically necessary.

The evidence of focused groundwater recharge to the Makutapora Wellfield in central, semi-arid Tanzania is consistent with past research highlighting the importance of this groundwater recharge pathway in drylands (Alley, 2009; Scanlon et al., 2006) that has recently been demonstrated more widely in tropical Africa by Cuthbert et al. (2019). Moreover, the specific identification of ephemeral streams as a source of focused groundwater recharge is consistent with limited evidence from other semi-arid regions (Acworth et al., 2021; Cuthbert et al., 2016; Goni et al., 2021; Simmers, 2003; Simmers et al., 1997). The findings presented here also support the basic conceptual model proposed earlier by Taylor et al. (2013b) whereby leakage from ephemeral streams, as they flow over coarser-grained soils along the basin floor, contributes to groundwater recharge to the Makutapora Wellfield.

5.2. Implications from the local to the global

The identification of focused groundwater recharge to the Makutapora Wellfield is of local, pragmatic importance. Currently, the wellfield is the sole source of the public, piped water supply to Dodoma, the capital city of Tanzania (DUWASA, 2015), which is rapidly expanding (The East African, 2017) and was estimated to have had a population of more than 700,000 in early 2018 (The Citizen, 2018). Recognition of the contribution of ephemeral stream discharges in the Little Kinyasungwe Catchment to the replenishment of the Makutapora Wellfield can inform requisite catchment-wide wellhead protection measures to sustain the quality and quantity of pumped groundwater as well as inform potential strategies to enhance wellfield replenishment through Managed Aquifer Recharge (e.g. Murray et al., 2018). The evidence presented here and in a companion paper (Zarate et al., 2021) in this volume provide a well-documented case study to compare to other dryland environments in tropical Africa. More research is, nevertheless, required: (1) to examine more fully additional groundwater recharge pathways to the Makutapora Wellfield; (2) to test this conceptual and quantitative understanding of groundwater recharge with numerical models reconciled to improved monitoring data; and (3) to better understand the hydrological conditions producing catchment runoff in the Little Kinyasungwe Catchment driving focused groundwater recharge events. On the latter, the important contribution of heavy rainfall to the generation of focused groundwater recharge identified here points to the potential resilience of groundwater to climate change as the intensification of tropical rainfall under global warming leads to fewer but heavier rainfall events (Allan et al., 2010; Donat et al., 2016; Fischer and Knutti, 2016).

The central finding of the importance of focused groundwater recharge derived from ephemeral streamflow in a dryland Tanzania adds to a growing body of research globally (Acworth et al., 2021; Cuthbert et al., 2019, 2016; Dahan et al., 2008; Nowreen et al., 2020; Villeneuve et al., 2015) demonstrating the pervasiveness of focused groundwater recharge. As focused groundwater recharge processes remain largely ignored in large-scale hydrological models (e.g., Global Hydrological Models, Land-Surface Models), pessimistic projections of groundwater availability in drylands and the impacts of climate change (Jiménez Cisneros et al., 2014) can be misrepresentative. The latest version of WaterGAP (2.2d, Müller Schmied et al., 2021), the only large-scale model to represent focused recharge, simulates groundwater recharge from standing water bodies (i.e., lakes, reservoirs, wetlands) but not ephemeral streamflow. Numerical experiments and the development of codes to address this oversight are on-going (e.g., Quichimbo et al., 2020, 2021). Inclusion of focused groundwater recharge via ephemeral streamflow in large-scale models presents a significant challenge yet one of increasing necessity as the spatial resolution of such models increases (Gleeson et al., 2021).

6. Conclusions

Empirical evidence from hydrometric observations and stable isotope ratios of O and H in a dryland environment in central Tanzania shows the importance of focused groundwater recharge in sustaining the sole perennial source of freshwater to its rapidly growing capital, Dodoma. Groundwater recharge estimated from piezometry is more strongly correlated with ephemeral streamflow than rainfall. Strongest associations are found between groundwater recharge and the duration of streamflow exceeding a threshold stream stage value. This latter finding is consistent with permeable pathways in the superficial geology alongside ephemeral stream channels, identified by surface geophysics in a companion study, that are accessible by overbank flood discharges. Further, the examination of individual groundwater recharge events using hourly observations of groundwater-levels and stream stage with daily rainfall and wellfield pumpage shows that sustained groundwater-level rises, indicative of groundwater recharge, correspond better to the timing and magnitude of rainfall observed in areas upstream of the wellfield, remote from piezometry, and in association with observed pulses of stream discharge. Finally, stable isotope ratios of O and H in groundwater more closely match the composition of ephemeral streamflow in the Little Kinyasungwe Catchment than average rainfall and regress to a value along the Local Meteoric Water Line that is consistent with the mean composition of intensive (90th percentile) daily rainfall. The combined hydrometric and isotopic evidence sheds new light on the contribution of focused groundwater recharge via ephemeral streamflow in a tropical dryland. This new insight serves not only to inform strategies to protect and potentially augment the replenishment of the water supply to the rapidly growing, dryland city of Dodoma but also to evaluate how climate change may influence the renewability of groundwater resources in tropical drylands as precipitation intensities increase in a warming world and amplify flood discharges.

Author statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejrh.2021.100919>.

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