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PAPER

Groundwater recharge in basement aquifers in subhumid drylands of sub-Saharan Africa

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Abstract

Characterising groundwater recharge is fundamental for sustainable groundwater management. This study focuses on assessing recharge in drylands using four experimental plots under different land-use practices in crystalline basement aquifers in three southern African countries (Chitedze in Malawi, Kabeleka and Liempe in Zambia, and Domboshawa in Zimbabwe). Several methods, including water-table fluctuation (WTF), chloride mass balance (CMB), water stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) and dissolved gases, were used to quantify annual recharge rates, recharge sources and groundwater residence times. This informed the development of a conceptual model of groundwater recharge in unpumped basement aquifers. Using WTF, across all sites/years, the range of annual median recharge was found to be in the range of 2.8–14.1% rainfall. Recharge was observed for most years across all sites and was controlled by hydrogeological settings, rainfall totals and antecedent conditions, i.e. the groundwater level at the end of the preceding dry season. Based on groundwater level observations and water stable isotope analysis, for sites where there has been extensive use of conservation agriculture (in time and space), there is some evidence of earlier and greater recharge compared to conventional agriculture at paired sites. Additionally, there is evidence of high lateral connectivity in shallow, permeable layers and high local connectivity in the aquifers which facilitate discharge to surface drainage. This leads to a lower proportion of modern recharge at these unpumped sites (typically $<10\%$) compared to other studies using comparable methods in pumped boreholes, which highlights the importance of groundwater capture due to pumping.

Keywords Groundwater management · Recharge · Sub-Saharan Africa · Conservation agriculture

Introduction

Shallow weathered and fractured basement rocks provide a highly distributed and varied aquifer system, capable of supporting low-to-moderate abstraction across vast regions of Africa, depending on the connectivity of fractures (MacDonald et al. 2012). Assessing recharge is crucial to understanding the impact of different groundwater uses, such as irrigation, on changes in groundwater stores as well as long-term water security (Scanlon et al. 2002; Taylor et al. 2013; MacDonald et al. 2021). To date, there has been limited use of groundwater resources for cultivation in

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southern Africa (Siebert et al. 2010; Cobbing 2020). However, increasing populations, unreliable rainfall patterns, a greater demand for locally produced crops, the need for improved food security and technological advances such as the use of solar pumps and drip irrigation are likely to increase the demand for groundwater irrigation in Africa in the near future (Cobbing 2020), as has been observed elsewhere globally (Scanlon et al. 2012; MacDonald et al. 2016; Rivett et al. 2018).

Quantifying groundwater recharge, i.e., assessing the volume of water that reaches the water table, can be carried out using various methods employed at different spatial and temporal scales (Scanlon et al. 2002; Healy 2010; West et al. 2023). These include water-table fluctuation (WTF), baseflow (BF) estimation, catchment water balances, geophysical methods and chloride mass balance (CMB), among others. Large-scale groundwater recharge assessment methods include various modelling approaches and aerial/satellite geophysical methods (e.g., Bonsor et al. 2010). However, large-scale methods tend to mask underlying spatial variability to changes in groundwater storage and in situ observations challenge the utility of these large-scale assessments (Scanlon et al. 2018; MacDonald et al. 2016; West et al. 2022, 2023). Environmental tracers (such as sulphur hexafluoride – SF_6 or chlorofluorocarbons – CFCs) have been used to assess groundwater residence time and apparent bulk ages of groundwater (Busenberg and Plummer 2000; Banks et al. 2021). Residence time information is useful for estimating aquifer recharge when used in combination with depth and aquifer porosity values for observations close to the water table (Healy 2010). Stable isotopes of water can be used to assess recharge processes and mixing between different sources of recharge (e.g. Kendall and Doctor 2003) and assess the importance of rainfall intensity for groundwater recharge (Owor et al. 2009).

Although there are many groundwater recharge studies in southern Africa (MacDonald et al 2021), most of these are focused on semiarid and arid areas, with only a handful in subhumid areas where most of the population live. There is also a lack of empirical studies that explicitly consider the effects of land use on groundwater recharge. Long-term changes to land use in Africa have been linked to changes in groundwater recharge (e.g. Leblanc et al. 2008; Favreau et al. 2009). Recharge may also be enhanced by irrigation returns (Scanlon et al. 2010) and urbanization (Lapworth et al. 2017). The process of enhanced groundwater capture due to pumping and impacts on environmental flow in rivers is also of note (e.g., Gleeson and Richter 2018) and raises the question of how long-term recharge may change as groundwater pumping increases in basement settings.

Various farming typologies characterize most African smallholder systems, including conventional tillage (CT), i.e. deeper tillage methods using either traditional handheld hoes, mouldboard or disc ploughs that cut and break up the soil to depths of 20–30 cm, residue removal and limited use of intercropping or crop rotations. Conventional agriculture has become associated with increased soil degradation, while the so-called climate-smart agricultural systems,such as conservation agriculture (CA), have gained prominence in Africa and elsewhere to improve crop resilience and yield (FAO 2014; Thierfelder et al. 2018). CA systems are highly varied but typically include one or more elements of reduced tillage, plant residue retention or addition (to protect the soil surface and to build its organic carbon status) and intercropping or crop rotation (to diversify the system thus increasing its resilience to pests and diseases and to build soil fertility by including of legume crops). In the light of recurrent droughts across southern Africa, a range of CA systems are being widely promoted through agricultural extension programs and farming system NGOs (Wall et al. 2014), leading to a wide range of different agronomic approaches being used, ranging from "full scale" CA to more rudimentary minimum tillage systems. In this study, the term CA is used to encompass the range of agricultural practices employed at the study sites that include full scale CA, or its partial implementation at various scales, on larger 5-ha cultivated fields to smaller mosaics of research treatment plots.

In 2016 it was estimated that ~12% of global cropland was under CA (Kassam et al. 2019). In over 50% of studies considered in a recent review by Mudimbu et al. (2022), assessing the evidence of groundwater recharge under CA and CT, CA was found to have the potential to improve surface-water infiltration and therefore potential recharge to the groundwater, including all the studies ($n = 5$) in the Southern African Development Community (SADC) region. However, very few studies have used direct observations of groundwater level changes to assess recharge directly, with most relying on proxy indicators such as changes in soil moisture (Mudimbu et al. 2022).

In this study, a suite of field-based measurements was used to provide estimates of groundwater recharge in basement aquifers from rainfall under different land use and agricultural systems in three countries in the SADC. This is part of a larger knowledge exchange project (CEPHAS 2024) assessing the impacts of CA systems on the water cycle by employing a range of field-based techniques. Specific objectives of this study are to (1) use high-frequency rainfall and groundwater level observations from a network of sensors to assess groundwater recharge responses to rainfall over three consecutive recharge seasons, (2) assess differences in recharge estimates of groundwater below conventional and conservation agriculture sites, and (3) employ a range of environmental tracers (O and H stable isotopes and SF_6) to assess recharge sources and groundwater residence times.

Methods

Study sites

A suite of dedicated boreholes was drilled at each of the study sites in Malawi, Zambia and Zimbabwe (Fig. 1). The boreholes were drilled in a range of different land-use and hydrogeological settings. All sites are underlain by crystalline basement geology (Fig. 1). The details of each experimental site, in terms of underlying geology, plot size and history of use, and a summary of CA/CT measures used, are given in Table 1, and further details are provided in Table S1 of the electronic supplementary material (ESM). The Malawi site (Chitedze) is underlain by medium- to high-grade metamorphic rocks predominated by gneiss, and this site is notable for having a ~1-m-thick layer of silcrete at ~2 m depth across the whole site. The Zambia sites (Kabeleka and Liempe) are underlain by micaceous schist with visible quartz veins. The Zimbabwe site (Domboshawa) is underlain by granitoid rocks of various ages. Water strikes were encountered in the bedrock during drilling which coincided with local fracture networks. Static groundwater levels are shallow at all sites, and the monitoring wells were largely located on areas of low topographic relief to maximise vertical recharge signals. The majority of water-level-monitoring boreholes (MB) were drilled to a depth ~5 m below static water level. Some deeper pumping test wells were also drilled at each site, the deepest being 34 m below static water level (ranging between 12–46 m below ground level).

The field sites were planted with maize (*Zea mays*) as a rain-fed test crop with neither supplementary irrigation inputs nor significant groundwater abstractions within the vicinity of the sites. Sites (CA and CT) on flat terrain were selected to minimize surface runoff and minimize lateral groundwater flow, with one exception, the Domboshawa NUESOM CA site which is located between a small inselberg and upgradient of a dambo. NUESOM refers to a long-term experiment anchored on repeated application of different quality and quantities of organic resources primarily established to investigate nutrient use efficiency and soil organic matter dynamics on a sandy soil (Mtambanengwe et al. 2006). At each study site, a single constant discharge pumping test was undertaken to quantify aquifer properties (e.g. hydraulic conductivity K and specific yield S_y) and these results are reported separately. The S_y ranges of 0.01–0.05 were used for recharge estimates using the WTF

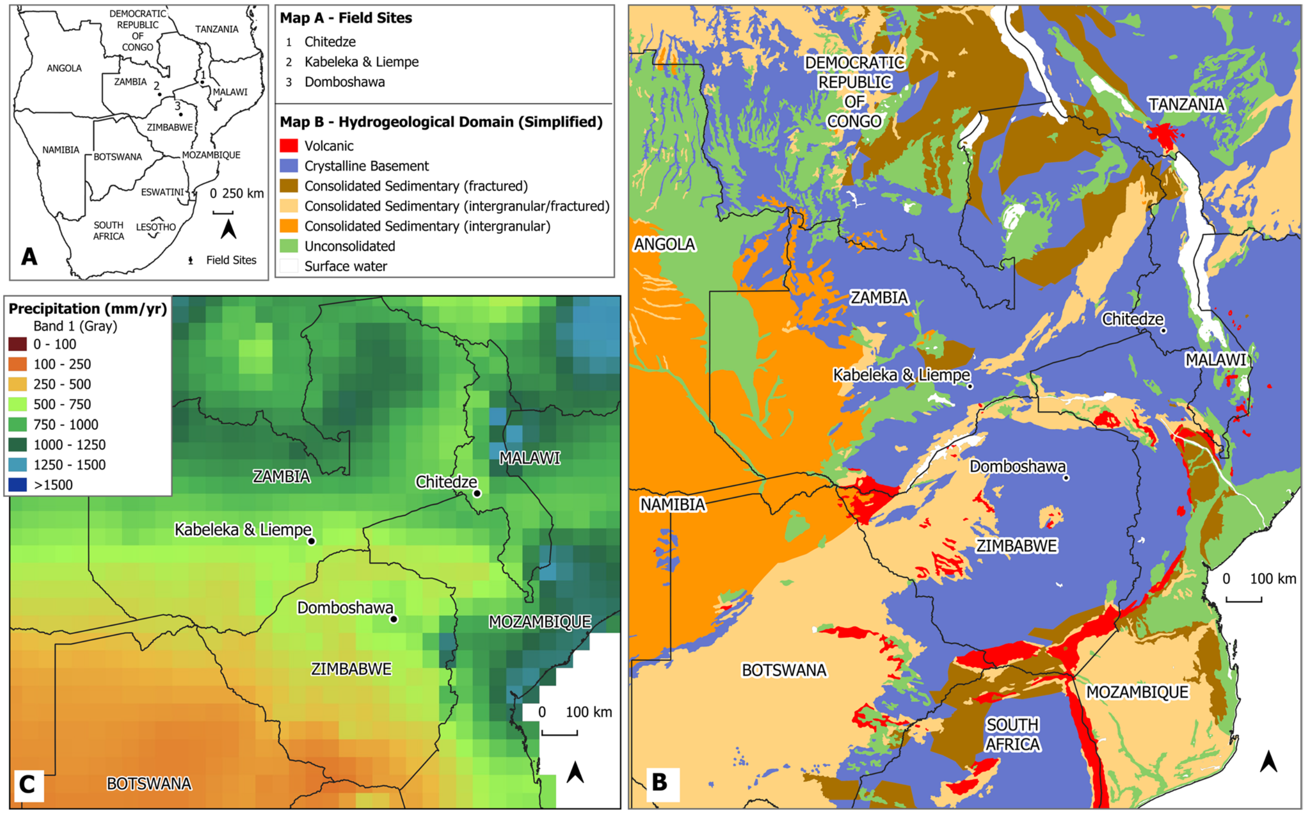


Fig. 1 Study area: **a** location of field sites in Malawi, Zambia and Zimbabwe, **b** Map of regional aquifers) (MacDonald et al. 2012) and **c** long-term annual average rainfall (Harris et al. 2020)

Table 1 Selected site details and farming systems used at each study site

Country	Geology	Site name	Treatment	Size	Duration	Crops	No. of monitoring boreholes and total depth
Malawi	Precambrian gneiss	Chitedze CA	CA with two subplots CT. Minimum till, direct seeding, residue and mulch	0.28 ha	10 years	Rotation/intercropping: maize and legumes	5 (16 m, 17 m, 20 m, 24 m, 42 m)
		Chitedze CT	CT – ploughed	> 2 ha	10 years	Maize	4 (17 m, 22 m, 43 m, 44 m)
Zambia	Precambrian schist	Kabeleka CA	Ox tillage; plant residues retained, intercropping	> 5 ha	>26 years	Maize, pumpkin, legumes intercropping	6 (16 m × 2, 21 m × 2, 39 m, 42 m)
		Kabeleka CT	Conventional to moderate tillage	> 2.5 ha	>26 years	Maize predominantly, rotation with sorghum and soya	5 (15 m × 2, 21 m, 36 m, 42 m)
		Liempe CA	Minimum till and residue retention	1.2 ha	<1 years	Maize; maize/soybean intercrop	2 (21 m, 46 m)
Zimbabwe	Precambrian granitic gneiss	DTC CA	Mozaic of hand till (10 × 10 m) plots, 0–5 t/ha residues, herbicide glyphosate	0.1 ha	8 years	Maize	2 (15 m × 2)
		DTC CT	Tractor ploughed	0.4 ha	6 years	Maize	2 (15 m, 33 m)
		Woodlot	Medium-density forested plot	3.9 ha	>11 years	Trees	1 (15 m)
		NUESOM CA	Mozaic of hand till plots (6 × 6 m), variable residue retention	0.35 ha	15 years	Maize	1 (25 m)

method based on literature estimates for shallow basement aquifers (e.g. Cuthbert et al. 2019). The values of S_y obtained from the short-term pump tests (0.009–0.011) were consistent with the lower estimates of S_y from literature.

Groundwater level and rainfall monitoring

All borehole water levels were logged at a 30-min frequency using in-situ Rugged Troll down-hole sensors that measure pressure and temperature. One of the boreholes at each site was also equipped with a barometric logger for barometric corrections. Daily rainfall records were collected at each site either using an automatic weather station or manually using a rain gauge. For the Kabeleka site, rainfall data from Lusaka airport (~35 km NE) was used.

Groundwater and rainfall sampling

Monthly groundwater samples were collected from the monitoring wells for water isotope analysis and major anion chemistry over a 2-year period ($n = 455$). A flow-through cell was used on site to ensure stable field parameters—pH, Specific Electrical Conductivity (SEC), Dissolved Oxygen (DO)—prior to groundwater sample collection. In addition, alkalinity (HCO_3) was determined on-site using micro-titration. All samples for stable water isotopes were collected unfiltered and stored unacidified in Nalgene bottles prior to analysis. Borehole waters for major anions, including chloride, were filtered (0.45-µm cellulose nitrate) and stored unacidified in Nalgene bottles prior to analysis. Groundwater residence time indicator samples for chlorofluorocarbon (CFC-11, CFC-12) and sulphur hexafluoride (SF_6) were collected on two separate sampling rounds ($n = 46$) unfiltered, and without atmospheric contact, in sealed containers by the displacement method of Oster et al. (1996). Rainfall samples were collected unacidified throughout the monitoring period ($n = 60$) using a totalizer with a tube and 'dip-in' design which minimizes evaporative effects and is suitable for the climate of southern Africa (IAEA/GNIP 2014). Rainfall samples were collected on an event basis where possible or bulked on a monthly basis.

Water analysis

All chemical analyses were undertaken at BGS Geochemistry and Groundwater Tracer Laboratories in the UK. Anions were analyzed by ion chromatography. Stable isotope analysis (δ^{18}O, δ^{2}H) was carried out using standard preparation techniques followed by isotope ratio measurement on a VG-Micromass Optima mass spectrometer. CFCs and SF_6 were measured by gas chromatography with an electron capture detector after pre-concentration by cryogenic methods (e.g., Busenberg and Plummer 2000). Measurement precision was within ±0.1‰ for δ^{18}O and ±1‰ for δ^{2}H, and ±5% for the CFCs, with detection limits of 0.01 pmol/L (CFC-12), 0.05 pmol/L (CFC-11) and 0.1 fmol/L (SF_6). Average annual air temperatures from each site were used to assess CFC and SF_6 recharge concentrations (USGS 2024). Stable isotope results are reported as a deviation from Vienna Standard Mean Ocean Water (VSMOW) in per mil (‰) difference using delta (δ) notation.

Data analysis

All data analysis and plotting were undertaken in R version 4.3.1, using the packages tidyr and reshape2 for data manipulation and ggplot2 for graphics. Logged groundwater level data were plotted alongside dip measurements to QA and correct logger data.

Average amount-weighted isotope values for precipitation can be used to compare with groundwater isotope values to understand recharge sources and processes (e.g., Darling et al. 2003; Lapworth et al. 2015). For interpretation purposes, measured stable O and H isotope values were compared to the local meteoric water line (LMWL) and weighted mean rainfall values collected during the study. Local rainfall data was compared with the nearest GNIP rainfall data (IAEA/WMO 2023) to check for consistency with longer-term rainfall isotope values.

Chloride values from rainfall and groundwater can be used to assess recharge using the CMB method (Edmunds et al. 1999). This is a simple estimation of potential direct recharge R calculated using the formula $R = P \times C_p / C_s$ where P is the regional annual rainfall (mm), C_p is the spatially averaged rainfall Cl (mg/L), and C_s is the groundwater concentration Cl (mg/L). In rainfall samples where there was obvious Cl contamination, i.e. very high outlier values compared to the interquartile range, these were screened out. The rainfall Cl data were weighted and then averaged across the year. For groundwater Cl values the median and interquartile range (IQR – P25, P75) was used to estimate recharge for each observatory, then recharge relative to rainfall as a percentage was presented. The CMB approach is typically used in semiarid settings but has also been applied in more humid locations where runoff can be measured or assumed to be low. The technique is also sensitive to localized Cl contamination from sources other than atmospheric inputs (Diouf et al. 2012; Lapworth et al. 2013). Others have successfully used CMB in subhumid areas in Africa (Banks et al. 2021) by applying modelled runoff values and found runoff effects to be small (<20% in southern Africa) and, therefore, similar to uncertainties from measuring Cl in rainfall. Nevertheless, estimates of recharge using CMB should be assumed to give an upper bound to recharge in dry subhumid areas.

Annual recharge estimates were calculated using the graphical WTF method (Healy and Cook 2002). This method uses individual hydrologic episodes that are summed over a 12-month period rather than fixed time intervals and can estimate and correct for recession. The effective groundwater rise due to a recharge episode is taken as the difference between the peak water-table position and the extrapolated (linear) recession at the time of the peak, and requires careful attention for each episode (Nimmo et al. 2015). The groundwater level hydrographs were also used to infer the recharge mechanisms and processes and to identify the key properties and features contributing to groundwater recharge. The groundwater level data, recorded every 30 min, is this study's most granular field data set and the analyses and interpretations are constrained by details observed in these hydrographs. SF_6 data were corrected for excess air at 3 cc/L based on the data of Wilson and McNeill (1997). Residence time data was compared using box plots, dot plots and bow plots (e.g., CFC vs SF_6) and compared graphically with a range of different model flow curves (piston flow, binary mixing and exponential mixing model) to assess dominant flow processes and CFC contamination effects on the interpretation and use of residence time data.

There are many local factors that may impact groundwater level fluctuation that are similar within individual small sites. These include: (1) rainfall (amount, duration, intensity, consecutive wet days), (2) temperature, (3) geology and hence bulk permeability and porosity, (4) relief and, hence, drainage gradient to local base level. Other variables that vary within each research site include: (1) land-use (CT, CA in all its variations, plot size, silviculture, natural woodland, etc.) and (2) local hydrogeological conditions, drainage conditions and runoff (see Table S1 of the ESM). Within each research locality, in assessing hydrographs with similar responses, those factors considered as constant across the site are likely to be the key drivers for differences in the groundwater response hydrograph between sites. Similarly, in assessing those hydrographs with variable responses, those factors considered to be variable within the site are likely to be the key drivers of the variability at the site level. This strategic analytic approach provides a tool to help identify the most probable key factors affecting the groundwater recharge mechanisms /processes.

Results

Temporal variations in rainfall and groundwater levels

Groundwater hydrographs and daily rainfall data for all sites are shown in Fig. 2. Since the start of monitoring in 2019, there was an overall increase in groundwater levels between 2019–2021 at all sites except Liempe CA. For 2021–2022 at Chitedze and Domboshawa, this trend continues, while at Kabeleka, groundwater levels were comparable to those in 2020–2021. By contrast, the Liempe CA site shows varying responses in groundwater levels over the 3 years of monitoring despite relatively consistent rainfall overall, and a large drop in groundwater level is observed in the 2021–2022 recharge season where a large proportion of the rainfall occurred late in the season (after March). Trends are summarized below for each site.

At *Chitedze* (Malawi), the groundwater hydrographs for individual boreholes are similar. All the hydrographs peak in June/July, after the end of rains in Feb/Mar. Hydrographs show a smooth and damped response and do not reflect individual rainfall events, and there are no discernable differences in recharge between CA (zero till, crop residue retention and intercropping) and CT sites. Annual groundwater level fluctuations are ~1 m. This suggests that the impacts of the variable land-use at Chitedze are masked by the hydrogeological conditions at the site. Borehole records show a widespread hard low-permeability layer comprised

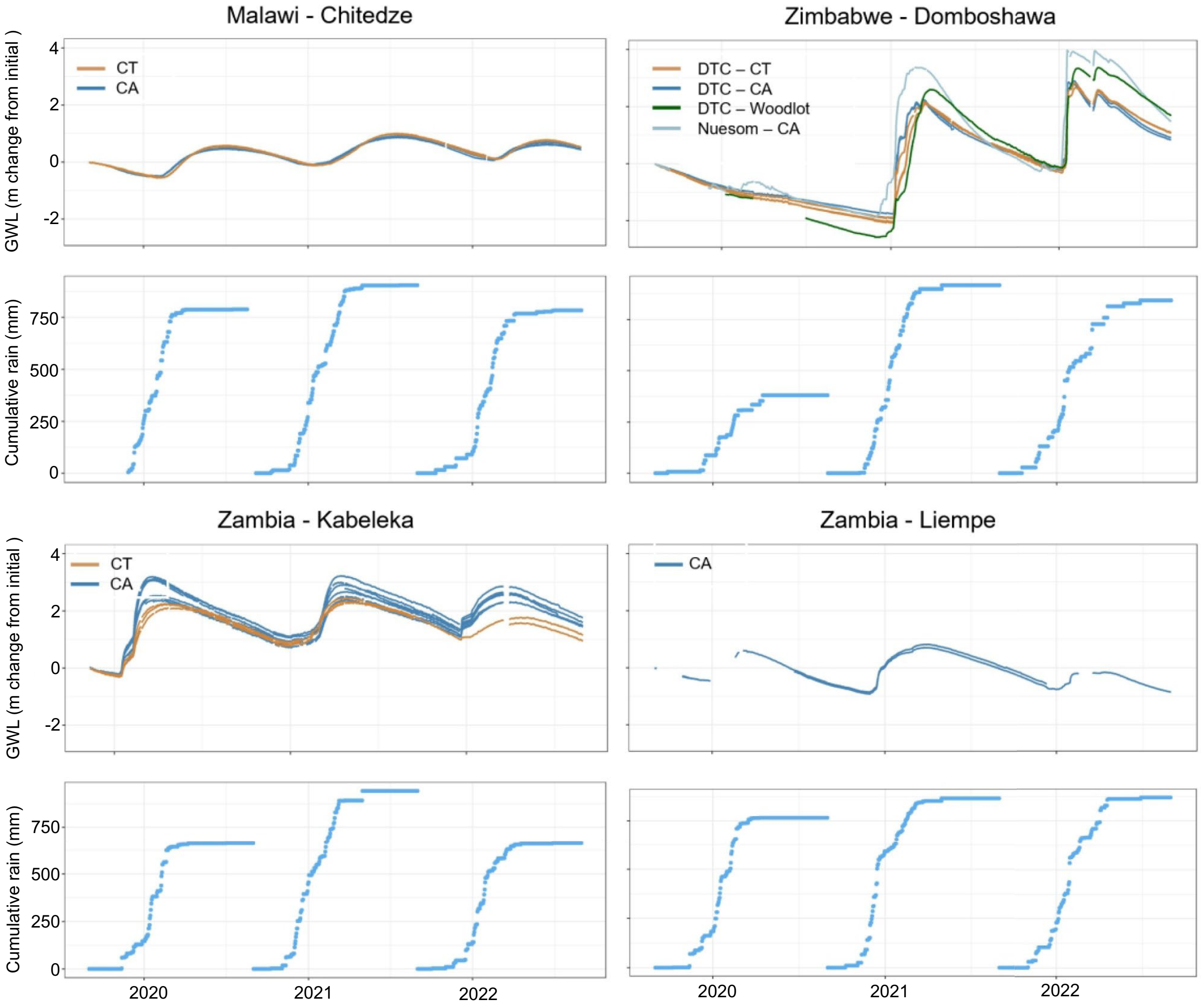


Fig. 2 Groundwater level (GWL) and daily cumulative rainfall time series

of silcrete (a pedicrete) ~2 m below the surface. As such, the aquifer below may be considered partly semiconfined, and this could likely mask any impacts of the different land-use systems.

At *Domboshawa* (Zimbabwe), hydrographs appear responsive to different rainfall conditions. During the 2019–2020 rainfall season, there was only 380-mm total rainfall and all the hydrographs, except NUESOM CA, show no recharge response. During the 2020–2021 season recharge begins at the CA and CT sites after ~200–400-mm rainfall and hydrographs begin to fall abruptly once the rains end. There is, however, an earlier and greater hydrograph response for the NUESOM CA and Woodlot sites, which suggests the influence of some variable local factor(s) at these two boreholes. At NUESOM CA, there is a large granite outcrop focusing runoff upslope of the borehole. In addition, during drilling, a narrow ~1-m thick fractured quartz vein was intersected in the borehole. Both of these indicate localized factors that could explain the pronounced difference in the hydrograph responses at NUESOM CA. At the Woodlot site, the deeper infiltration from preferential flow pathways associated with tree roots could also explain the higher and earlier recharge response observed at the Woodlot borehole.

The CT sites are typically tractor tilled, chemical fertilizer applied and planted to mono-crops, usually maize (Table S1 of the ESM). The CA sites are typically a research plot mosaic with zero till, herbicide, and with variable amounts of crop residues used as a thin mulch (Table S1 of the ESM). For the 2021–2022 season, rains persist at Domboshawa with a second period of intense rainfall events in the later part of the season, and hydrographs show a double peak response before recession starts.

The recession limbs of all hydrographs decline to the same local groundwater base level. Regardless of the relative differences in the hydrograph peaks, the troughs for all hydrographs attain the same value at the end of the dry season, suggesting a high connectivity of the aquifer system (Fig. 2).

At *Kabeleka* (Zambia), comparable rainfall/recharge patterns to Domboshawa are shown, suggesting local recharge. The hydrograph responds to rainfall each year, with recharge occurring after different cumulative rainfall totals each year at ~350 mm (2019–2020), 550 mm (2020–2021) and only 125 mm (2021–2022). Compared to Domboshawa, the hydrographs are slightly smoother, hydrograph peaks are slightly delayed and the magnitude of water level response is slightly less at 2–3 m.

There are two distinct farming systems covering much larger cultivated areas. These are CT, based on tillage, fertilizer and mono-cropping and CA, which at Kabeleka is a CA land-use, based on deep mulch applications, intercropping, together with some level of tillage (Table S1 of the ESM). The most significant finding is that, in most years (except 2021–2022 where they are comparable), recharge appears greater under CA than CT (Table 2). The difference in the peak hydrograph levels can be up to 50% for individual sites (e.g. 3 m vs 2 m in 2019–2020) with more recharge under the CA than CT (Fig. 2). This is seen in every season but the response is greatest in the 2019–2020 recharge season.

At *Liempe CA* (Zambia), hydrographs are muted and have a delayed response to rainfall and a peak that is shortly after the end of the rains. The Liempe hydrograph pattern appears to have similarities to the Malawi hydrographs, but is less muted and with less delay to the recharge. The hydrograph responses for the 2021–2022 season are much less despite the similar rainfall totals to other consecutive years.

Table 2 Recharge estimates using the WTF method

Country-site	Recharge mm/year						Recharge as percentage rainfall					
	19–20		20–21		21–22		19–20		20–21		21–22	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Chitedze -CA	17	85	20.3	101.5	14	70	2.2	10.8	2.2	11.2	1.8	8.9
Chitedze -CT	17.3	86.5	19	95	12.8	64	2.2	11.0	2.1	10.5	1.6	8.2
Kabeleka-CA	37	185	29.5	147.5	19.5	97.5	5.6	27.9	3.1	15.7	2.9	14.7
Kabeleka-CT	30.5	152.5	25.5	127.5	19.6	98	4.6	23.0	2.7	13.5	3.0	14.8
Liempe-CA	NA	NA	21.7	108.5	11.8	59	NA	NA	2.5	12.5	1.4	6.8
DTC-CA	0	0	42	210	33.4	167	0.0	0.0	4.6	22.9	4.0	19.8
DTC-CT	0	0	41.5	207.5	33	165	0.0	0.0	4.5	22.6	3.9	19.6
DTC-Woodlot	0	0	58	290	39.3	196.5	0.0	0.0	6.3	31.6	4.7	23.3
NUESOM-CA	5.8	29	56	280	47.5	237.5	1.5	7.6	6.1	30.6	5.6	28.2

NA loggers failed at these sites for some monitoring periods. S_y range of 0.01 and 0.05 used for consistency with other studies in similar geology (e.g. Cuthbert et al. 2019)

Relationship between cumulative rainfall and groundwater levels

The relationship between the changes in cumulative rainfall and groundwater levels is shown in Fig. 3. The rainfall intensity (in mm) for each event is also displayed as a ribbon along the top of each annual hydrograph to allow an assessment of the impact of individual rainfall events, which vary considerably in magnitude and duration, on groundwater level responses. Temporal changes in groundwater levels and cumulative rainfall by recharge year are also shown in the supplementary information for completeness (Fig. S1 of the ESM).

Based on groundwater response and cumulative rainfall curves (Fig. 3) at the four study sites, there are two basic types of response—rapid and delayed responses. Domboshawa and Kabeleka may be considered rapid response sites; Chitedze is a delayed response site, while Liempe falls somewhere in between. At the ‘rapid’ response sites, there is an initial period of soil-moisture replenishment with rainfall but no groundwater recharge. Thereafter recharge is controlled by the amount and intensity of the rainfall and the balance between those and losses to evaporation and soil-moisture replenishment and minimal runoff. At the ‘delayed’ response sites, groundwater recharge is delayed by a low permeability surface. At Chitedze this appears to be a widespread thin (10–25 cm) indurated silcrete layer a few meters below the surface.

Annual recharge estimates using WTF and CMB

Comparing the groundwater level responses and rainfall dataset in Figs. 2 and 3, there is a noticeable effect of the antecedent conditions, i.e. an effect of the groundwater level of the previous year on recharge for a given year, irrespective of rainfall totals. This observation is clearest at the Kabeleka and Domboshawa sites, but is also noticeable but more subdued at Chitedze and can be attributed to the capacity of the groundwater system to receive more recharge under lower groundwater level antecedent conditions compared to higher groundwater level conditions and the fact that these shallow aquifers appear to be conductive with interconnected flow paths, resulting in individual piezometers returning to similar levels at the end of the groundwater recession.

Recharge estimates using WTF (Table 2) and CMB methods (Table 3) are presented, using Sy ranges of 0.01 and 0.05 for consistency with other studies (see Cuthbert et al. 2019). WTF estimates in Table 2 are shown separately for CA and CT sites for Chitedze, Kabeleka and Domboshawa DTC, as well as results for the NUESOM CA and Woodlot sites for comparison. Absolute recharge (mm/year) and recharge as a percentage of rainfall are shown for each site. For Chitedze, the percentage of rainfall values show comparable results for 2019–2020 and 2020–2021 recharge seasons (~2–11%) and slightly lower recharge for 2021–2022 (2–9%), with overall similar ranges for both CA and CT. Kabeleka shows the highest recharge for the 2019 season (5–28%), which is nearly double that for the two subsequent recharge seasons

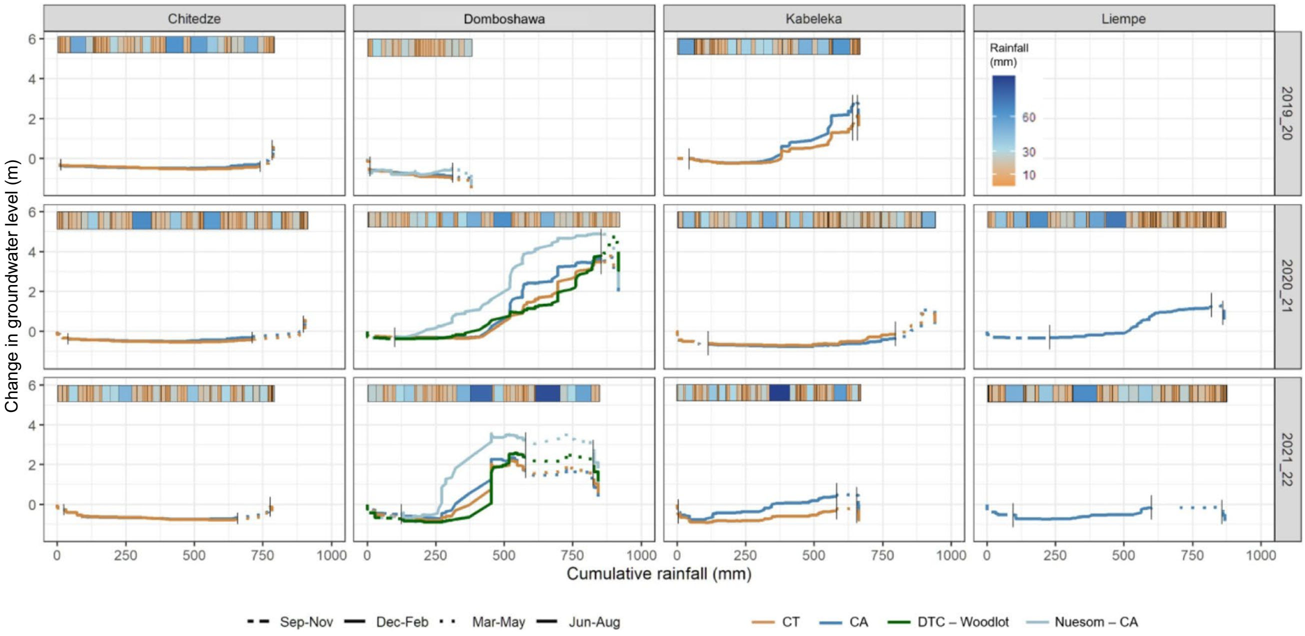


Fig. 3 Relative changes in temporal trends in rainfall and groundwater levels for all sites. The ribbon plots at the top of each subplot show rainfall totals for each event in mm. There are no observations for Liempe in the 2019–2020 season

Table 3 Recharge estimates using the CMB method

Site	Year	Groundwater Cl mg/L		Upper bound of recharge as percentage of rainfall			
		Average	Median	P25	P75	Median	Range
Chitedze	19–21	0.24	0.26	0.18	0.67	94	36–134
DTC CA and CT	20–22	0.63	1.76	1.53	1.96	36	32–41
NUESOM CA	2020–2021	0.63	5.28	5.13	5.49	12	12
Liempe CA	2020–2021	0.15	2.99	2.61	11.2	5	1–6
Kabeleka CA and CT	2020–2021	0.15	1.71	1.09	4.76	9	3–13

CMB estimates averaged across CA and CT for individual sites, inadequate data collected from DTC-Woodlot site for comparison using CMB. Average rainfall Cl values are weighted for 2020–2022. P25 = 25th percentile, P75 = 75th percentile

(3–16%). For the 2019–2020 and 2020–2021 seasons there is higher recharge at the CA sites compared to the CT sites, whereas for that of 2021–2022, recharge estimates were comparable (Table 2). In 2019–2020, there was no recharge at the main Domboshawa sites for either CA or CT treatments or the Woodlot; however, there was 2–8% rainfall recharge at the NUESOM CA site, while for DTC, recharge was slightly higher in 2020–2021 (5–23%) compared to 2021–2022 (4–20%) and comparable for CA and CT. The Woodlot and NUESOM CA sites had higher recharge compared to the DTC sites for the 2020–2021 and 2021–2022 recharge seasons.

CMB recharge values as percentage of rainfall are shown in Table 3. The CMB recharge estimates for DTC and NUESOM give internally consistent results (see small IQR), with median values for recharge as 32–41% rainfall (far exceeding typical literature values) and 12% rainfall respectively. CMB estimates from the Kabeleka site give a median of 9% and IQR of 3–13% rainfall, whereas the Liempe site gives the lowest median (5% rainfall) and a range of 1–6% rainfall. For Chitedze, the CMB results for recharge are very high and are with a median of 94% and IQR or between 36–134% rainfall. Runoff from the sites used in this study is likely to be low, with perhaps the exception of the NUESOM CA site where there may be some localized runoff due to a granitic outcrop and, as such, provide an upper bound for groundwater recharge.

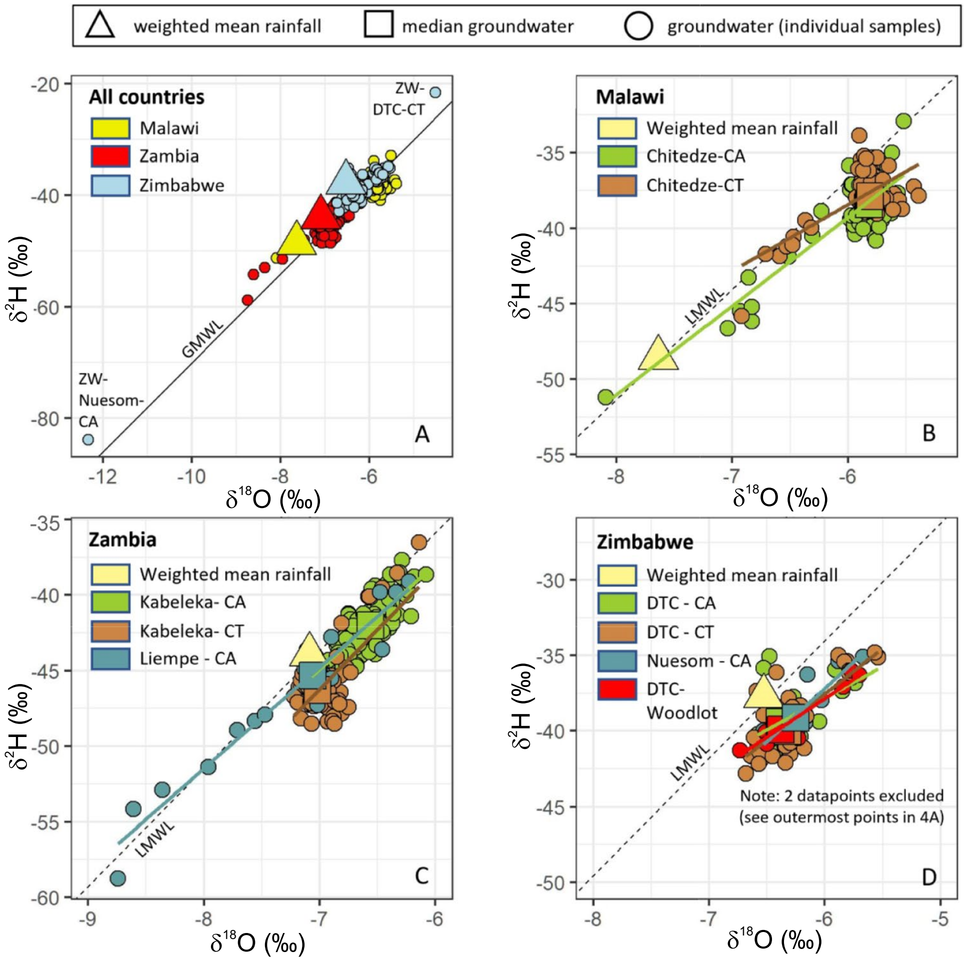
Stable isotopes

Figure 4 shows the stable isotope results (δ^{18}O vs δ^{2}H) in the groundwater in all three research countries, together with the median groundwater values, the LMWL (local meteoric water lines) and the mean weighted rainfall values. The rainfall results from this study used to define the LMWL were consistent with available data from the GNIP database (IAEA/WMO 2023). Figure 4a shows the results from all the sites on a single plot for comparison purposes. Figure 4b–d shows the results by country and the groundwater samples have been differentiated based on whether they have been collected from boreholes beneath CA or in CT systems. Groundwater isotope values fall close to the GMWL and below the LMWL in most cases.

At the Kabeleka site, there were also statistically significant stable isotope differences in the results (δ^{18}O and δ^{2}H) between CA and CT sites ($p > 0.00001$, Wilcoxon rank sum test), with groundwater beneath CA fields showing a much larger variation and more enriched stable isotope values compared to those beneath CT (see Fig. S2 of the ESM, a histogram of δ^{18}O for the Kabeleka site). These groundwater stable isotope results (see Fig. 4c) suggest that while both CA and CT techniques capture 'depleted' heavy rainfall events, the CA plots also capture the more 'enriched' lighter rainfall events giving a more enriched stable isotope signature from the CA groundwater monitoring points. This is consistent with the Kabeleka hydrograph data which also shows greater recharge at CA sites than CT sites. CT samples plot further away from the LMWL compared to CA samples with enrichment in δ^{18}O relative to δ^{2}H (see differences in slopes for the two populations), indicating that there may be some small evaporative effects prior to recharge (Fig. 4c).

No statistically significant differences ($p > 0.05$) in terms of CA vs CT were observed at Chitedze or Domboshawa (Fig. 4). There were significant differences between weighted mean rainfall values for Chitedze and average groundwater concentrations with significant enrichment in groundwater isotope values (Fig. 4a,b). This is consistent with evidence from the Chitedze hydrographs (Fig. 2), which indicate delayed recharge, considered due to a widespread low permeability siliceous pedicrete. There is some evidence for a small amount of evaporative enrichment in groundwater isotope values at sites in Malawi and Zimbabwe by comparing groundwater regression lines to weighted mean rainfall values and LMWL (Fig. 4b,d). For the Zambia data (Fig. 4c), the Liempe CA site shows the greatest spread of groundwater isotope values, and there is no clear evidence for evaporative enrichment in groundwater isotope values by comparing these results with the LMWL.

Fig. 4 Groundwater stable isotope results, **a** all results plotted with weighted mean rainfall values, **b** Chitedze isotope results, **c** Kabeleka and Liempe results, **d** DTC CA and CT, NUESOM CA and DTC Woodlot results. Square symbols show median groundwater results, solid-coloured lines are individual groundwater regression lines for different sites. GMWL shown as black line (**a**), LMWL are shown as dashed lines (**b**-**d**)



Groundwater residence times

Groundwater residence time tracer results for SF_6 are shown as box and dot plots from all three research countries in Fig. 5. There was good agreement between the two sampling rounds and between the different observatories. There was no significant difference ($p > 0.05$) between median results, pooled across both rounds, from the four different observatories (Wilcoxon rank sum test).

Cross-plots of CFC-12- vs SF_6 (Fig. S3a of the ESM) and CFC-11 vs CFC-12 (Fig. S3b of the ESM) are given in the ESM. The cross-plot of CFC-12 vs SF_6 may at first suggest that the dominant flow mechanism is piston flow (Fig. S3 of the ESM). However, Fig. S3b of the ESM shows that few samples fall within the envelopes of the piston flow mixing model. This strongly suggests that both tracers are influenced by a small but significant degree of contamination and that a piston flow model may not be an appropriate flow model to use for these samples. While the contamination makes the CFC data unsuitable as a quantitative tracer in these samples, the low level of CFC contamination does suggest that there may be a relatively small component of modern recharge reaching the groundwater at the screened sections within these monitoring piezometers.

There is no evidence of SF_6 contamination in these samples (Fig. 5); thus, the remaining interpretation of residence time results will use these data (CFC data are not considered further). Given that these sites are not pumped, are not particularly shallow (screens are completed typically between 8–10 m below ground level), and have relatively narrow screens which intersect the weathered basement, a binary mixing model between SF_6 'dead' (>50 years) and modern recharge is considered the most appropriate mixing model to use to interpret the residence time data. On this basis, groundwaters have overall a low but highly variable fraction of modern water <0.01- 0.049 for DTC, <0.01–0.22 for Chitedze and <0.01–0.36 for Kabeleka. The NUESOM CA site at Domboshawa has a significantly higher fraction of modern recharge (0.19, see outlier in Fig. 5) compared to the other sites. There is a single sample with a high fraction of modern value from the second round of sampling in 2020 at Chitedze (0.22, see outlier in Fig. 5); if this sample is not included then the modern fraction range for Chitedze is <0.01- 0.048, almost identical to that of DTC.

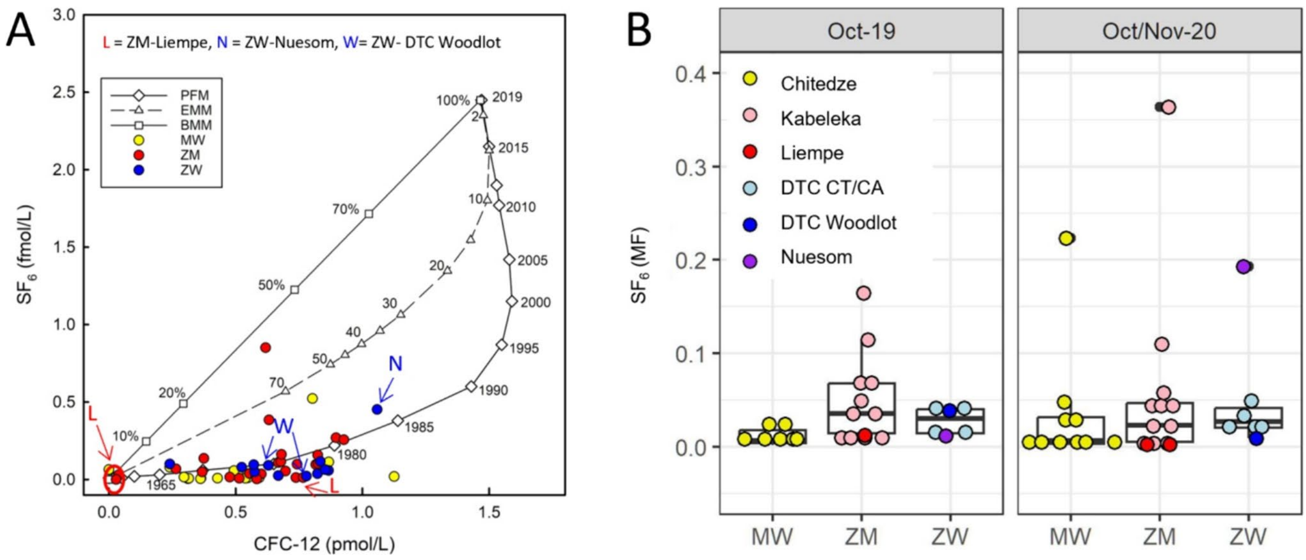


Fig. 5 Groundwater residence time data: **a** Bow-plot of CFC-12 vs SF_6, **b** box-plots and dot-plots of SF_6 modern fraction results from the three observatories by sampling round. Some clear outlier values referred to in the text are highlighted. MW Malawi, ZM Zambia, ZW Zimbabwe, PFM piston flow model, EMM exponential mixing model, BMM binary mixing model

Discussion

Groundwater recharge estimates

The groundwater recharge values estimated for these four study sites using the WTF method show considerable variation between year and between sites. Across all sites and years, the range of recharge was found to be between 0–28% rainfall. Using a S_y of 0.01 for years when recharge occurred, recharge ranged between 1–6% rainfall, whereas with an S_y of 0.05 the range was 7–28% rainfall. S_y values obtained from short duration pump tests were comparable or lower than 0.01 and may lead to an underestimate of S_y and recharge (Cuthbert et al. 2019). Chloride mass balance estimates result in higher estimates by comparison due to underlying assumptions regarding inputs of Cl and minimal runoff. There were no statistically significant differences in recharge (in terms of rainfall percentage) between Domboshawa, Kabeleka and Liempe (Table 2). However, using data from 2020–2021 and 2021–2022 for comparison from CT and CA sites (where recharge occurred at all sites), in terms of absolute recharge ranges (mm/year), Domboshawa (22–210) > Kabeleka (20–147) > Liempe (12–108) = Chitedze (13–101).

Water-table fluctuation recharge estimates in this study are comparable with the range of previous recharge estimates using different techniques in all three countries, including long-term average (LTA) recharge estimates. The results from this study show a highly variable recharge, which changes each year in relation to antecedent groundwater conditions as well as rainfall totals and rainfall distributions. This concurs with the wide range of rainfall threshold values reported in groundwater studies across Africa (Houston 1988; Macdonald and Edmunds 2014; Bredenkamp 1988; Kotchoni et al. 2018; Sibanda et al. 2009). Furthermore, MacDonald et al. (2021) found little evidence for a generalisable threshold and found that significant recharge can occur even with rainfall below 250 mm/year depending on the nature of the rainfall, especially the number of consecutive wet days and the hydrogeological setting. This study corroborates this, while there was no recharge quantified at the sites located nearer the interfluve at Domboshawa in 2019–2020, there was recharge at the NUESOM CA site which was located closer to the local dambo and may represent either localised focussed recharge and enhanced runoff from a large nearby granite outcrop or lateral flow from the interfluve towards to valley bottom (MacFarlane 1992).

In Zambia there are no previous recharge estimates for basement settings; however, for the dolomites Houston (1982) estimated LTA recharge as between 10–20% which is higher than WTF estimates for Kabeleka and Liempe but is more comparable with CMB estimates for these sites in this study (Table 3). In Malawi Smith-Carington and Chilton (1983) reported recharge estimates between 10–35 mm/year using WTF methods in basement settings which are higher but comparable with our average recharge estimate of 8±1.5 mm/year at the Chitedze site. This and other recent work by MacDonald et al. (2021) using LTA rainfall do suggest that the Chitedze site is at the lower end of the rage of recharge totals in basement settings that have been reported in Malawi and elsewhere in southern Africa.

Driving factors of groundwater recharge

Annual rainfall totals were an important control on recharge in the presented study areas (Fig. 2), as has also been demonstrated recently using LTA rainfall across Africa (MacDonald et al. 2021). However, there are also clear hydrogeological controls—for example the effect of the low permeability silcrete horizon at Chitedze, which affects the magnitude and timing of recharge and length of lags between rainfall and recharge peaks and recession. Rainfall threshold controls are demonstrated by the lack of recharge in 2019–2020 in Domboshawa at all sites except the NUESOM CA monitoring well and the overall timing of recharge for the other two recharge seasons. The consistently earlier response to rainfall at NUESOM CA and greater recharge totals at this and the Woodlot site compared to the other sites at Domboshawa are likely due to (1) focused fracture flow recharge and locally enhanced recharge due to high run-off from nearby solid granite dome at the NUESOM CA site and (2) enhanced macropore flow at the Woodlot site due to the effects of tree roots (Bargués-Tobella et al. 2020).

Low antecedent groundwater level conditions work to increase recharge in years where there is a lower starting groundwater level at the end of the recession. Conversely, there is lower recharge in years where the starting groundwater levels are higher. This is illustrated by plotting pre-recharge WL vs maximum estimated recharge (% rainfall) for each recharge season and site (see Fig. S4 of the ESM). This finding is consistent across all four study sites; however, slopes do differ between sites, and it must be noted that these relationships are based on a limited set of observations.

At Kabeleka there was a large recharge response relative to rainfall in 2019–2020 compared to 2020–2021 and 2021–2022. This is likely to be due to the low antecedent groundwater levels prior to recharge. However, the nature of the rainfall could also be a factor, with a larger number of consecutive large (>30 mm) events in 2019–2020 compared to the other seasons when larger events were more isolated by low rainfall events, although the effect of a large intense rainfall period in the middle of the 2021–2022 season is still clear (Fig. 3). For Chitedze there is a consistent lag of ~3 months between peak groundwater levels and the end of the period of greatest cumulative rainfall (Fig. 2), and a much more subdued groundwater level response to rainfall. The effect of antecedent groundwater level controls is also apparent (Fig. 2), likely due to an extensive semiconfining silcrete layer present at ~2 m depth at the Chitedze site. This could act as a barrier and a delay to recharge, leading to the formation of a temporary perched water table which slowly leaks downwards over a period of months to the groundwater table below. Silcrete, calcrete and lateritic layers are common in basement aquifer systems in Africa and have been shown to be important for controlling recharge rates (MacFarlane 1985; Thiry 1991; Lee and Gilkes 2005) and in some settings enhance focused recharge (Scanlon et al. 2006). Overall, temporal recharge patterns for Chitedze and Kabeleka were similar with an increase in maximum and minimum groundwater levels in the first two recharge seasons followed by a decrease in maximum groundwater levels in the final recharge season, likely driven by antecedent conditions and the overall lower rainfall totals in 2021–2022 at both sites.

At Liempe CA, there are small groundwater level responses and resulting low recharge in the 2021–2022 season that had comparable rainfall totals to the previous year. This could be linked to the lack of high-intensity rainfall events early in the rainfall season and the lack of consecutive high rainfall events later in the rains (Fig. 3).

There was no significant difference in recharge totals between most CA and CT sites over the study period (Table 2). However, there were some differences in the onset and timing of recharge at two sites—Kabeleka and Domboshawa (Fig. 3)—and perhaps some evidence for this for the first two recharge seasons at Chitedze (Figs. 2 and 3). Over the three years the onset of recharge is earlier under CA and the response to individual recharge events is greater, while at Kabeleka, the total annual recharge under CA is greater than under CT. This is particularly apparent for larger consecutive rainfall events at Kabeleka in 2019–2020. These findings, together with the differences in stable isotope values at Kabeleka (Fig. 4c), suggest, that at some sites, CA is leading to groundwater recharge from a broader range of rainfall events compared to conventional tillage with no mulching. There is no irrigation done at Kabeleka which rules this out as a possible explanation for the differences in water isotopes and recharge totals and timings observed under CA and CT. It is also possible that small-scale differences in localised flowpaths (e.g. better connectivity of soil porosity), which could bypass soil moisture demands, could also explain some of the differences evidenced at Kabeleka (Cooper et al. 2021; Zarate et al. 2021). Further investigations using temporal soil moisture and/or resistivity measurements could shed light on the importance of a by-pass mechanism at these sites.

The higher organic matter content in the overlying soil at CA sites, through the addition of mulch/crop residues, may enable the soil to retain greater moisture during the onset of the rainy season and during dry spells (Thierfelder and Wall 2009; Ligowe et al. 2017; Mbanyele et al. 2021) and can therefore capture recharge from a wider range of rainfall events. It was noted that the CA practices at Kabeleka were more intensive than those observed at Domboshawa and Chitedze. Peak hydrographs are higher for CA compared to CT at Kabeleka. It was also found that the end-of-dry-season baselines for all hydrographs largely coincide for the CT and CA sites. This is considered due to the high connectivity of the aquifer within these systems, with the implication being that if CA, as intensive CA farming such as is undertaken at Kabeleka, is widely adopted, then the local groundwater levels could rise above the levels attained under CT, corroborating the findings from some studies using indirect methods of assessing recharged under CA and non-CA reviewed by Mudimbu et al. (2022).

Groundwater residence times in unpumped aquifers

The groundwater residence time tracer results show that for most sites there is only a very small fraction of modern recharge present in the groundwater systems beneath the four observatories, typically less than 0.05 or 5% for most observations (Fig. 5b). The concentrations of CFC and SF_6 tracers found in this study are significantly lower than those found in shallow handpump samples from the basement setting in West Africa (Lapworth et al. 2013), and more recently in southern and eastern Africa (Banks et al. 2021), using common sampling and analytical methods. The pumped sites are also typically drilled deeper than the monitoring sites used in this study, which together, strongly suggests that the groundwaters from the monitoring wells in this study have a much lower fraction of modern recharge compared to pumped sites in similar basement settings. At pumped sites, there may be enhancing groundwater capture (Bredehoeft 2002) due to decreases in outflow to gaining streams. The high outlier modern fraction results in Fig. 5, and low Cl groundwater values could be interpreted as evidence for localized focused recharge at some sites/occasions (Lapworth et al. 2013). While this has been proposed as the dominant pathway in some more arid settings (e.g. Seddon et al. 2021; Lapworth et al. 2013), the evidence from hydrographs, isotopes and age tracers in this study suggests that, in more humid basement settings with more limited alluvial storage, diffuse recharge pathways dominate over focused recharge. However, where there is no pumping, replenishment with more modern recharge is more limited due to the good lateral connectivity within the aquifer and discharge to the surface drainage network. Furthermore, given the good aquifer connectivity at this study's sites, there may be a plot scale effect, i.e. at locations where plot sizes were relatively small (e.g. Liempe and Chitedze for CA), any difference between recharge due to CT and CA would be small, which is what has been observed in this study.

Conceptual model of groundwater recharge processes

A generalized schematic conceptual model of recharge processes is shown in Fig. 6. This incorporates findings from the observatories in this study which include a range of basement hydrogeological conditions found in this region. The magnitude of changes in groundwater levels, and hence annual recharge, are controlled by a number of factors: (1) rainfall totals, (2) the nature and timing of larger rainfall events, (3) the location within the groundwater catchment and proximity to the interfluve, (4) the local hydrogeological conditions in the shallow subsurface and (5) the presence of low permeability horizons which may dampen and delay the recharge response. High lateral flow and good connectivity are required in the shallow groundwater system to remove annual recharge and redistribute it effectively within the shallow aquifer. This leads to common baseline points at the end of the recession each year for different sites which may vary between years depending on antecedent conditions. Bonsor et al. (2014) noted the effect of shallow laterite layers in Nigeria leading to rapid lateral flow and common baseline points each year.

Under unpumped or low pumping conditions, groundwater levels are relatively high, potentially leading to enhanced lateral flow and connectivity with surface-water bodies. This leads to reduced groundwater recharge relative to pumped conditions where groundwater capture reduces losses to rivers and increases the fraction of modern recharge at abstraction sites, which is reflected in the overall low fraction of modern recharge found at the sites in this study (Fig. 5b) compared to other studies using shallow pumped sites in sub-Saharan Africa (e.g. Lapworth et al. 2013; Banks et al. 2021). Pumping will enhance drawdown of recent recharge in the shallow saprolite, activate fracture flow and focus groundwater flows towards abstraction points.

This study supports the hypothesis that annual recharge totals in most cases do not differ significantly under CA vs CT, and are largely controlled by antecedent conditions and rainfall totals. However, there is evidence from both water isotope results and hydrograph responses that, where CA is practiced more rigorously over larger areas, groundwaters are recharged from a wider range of rainfall events and have an earlier recharge response at the onset of the rainy season. These effects are particularly noticeable at the Kabeleka field site. At smaller plot experiments, these differences were much less obvious, and it is also likely that the good aquifer connectivity at these sites leads to a more uniform response during the recharge and recession period.

Conclusions

Empirical evidence from hydrometric measurements, groundwater chemistry, water stable isotopes and groundwater residence times tracers have shown the dominance of diffuse groundwater recharge processes and rainfall variability controls in three subhumid dryland settings across the SADC region. Absolute recharge varies considerably and is linked to both interannual rainfall variability, as well as

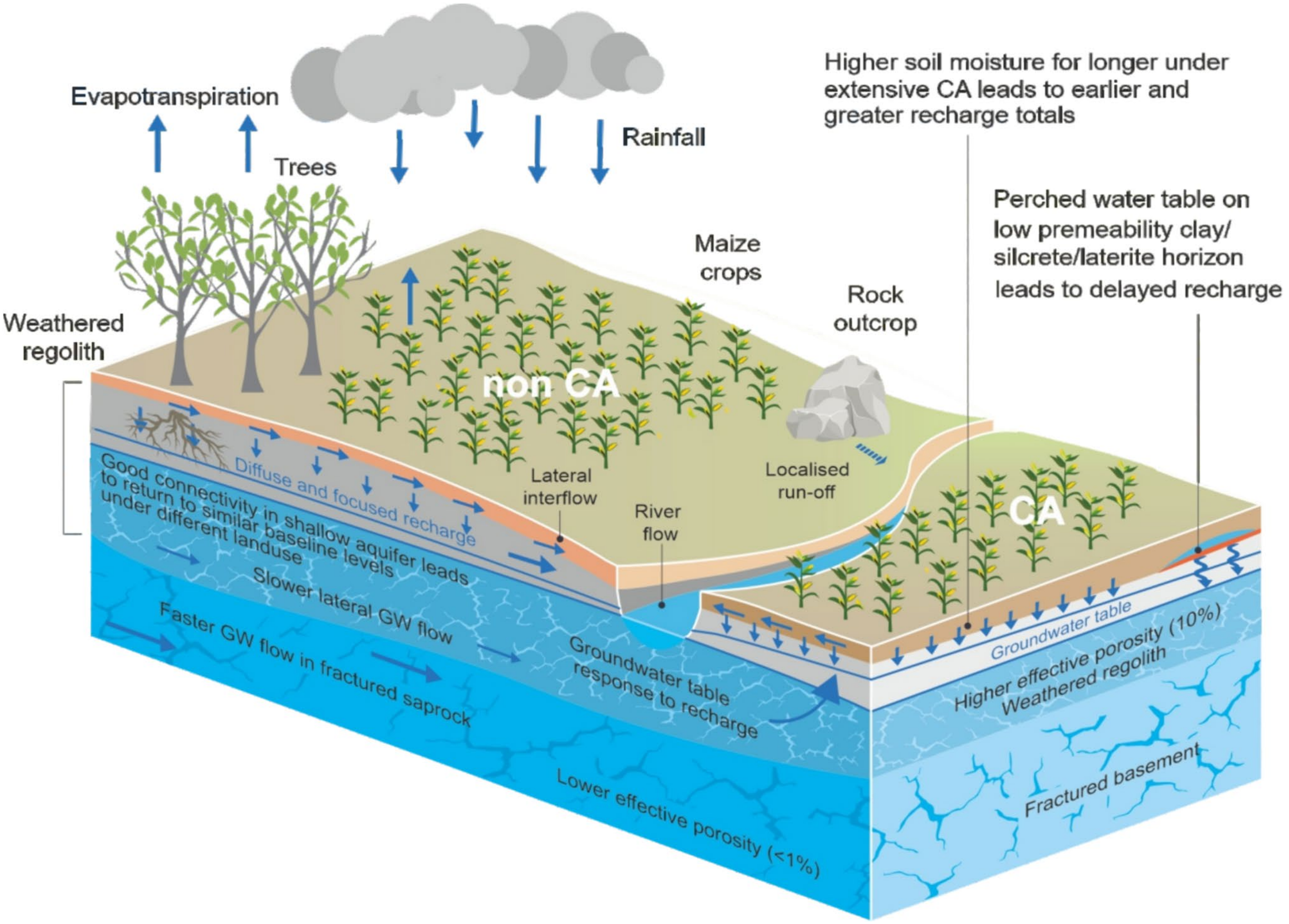


Fig. 6 Conceptual model of groundwater recharge in humid dryland basement settings. CA conservation agriculture

local hydrogeological conditions and the timing and magnitude of rainfall events. Annual recharge estimates using WTF at these sites show a wide range of results for recharge (0–28% of rainfall, median range 21–105 mm/year), and no significant difference between the three sites in Zambia and Zimbabwe.

Lower recharge at Chitedze (Malawi) is likely due to local hydrogeological controls associated with an extensive low permeability silcrete horizon which delays recharge responses and enhances lateral flow processes at this interface.

There is evidence from hydrometric and isotope results that there is an earlier recharge response, higher total recharge and recharge from a greater range of rainfall events at Kabeleka CA sites where significant mulching with zero tillage practices are employed. Groundwater levels in these CA boreholes showed less decline compared to CT sites by the end of the dry season, indicating greater recharge under extensive CA. However, groundwater recession trends were similar, and this is considered to be due to significant lateral flows to the local groundwater base levels.

Groundwater residence time results gave low modern fractions of recharge in this network of unpumped sites, and concentrations of tracers (CFCs and SF_6) were significantly lower than those from pumped sites in published studies across Africa collected using comparable methods. This underlines the importance of lateral connectivity and flows to natural discharge points such as rivers and wetlands in unpumped systems, which are ‘full’ and in ‘equilibrium’ with LTA rainfall, and in contrast, the role of groundwater capture of modern recharge in pumped systems. These new insights inform our understanding of rainfall controls on groundwater recharge and provide some early insights regarding the limited impact of nature-based solutions (NbS) such as mulching and zero tillage on annual recharge totals in humid dryland settings in the SADC region. Further work is needed to improve the spatial and temporal resolutions for empirical observations required to underpin or understand the impact of climate change on water resources, the impact of policies related to NbS and to inform use and management of groundwater resources in this region.

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Declarations

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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