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Optimizing the contributions of sand dam water storage through understanding their spatiotemporal variability: Evidence from the Shashe catchment, Limpopo, River Basin

Girma Yimer Ebrahim [a,*], Jonathan F. Lautze [b], Matthew McCartney [c], Fortune Batiya [d], Stephen Hussey [d], Joyce Dube [d]

[a] International Water Management Institute, Addis Ababa, Ethiopia
[b] International Water Management Institute, Pretoria, South Africa
[c] International Water Management Institute, Colombo, Sri Lanka
[d] Dabane, Bulawayo, Zimbabwe

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ABSTRACT

Study region: Shashe catchment, Limpopo River basin, Zimbabwe

Study focus: Sand dams, small structures built in ephemeral rivers to capture and store river flows in the sand, provide an important water source for rural communities that lack formal infrastructure. While their potential benefits are increasingly recognized, the spatiotemporal variability in the water they store remains unstudied. This knowledge gap constrains evidence-driven planning for sand dam development and limits the incorporation of sand dams into an integrated storage framework, a key approach to enhance resilience by satisfying storage needs from a diverse range of sources. To address this gap, this study uses in situ data to report on the spatiotemporal variability of water storage in sand dams in the Shashe catchment of the Limpopo River Basin. Five sand dams and two natural (i.e., undammed) sites were monitored weekly for water level fluctuations from January to December 2024.

New hydrological insight for the region: Results indicate that all sand dams greatly improve water availability during the dry season compared to natural sites. Sand dams built on larger rivers are nonetheless more effective at maintaining water supply throughout the dry season. Seepage is identified as the primary pathway for water loss from the sand dams. To unlock the full potential of sand dams, planners should actively consider siting parameters, namely the river width, sediment accumulation thickness, sand accumulation area, and catchment area. Utilizing these criteria to inform planning can enhance the contribution and impact of sand dams, building more resilient and sustainable water systems.

1. Introduction

There is a growing consensus on the benefits of sand dams (Lasage et al., 2008; Lazurko et al., 2024; Maddrell and Neal, 2012; Ritchie et al., 2023; Ryan and Elsner, 2016), impermeable concrete structures constructed across seasonal alluvial rivers to capture and store water in the sand that accumulates upstream of the dam. Sand dams contribute to the resilience of dryland communities, making

* Corresponding author.
E-mail address: g.ebrahim@cgiar.org (G.Y. Ebrahim).

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them valuable tools for climate change adaptation in arid regions (Ryan and Elsner, 2016). As the population grows and climate change intensifies, water demand is expected to rise, making sand dams even more crucial for water security.

At least two key knowledge gaps limit the optimal roll-out of sand dams. First, the temporal dynamics of water level variations are not well understood. This limits the ability of communities to predict the duration of dry season support that sand dams will provide, as

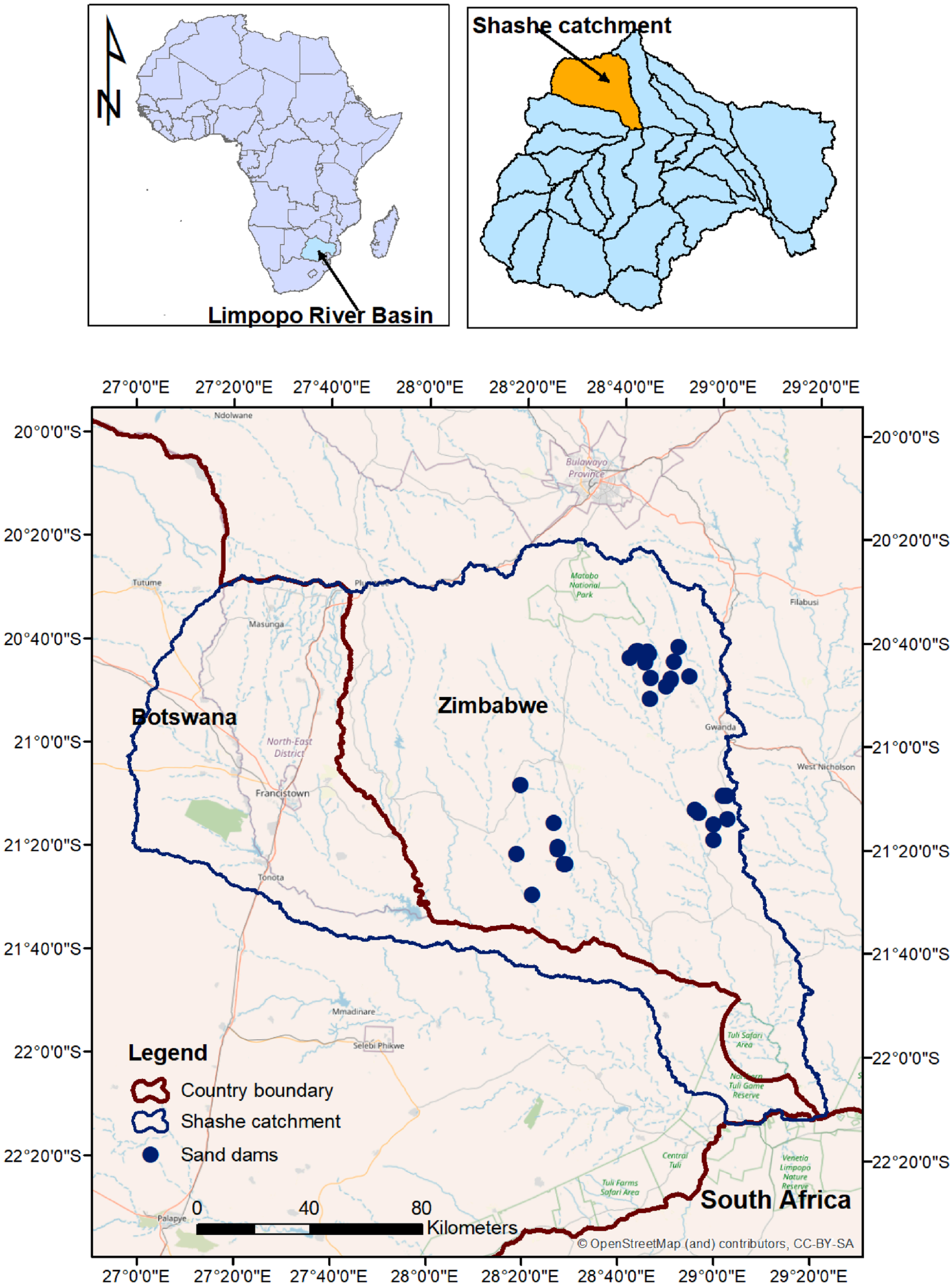

Fig. 1. Sand dams in Shashe catchment.

well as the capacity of planners to integrate sand dams into an overall storage framework – one that considers the role of sand dam storage alongside groundwater, conventional surface reservoirs, and soil to enable decision-making that leverages the comparative advantages of different storage types across seasonal water availability. Second, the spatial variability of sand dam impacts remains unexamined using in situ data. Assessing this variability can provide practical guidance on the conditions and sites that derive the greatest benefits, which is crucial for maximizing the effectiveness of this technology.

Research on the spatial and temporal dynamics of sand dams is limited. Ritchie et al. (2023) inferred from abstraction data that sand dams significantly contributed to water availability during the dry season in Kenya. Lazurko et al. (2024) utilized focus group discussions to identify that sand dams significantly enhance community resilience to climate variability by improving local water availability, especially during droughts, in Zimbabwe. While Quinn et al. (2019) provided critical foundational insights into water balance variability across sand dams in Kenya, their study was a targeted assessment of water transfer mechanisms between the sand dam and the surrounding aquifer during a specific two-month dry season window (late May to late July), using biweekly water level data. To build on these findings, the present study expands the temporal, spatial, and geographic scope of sand dam research. While Quinn et al. (2019) offered a valuable snapshot of water level fluctuations within a single geographic region, this research incorporates sites distributed across two distinct regions to assess spatial variability in storage dynamics. By utilizing high-frequency weekly sampling across both wet and dry seasons, this study provides a comprehensive evaluation of storage dynamics over a year. This approach, combined with a comparative framework between natural river channels and sand dam sites, allows for quantification of the specific hydrological impacts of these structures relative to baseline conditions. This study addresses a key knowledge gap by offering the first granular assessment of sand dams in Zimbabwe, where sand dam performance remains under-researched.

The objective of this study was to quantify and analyze the temporal and spatial variability of water storage capacity in sand dams within the Shashe catchment of Zimbabwe, to support optimization of their placement and facilitate their incorporation into an integrated water storage decision-making framework. This study addresses the following research questions:

1. How does sand dam water storage fluctuate over time?
2. How does the capacity of water storage vary among sand dam sites?
3. What are the main factors affecting the duration of dry season sand dam water storage?

2. Study area

The Shashe catchment covers approximately 30,000 km^2 and is home to 430,000 people (WorldPop, 2020). It is shared by Botswana and Zimbabwe and has the third-largest flow among sub-basins in the Limpopo River Basin. Rainfall in this area is highly variable and often unreliable. The average annual rainfall in the Shashe catchment is 450 mm, with 95 % of the rainfall occurring between October and April. The annual rainfall varies greatly, with an interannual coefficient of variation (CV) of 107 % from 1981 to 2021. The catchment is classified as semi-arid, with an aridity index of 0.25. The average annual potential evapotranspiration is 1954 mm, and temperatures range from 28°C to 15°C.

Geologically, the study area mainly consists of basement rocks, mostly igneous and metamorphic varieties, with Granite, Syenite, Gabbro, Gneiss, and migmatites covering approximately 79 % of the region. The soils are immature and highly erodible, primarily sandy loam covering about 77 % of the area. Luvisols make up nearly 67 % of the land, followed by Leptosols (18 %), Arenosols (8 %), and Lixisols (5 %). Luvisols are effective at retaining water due to their well-developed structure (Jones et al., 2013). Shrubs cover roughly 57 % of the Shashe catchment.

Over 30 sand dams have been built across the Shashe catchment, ranging from newly completed to fully operational structures (Fig. 1). All these sand dams are built in the Zimbabwe portion of the basin, and none exist in the Botswana portion. Dabane, a local non-governmental organization, built most of the sand dams. Dabane started constructing sand dams in the area in 2004, with the Jabulani sand dam being their first project. Unlike traditional dams that store water in open reservoirs, sand dams store water within the sediment that accumulates behind the dam wall. Because of their low capital costs, typically between $8000 and $12,000 per dam, sand dams are suitable for poor rural communities (Ritchie et al., 2021; UNDP, 2014). The sand acts as a natural filter, reducing contamination and minimizing evaporation. A major advantage of sand dams is that they can be managed and operated by low-income communities, giving them greater control over their water supply. Their decentralized structure allows sand dams to be built in various locations across a landscape, effectively reaching dispersed rural populations. A typical sand dam built by Dabane is shown in the Electronic Supplementary Material (ESM), section S1.

Several factors have been presumed to influence the degree of benefits derived from particular sand dams. Sediment characteristics play a crucial role; fine sediment indicates limited total void space, reducing water storage capacity, while well-sorted, coarse-grained sediment with minimal silt suggests better storage potential. Coarse sand from granite or gneiss has good water storage potential (Hussey, 2007). Rivers flowing over hard, crystalline terrains erode slowly, while those crossing softer, unconsolidated sedimentary rocks carry larger sediment loads and are good for sand dams (Chakrapani, 2005). The river gradient is another important factor, as a steep gradient prevents sediment from being deposited. If the flow is too fast, especially in the headwaters, sediment won't settle. Generally, sand dams are most effective when built on gentle slopes, typically ranging from 1 % to 2 %, as these gradients provide the best water storage (SSWM, 2025). A steeper gradient also decreases the throwback distance and dam capacity; a Kenyan study demonstrated that lowering the gradient from 2 % to 1 % doubled sand dam storage (Maddrell and Neal, 2012). The location of the sand dam is also important, as sand dams farther downstream tend to experience faster sedimentation due to increased water discharge and sediment load. At the same time, sites near the head of a valley collect less sediment (Maddrell and Neal, 2012). Finally, accessible and shallow bedrock is necessary to ensure the sand dam can be built on an impermeable layer cost-effectively.

3. Methods

3.1. Selection of sites for instrumentation

Based on our objectives outlined above, we decided to focus on a combination of sand dams and natural sites. The natural sites serve as benchmarks for comparison with sand dams. A natural site refers to the unmodified bed of a sand river where a sand dam has not been constructed. At these locations, water continues to flow through the sand without being trapped, unlike at sites with sand dams. Due to budget constraints, we were able to study only seven sites.

Sand dam sites were selected based on five criteria: i) accessibility, ii) availability of design documents, iii) maturity level of the sand dams, iv) availability of water points, and v) geographic distribution. Accessibility refers to how easily researchers can reach and work at a specific location. An easily accessible site simplifies field activities, such as instrumentation, data collection, monitoring, and communication. The availability of design documents was essential for the sand dam selection process, providing key details such as the dam's height and width. Maturity level is important because it indicates how much sand has accumulated behind the dam. A sand dam is considered mature when the sediment buildup reaches the spillway, indicating that it has achieved its full water storage capacity. Since the primary goal is to evaluate the maximum water storage capacity of the sand dam, it is essential to analyze structures that have achieved full sediment retention. The criterion of water point availability was used to exclude locations with multiple unregulated extraction points, like numerous scoop holes, which could affect data accuracy and complicate analysis of water use. Geographic location criteria guided selection across diverse areas, enabling an assessment of how topography, climate, soil, and geology influence sand dam water storage capacity.

The natural sites were selected from a list of locations where communities have submitted requests to Dabane for sand dam construction. The final selections were based on two main criteria: accessibility and the site's suitability for future sand dam construction.

Based on the five criteria mentioned earlier, five mature sand dams: Mzingwane, Nathi, Pangamano, Tadla, and Tshaheyi, and two natural sites: Mawane-Zhokwe and Nsimbi, were selected (Fig. 2). All the chosen sand dams are located within the Zimbabwe portion of the Shashe catchment, specifically in Gwanda District. The selected sites are strategically positioned within two distinct clusters: the northern cluster, which includes Mzingwane and Tadla, and the southern cluster, which comprises Mawane-Zhokwe, Nathi, Nsimbi, Pangamano, and Tshaheyi. Construction years and sand dam heights for these five mature sand dams are listed in Table 1 (see section S2 of the ESM for more details). Fig. 3 shows the catchment areas for all seven sites, outlined using the 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model. Pangamano has the largest catchment area, encompassing the catchments of Nathi, Mawane-Zhokwe, and Nsimbi. The Nathi catchment also includes Mawane-Zhokwe and Nsimbi. The Tshaheyi catchment is small and drains toward the southwest. In the northern cluster, the Mzingwane and Tadla catchments are adjacent. Further details are available in section S3 of the ESM.

3.2. Spatial rainfall variability across selected sites

Daily precipitation data from 1981 to 2024 were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), a quasi-global satellite-based observation system, and other precipitation estimates (Funk et al., 2014). The year 2024 experienced below-average rainfall, marking a dry year. The long-term mean annual rainfall from 1981 to 2024 is 520 mm in the upstream cluster and 432 mm in the downstream cluster. In 2024, the annual rainfall was 433 mm in the upstream and 406 mm in the downstream clusters. Fig. 4 shows the long-term average monthly rainfall for 1981–2024 and the monthly rainfall distribution for 2024. During the rainy season, especially in January, February, and March 2024, monthly rainfall was lower than the average for those months during 1981–2024. The reductions were 20 % in January, 91 % in February, and 61 % in March.

3.3. Piezometer fabrication

Piezometers were produced at the Dabane workshop. These piezometers consisted of 40 mm-diameter polyvinyl chloride (PVC) pipes, each 3 m long. A one-meter screen was provided at the bottom of each piezometer to allow water entry. Anchoring was done using V-shaped metal well points. Additionally, a geotextile wrap was placed around the screen section to block fine sand infiltration and prevent clogging. More details can be found in section S4 of the ESM.

3.4. Piezometer installation

Piezometers were strategically placed at different distances upstream of existing and potential sand dam sites to accurately measure the longitudinal variation in water levels. Each piezometer included a screened section embedded in the sand and a tube extending above ground for measuring water levels. Since the thickness of the sand layer varies across sites, piezometers were tailored to match the specific depth at each site. About 20 cm of the piezometer in mature sand dams protrudes above ground, serving as a clear reference point for water level readings. To prevent sediments from covering the piezometers in the future, especially with the upcoming construction of sand dams, the extended portion at natural sites was designed to be relatively large. The exact location of each piezometer was determined based on site-specific conditions, as a standard interval was not feasible given the varying conditions.

Before installing the piezometers, sediment probing was conducted at each site to determine sediment thickness and identify any underlying bedrock. This is because sand rivers often have uneven sediment distribution, with patches of sediment separated by

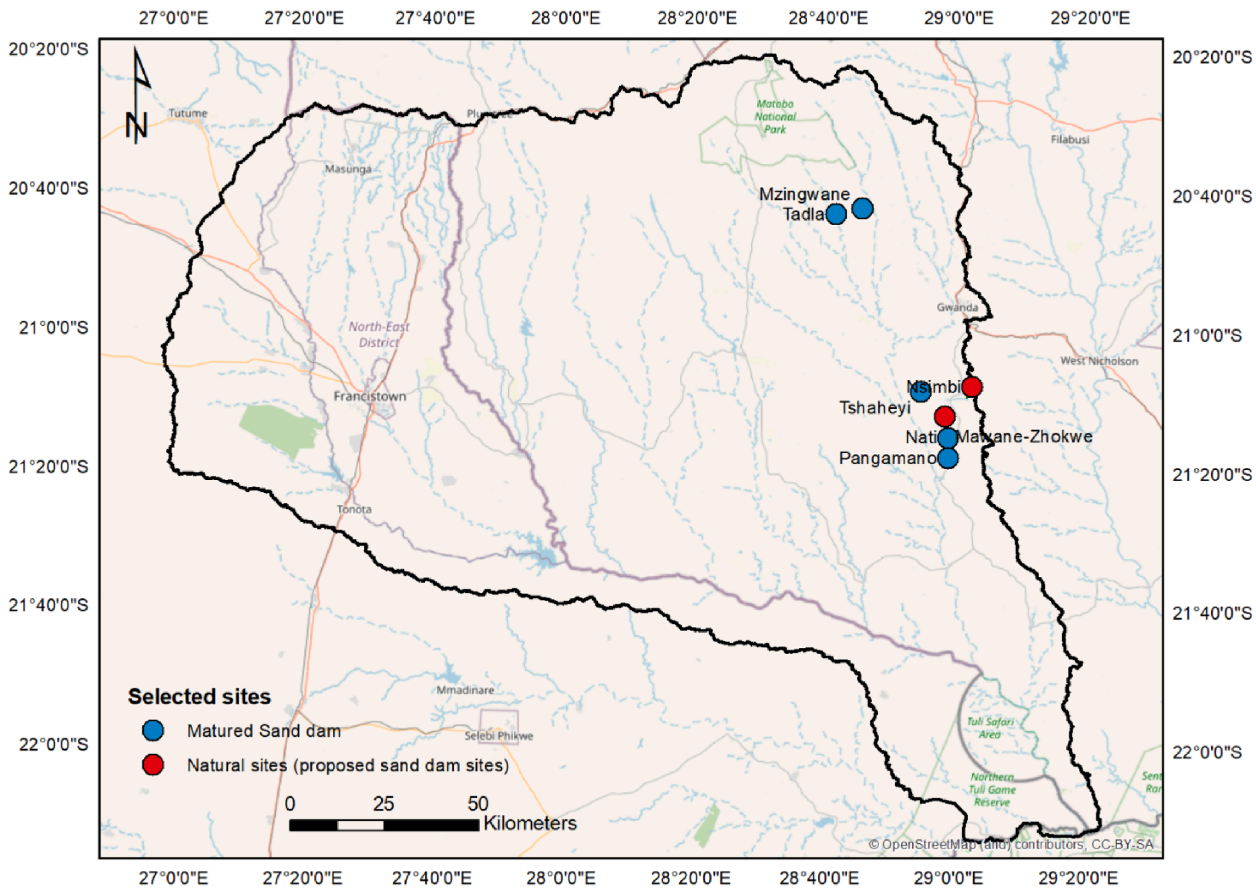

Fig. 2. Selected sites.

Table 1
Characteristics of sites.

Sites		Year of construction	Height (m)	Width (m)	Number of households	Total population	Catchment area (km^2)
Sand dam	Mzingwane	2015	2.12	16	131	524	11.6
	Nathi	2020	4.3	36.7	203	812	241.5
	Pangamano	2014	3.4	49	159	636	331.4
	Tadla	2014	1.3	18	113	452	17.4
	Tshaheyi	2013	1.7	20	110	440	8.4
Natural	Mawane - Zhokwe	-	-		76	304	197.5
	Nsimbi	-	-		104	416	9.1

obstructions like rocks or submerged structures. Sites with insufficient sediment thickness, such as those with underlying bedrock, were considered unsuitable for piezometer placement. A deep sediment bed indicates a reliable water reserve that is less likely to dry out. Augering was used to install piezometers. Table 2 shows the number of piezometers installed at each site. The piezometer configuration for the seven selected sites is detailed in section S5 of the ESM.

Each piezometer was assigned a unique identification number to distinguish it from others and avoid confusion during readings. The elevations of all piezometers were determined using SRTM data, except for the Tshaheyi sand dam piezometers, which were determined based on a Differential Global Positioning System (DGPS). The bottom elevations of the piezometers were calculated by subtracting the piezometer depths within the sand from the elevations of the piezometer tops.

3.5. *Field monitor selection and training*

Two field monitors were selected at each site to ensure reliable data collection. The secondary field monitors served as backups in case the primary monitors were unable to collect data due to unforeseen circumstances, such as illnesses or funerals. The field monitors received thorough training, including manual water level measurement using sticks and graduated tapes, emphasizing the importance of precision and accuracy during measurement, proper timing, proper tape-measure technique, and recording and reporting monitored data. They were provided with detailed guidelines for completing data recording sheets, which included specific fields for dates, times, and water level measurements. Practical exercises reinforced these instructions. Additionally, field monitors received the necessary tools, such as sticks, tape measures, and pipe wrenches for opening piezometer caps. Ongoing support was also provided to promote continuous improvement.

3.6. *Water level monitoring*

Water levels in each piezometer were manually measured weekly. Water levels were measured by removing the piezometer caps and inserting sticks into the bases of the pipes. The wetted lengths of the sticks were then measured with graduated tapes and recorded as water depths. The recorded data included the piezometer ID, measurement time, water level, and site observations. Every month, staff from the Dabane independently measured water levels at each piezometer to verify data accuracy. The collected data were shared weekly with Dabane staff, who verified data accuracy and entered it into a central database.

To determine the water level elevation, the depth to water was subtracted from a reference point's elevation, usually the top of the piezometer. To determine the water level relative to mean sea level, the total installed piezometer length was calculated by subtracting any cut-off from the standard 3 m, and the length above the sand surface was measured. Next, the length below the sand was determined by subtracting the length above the sand from the total installed length. The water depths below the sand were then obtained by subtracting the measured water thicknesses from the piezometer lengths below the sand. Finally, the water levels above mean sea level were determined by subtracting the water depths below the sand from the piezometers' ground elevations.

3.7. *Sediment grain size analysis*

To examine the spatial variation in sediment grain size, we collected sediment samples from three locations at each site, all from a depth of 1 m. Standard sieve analysis techniques were used for this purpose. Sieve analysis involves shaking sediment samples through a series of sieves with progressively smaller openings. The results are typically expressed as the percentage of the total sediment weight passing through each sieve. For this study, sieves with openings ranging from 4000 μm to 32 μm were used. Fig. 5 shows the average grain size distribution across all seven sites. Additional details can be found in section S6 of the ESM.

3.8. *Estimating porosity and hydraulic conductivity*

Porosity indicates the sediment's total water-holding capacity. Generally, sediment porosity increases with grain size. Medium to coarse-grained sands typically have the highest porosity. Silt and clay accumulation significantly reduce storage capacity. Sediment porosity (n) at the seven sites was determined using the Vuković and Soro (1992) empirical equation, which relates the coefficient of grain uniformity to porosity (Eq. 1). The uniformity coefficient (Cu) is calculated using Eq. 2. d10, defining the effective size is the

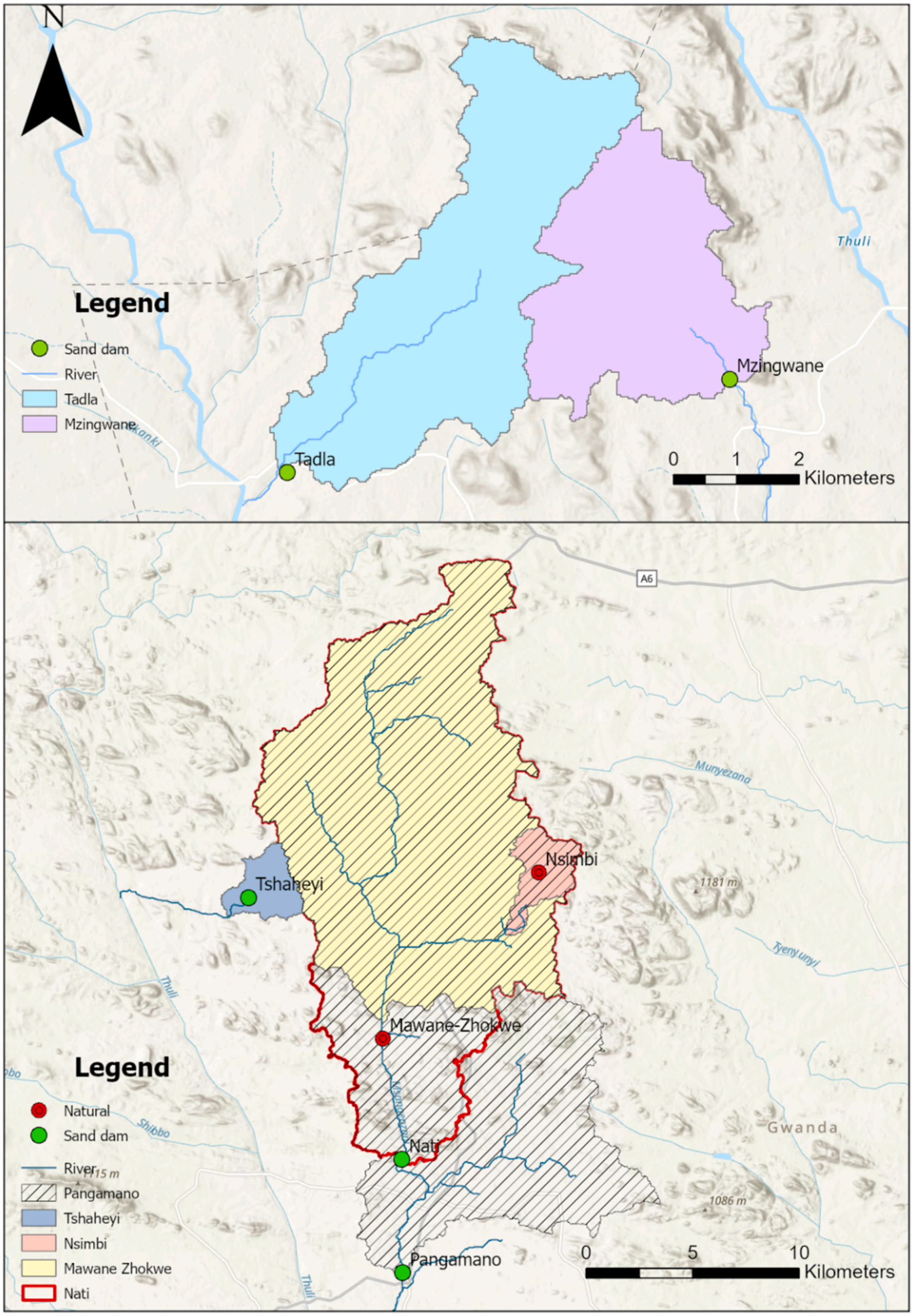

Fig. 3. Map of study area showing catchment boundaries for selected sites.

diameter where 10 % of particles are finer, while d60 marks the diameter where 60 % are finer. Table 3 shows the average coefficient of uniformity and porosity for the seven sites. The average porosity was 0.4, aligning with the findings of Mansell and Hussey (2005) for the Shashe catchment.

The hydraulic conductivity of the sediment at each site was determined using Eq. 3 (Wang et al., 2017). Our results indicate that the Mzingwane, Nsimbi, and Mawane-Zhokwe dams have the highest hydraulic conductivity values, while the Pangamano dam has the lowest (Table 3). These estimated values (60–126 m/d) fall well within the range of 20–300 m/d reported by Walker et al. (2018) for

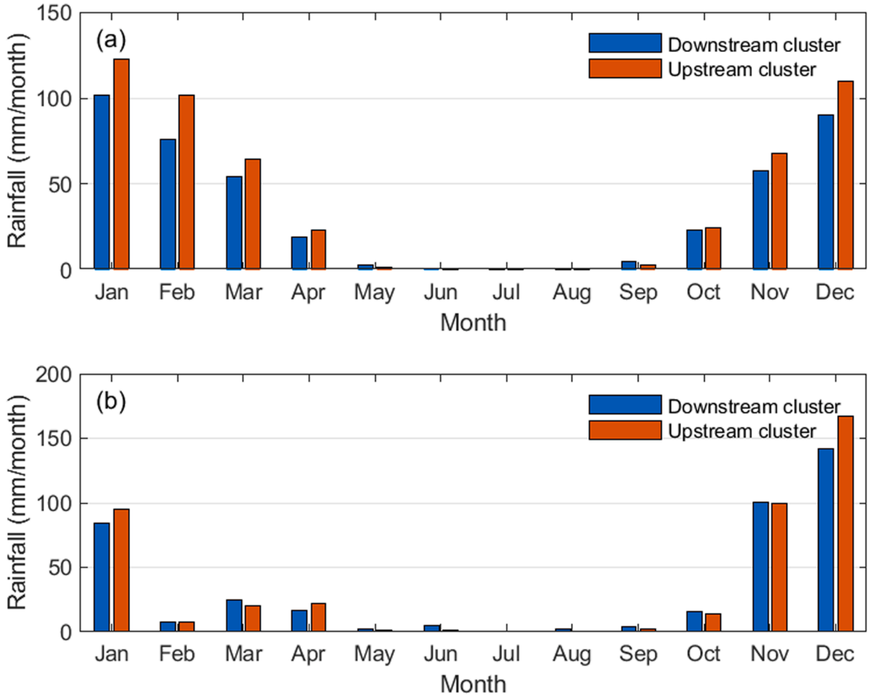

Fig. 4. Monthly rainfall distribution in the Shashe catchment (CHIRPS): (a) long-term mean [1981–2024] and (b) observed totals for the 2024 calendar year.

Table 2
Number of piezometers installed at each site and date of installation.

Site		Number of piezometers	Date of installation
Sand dam	Mzingwane	7	20th of May 2024
	Nathi	15	6th of February,2024
	Pangamano	15	26–29 Feb, 2024
	Tadla	8	March 1 and 2, 2024
	Tshaheyi	9	30th of November 2023
Natural	Mawane - Zhokwe	10	3rd of May 2024
	Nsimbi	10	27th of May 2024

the Molototsi Sand River in the Limpopo River Basin.

$$n = 0.255(1 + 0.83^{Cu}) \tag{1}$$

$$C_u = \frac{d_{60}}{d_{10}} \tag{2}$$

$$K = C_H \frac{g}{\nu} {d_{10}}^2 \tag{3}$$

Where:

K = hydraulic conductivity (m/s)
C_H=is unitless coefficient about 6.54×10^{-4}
g= gravitational acceleration (9.81 m/s^2)
ν= fluid kinematic viscosity (m^2/s) (ν= 0.89 ×10–6 m^2/s at 25 °C for water)
d_{10} = the diameter of the sediment where 10 % of particles are finer (m)

3.9. Estimating specific yield

Specific yield is the amount of water a saturated sediment releases under gravity. Medium to coarse-grained sands usually have the

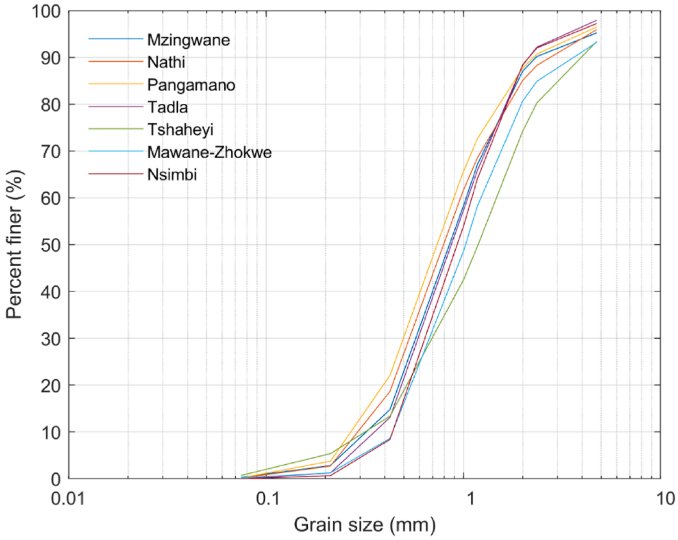

Fig. 5. The average grain size distribution curve for all sites.

Table 3
Average hydraulic properties of sediment [average of the three sampling sites at each site).

Sites		d10 (mm)	Texture	d60 (mm)	Cu (-)	Porosity (n) (-)	K (m/d)
Sand dam	Mzingwane	0.45	Coarse sand	1.18	2.67	0.41	126
	Nathi	0.36	Medium sand	1.11	3.00	0.41	81
	Pangamano	0.31	Medium sand	0.97	3.00	0.40	60
	Tadla	0.40	Medium sand	1.06	3.00	0.41	100
	Tshaheyi	0.38	Medium sand	1.52	4.67	0.37	90
Natural	Mawane-Zhokwe	0.44	Coarse sand	1.35	3.00	0.40	121
	Nsimbi	0.45	Coarse sand	1.18	2.67	0.41	126
Average		0.40		1.20	3.14	0.40	100

highest specific yields. Factors such as grain size, shape, sorting, compaction, and drainage time influence specific yield values (Kasenow, 2002). Rounded grains generally have higher specific yields compared to angular grains. After all the water has drained, a thin film of water remains on the sediment particles due to surface tension. This is known as specific retention. Specific yield is the difference between a saturated sediment's total porosity and the amount of water retained as specific retention (Morris and Johnson, 1967). The specific retention (Sr) of the sand at each site was calculated using Robson's (1993) formula $Sr = 0.055–0.1335 \log d50$), which depends on the median grain size (d50) obtained from grain size analysis. The estimated specific yield was then found by subtracting the calculated Sr value from the porosity. Table 4 shows the calculated specific yield values for each site. The average specific yield across the study area is 0.34. This value is slightly higher than the 0.15–0.32 range for medium sand reported by Johnson (1967) and significantly exceeds the value reported by Quinn et al. (2019), which ranged from 0.1 to 0.16. While Quinn et al. (2019) adopted a specific yield of 0.13 to account for silt and clay content, this value may be overly conservative for the current study area. Utilizing this lower specific yield value likely leads to a notable underestimation of the actual storage potential in the medium sand profile.

Table 4
Specific yield estimated from grain size analysis [Specific retention, porosity, and specific yield are dimensionless].

Site		d50 (mm)	Specific retention (Sr)	Porosity (n) (-)	Specific yield (Sy) (-)
Sand dam	Mzingwane	0.89	0.06	0.41	0.35
	Nathi	0.84	0.06	0.41	0.35
	Pangamano	0.79	0.07	0.40	0.33
	Tadla	0.91	0.06	0.41	0.35
	Tshaheyi	1.19	0.04	0.37	0.33
Natural	Mawane-Zhokwe	1.03	0.05	0.40	0.35
	Nsimbi	0.95	0.06	0.41	0.35
Average		0.94	0.06	0.40	0.34

3.10. Estimating sand dam water storage

Water storage was calculated by multiplying three factors: the sediment accumulation area, the saturated thickness, and the specific yield. The sediment accumulation area was determined using Google Earth, based on the dam height and the resulting throwback length for the sand dam sites. The throwback length is defined as the upstream distance to which accumulated sediment and retained water extend from the sand dam wall. In a mature sand dam, this distance corresponds to the elevation of the sand, which is equal to the spillway level of the sand dam. The throwback length for the natural site was determined based on the area of its sand accumulation.

The saturated thicknesses were calculated as the averages of the water thicknesses measured in all piezometers upstream of the dam walls or proposed sand dam sites for the natural sites. The maximum water storage capacity for each site was estimated by multiplying its area by the maximum sand thickness and the specific yield. This calculation provides insight into the theoretical maximum storage potential.

3.11. Estimating sand dam evaporation

Although previous studies on sand dam hydrology have used lysimeters to directly quantify evaporation (e.g., Quinn et al. 2019, Quinn et al. 2018), logistical and resource constraints at our remote sites in Zimbabwe rendered direct measurement impractical. Instead, we estimated sand evaporation as a fraction of open-water evaporation using an empirical polynomial equation (Eq. 4) developed by Mansell and Hussey (2005). This equation was derived from medium sand samples in the Shashe catchment in Zimbabwe, specifically, in the Shashane, Huwana, Wenlock, and Dogamuzi sub-catchments. Because water surface depth varies over time and across the sites, the evaporative fraction was determined using the average water surface depth below the sand surface. Evaporation was only considered when the water level was between 0 and 0.6 m below the sand surface. Monthly pan evaporation data from the Thuli Makwe dam in the Shashe catchment were used to provide open-water evaporation values (Table 5). Assuming uniform evaporative loss across sand reservoir areas at a given depth, the total evaporative water demand was calculated by multiplying the sand accumulation area by the evaporative fraction and the open water evaporation rate. Open water evaporation was obtained by multiplying pan evaporation by a pan coefficient. For a Class A pan, the pan coefficient typically ranges from 0.6 to 0.8; we used the commonly accepted value of 0.7.

$$y = 0.9778 \quad x^2 - 1.9333x + 0.92 \tag{4}$$

Where:

y = evaporation from the sediment, proportional to open water evaporation
x = water depth (m) below the sand surface

Monthly evaporation varied across the sites (Table 5). From June to September, all sites showed no evaporation because the water level had dropped below 0.6 m from the sand surface. The Nathi sand dam showed a higher evaporation from February to May. The Pangamano sand dam also recorded higher evaporation rates, specifically in May and December. Conversely, evaporation rates at the Mzingwane sand dam increased from October to December, which coincided with a rise in water levels. Evaporation from the natural sites was zero during the monitored period. Additional details can be found in section S7 of the ESM.

3.12. Estimating upstream longitudinal flow into sand dams

The upstream longitudinal flow depends on the presence of a sufficiently thick upstream sand deposit. Although six of the studied sites have sand deposits extending several hundred meters upstream, the Mzingwane sand dam differs because its deposition is

Table 5
Monthly evaporation from selected sites in millimetres per day (mm/d), with the corresponding values in cubic meters (m^3) in brackets.

	Epan (mm/d)	Sand dam					Natural	
		Mzingwane	Nathi	Pangamano	Tadla	Tshaheyi	Mawane-Zhokwe	Nsimbi
Jan	3.03					0 (0)		
Feb	6.81		1.2 (592)			0 (0)		
Mar	4.27		0.5 (257)	0.5 (278)	0.2 (16.8)	0 (0)		
Apr	2.82		0.3 (154)	0 (0)	0 (0)	0 (0)		
May	4.26	0(0)	0.2 (84)	0 (0)	0 (0)	0 (0)		
Jun	4.20	0(0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Jul	4.13	0(0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Aug	4.70	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Sep	6.21	0(0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Oct	6.57	0.2(13)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Nov	6.74	0.5(30)	0 (0)	0 (0)	1.0 (67)	0 (0)	0 (0)	0 (0)
Dec	6.92	1.0(57)	0.9 (482)	1.0 (512)	0.5 (43)	0.3 (11.2)	0 (0)	0 (0)

truncated by natural rock outcrops. Consequently, the data show that lateral flow at Mzingwane is significantly lower than at the other sites (see Section 4.4). The extent of deposition is determined by the throwback length, the upstream distance over which the riverbed elevation matches the sand dam spillway level. The upstream longitudinal flow was calculated by applying a form of Dupuit's equation under two distinct conditions to isolate the influence of the riverbed slope. First, the lateral flow was calculated assuming a horizontal bed (no slope) using Eq. 5. Second, the lateral flow was calculated using Eq. 6, which explicitly included the effects of the measured riverbed slope. The final upstream lateral flows were then calculated as the differences between the results from Eqs. 5 and 6.

$$Qupstream\ longitudinal\ flow = \frac{K * width\ eff}{2L} * \left(hu^2 - hd^2\right) \tag{5}$$

$$Qupstream\ longitudinal\ flow = \frac{K * width\ eff}{2L} * \ (Sediment\ bed\ level\ change)^2 \tag{6}$$

hu – head (saturated thickness) of the upstream piezometer (m)
hd – head (saturated thickness) of the downstream piezometer (m)
L= distance between piezometers (m)
K= hydraulic conductivity of the sand (m/d)
Weff = effective flowing (channel) width (m).

Sediment bed level change represents the difference between the bed elevations at the upstream and downstream piezometers.

3.13. *Dry season water balance assessment*

The dry season water balance for each sand dam and natural site was calculated using Eq. 7. The calculation assumes that during the dry season, the river water that infiltrates when the river is flowing (Qriv) is zero. The groundwater inflow from river riverbanks (Qriverbanks) is considered negligible; this assumption is strongly supported by field observations during the November site visit in Pangamano, where an adjacent borehole drilled next to the sand river was found to be dry.

The total water loss from the sand dam storage was categorized into three primary components: abstraction (Qabs), Evapotranspiration (ET) from the sand, and a combined seepage (Qseepage) term. This seepage component includes lateral, sub-surface, and longitudinal seepage, as defined in Ritchie (2024). According to Ritchie (2024), lateral seepage is the horizontal flow through the riverbanks between the alluvial and weathered basement aquifers, which requires their water tables to be connected; sub-surface seepage is the downward water loss from the reservoir into the weathered basement aquifer through the riverbed base, occurring regardless of water-table connection; and longitudinal seepage is the flow that bypasses the dam wall, moving beneath or around it from the upstream to the downstream riverbed. The ET losses were independently estimated based on available pan evaporation data and the depth of the water level below the sand surface, a methodology discussed in detail in the preceding section.

Directly quantifying total water abstraction (Qabs) was not possible due to the high diversity of extraction methods and the wide spatial distribution of access points across the sites. These sites support a complex array of activities, ranging from concentrated use at dedicated water points for domestic supply and livestock watering to highly distributed abstraction via numerous scoop holes for domestic water supply and garden irrigation. Furthermore, the presence of high-volume activities, such as brick moulding, small-scale irrigation, and donkey-cart transport, adds to the difficulty of measurement. To mitigate these challenges, water meters were installed at the Mzingwane and Tshaheyi sites, where scoop-hole use is negligible. However, the data only spans September through December; consequently, critical abstraction patterns during the peak dry season remain unrecorded. Furthermore, the wet season data are subject to uncertainty due to technical difficulties in fitting water meters to the rowa pumps properly (see ESM, Section S8). Therefore, due to the lack of specific abstraction data for the individual sites, independent determinations of the seepage components (Qseepage) were not possible. Hence, Eq. 7 was ultimately used to estimate the combined loss of abstraction and seepage (Qabs + Qseepage). The water balance equation (Eq. 7) was applied at all monitoring intervals (roughly weekly) to evaluate how the components of the water balance changed over time.

$$\Delta S = (P + Qriv + Qriverbanks + Qupstream\ longitudinal\ flow) - (ET + Qabs + Qseepage) \tag{7}$$

Where

- ΔS is the change in storage in the sand (volume of water) over a specific time period, determined by measuring the change in water levels within the sand
- P is precipitation falling directly on the sand dam reservoir and infiltrating into the sand
- Qriv is the river water that infiltrates when the river is flowing
- Qriverbanks is water that infiltrates from the surrounding riverbanks into the sand dam's stored water, or vice versa (which can be negative if water discharges to the banks. This was assumed to be zero.
- Qupstream longitudinal flow is water stored in the saturated sand upstream of the throwback distance that flows slowly but continuously into the reservoir due to the hydraulic gradient.
- Qseepage is the water flowing into the aquifer and seepage downstream through the sand dam structure or leakage.
- ET is evaporation from the sand surface

For this analysis, the change in reservoir storage was assessed using two methods: ΔS calculated, the change derived from the water balance equation, and ΔS direct, the storage difference measured directly between the start and end of the dry season. The relatively small ΔS error (0–13 %) in each water balance suggests that the main dry season processes are accurately represented.

4. Results

4.1. Maximum sand dam water storage

The maximum storage capacity, as shown in Table 6, varies greatly, from 150 m^3 in the Nsimbi natural site to 11,400 m^3 in the Nathi sand dam. As shown in Table 6, natural sites have a larger surface area-to-storage ratio. This means that each cubic meter of water storage in natural sites requires more surface area than in sand dam sites.

4.2. Spatiotemporal variations in water levels

Water level fluctuations varied notably across the sites (Fig. 6). Nathi sand dam maintains water throughout the dry season, unlike all other sand dams. Conversely, Pangamano, Tadla, and Tshaheyi exhibited a more rapid decrease in water level during the dry season. Furthermore, Mzingwane and Tadla showed earlier water level increases in November, whereas Pangamano, Nathi, and Tshaheyi showed delayed responses. A detailed overview of water level variations at each site is presented in section S9 of the ESM.

Saturated thickness is a a key factor in maintaining water availability during the dry season (Fig. 7). The data indicate that, except for the Nathi sand dam, the other three sand dams (Mzingwane, Pangamano, and Tshaheyi) have very little saturated thickness and nearly run out during the dry season. Even with a smaller surface area of accumulated sand, sand dam sites consistently show higher saturated thicknesses than natural sites. For example, the Mawane-Zhokwe natural site, although four times larger than the Tadla sand dam, still has a lower saturated thickness than the Tadla sand dam. A spatial map showing the saturated thickness at natural sites is available in the ESM section S10. Interestingly, the water point locations chosen for the Shashe sand dam align with areas of high saturated thickness. This is because, as river flow slows, coarser sediments settle further upstream from the sand dam wall, while finer sediments are carried and accumulate closer to the wall. Consequently, areas near the sand dam wall are less suitable for water point installation due to low yield, whereas upstream areas where coarser sediments are deposited are more appropriate for water points.

4.3. Spatiotemporal variations in water storage

Water storage patterns generally align with observed fluctuations in water levels. Among sand dam sites, Nathi has the highest water storage capacity, followed by Pangamano (Fig. 8). While Tadla and Tshaheyi experience considerable water level fluctuations, their actual water storage is minimal, primarily due to their smaller sand accumulation areas. Among natural sites, Nsimbi records near-zero water storage, while Mawane-Zhokwe exhibits higher water storage during dry periods than two sand dam sites (Tadla and Tshaheyi). The higher storage in Mawane-Zhokwe may be due to its large sediment accumulation area. Whatever the case, a key planning issue may be whether to prioritize sand dam construction at sites with high versus low natural storage. While sites with high natural storage offer greater opportunities for additional water storage, other factors may also be worth considering. In smaller alluvial rivers such as Nsimbi, where natural water storage is limited, sand dams are a critical option for communities because alternative water sources, like boreholes, are often unreliable. Table 7 details the monthly water storage during the main dry season. A comparison with the estimated water demand (assuming a consumption rate of 20 l/c/d) shows that only the Nathi sand dam can meet this demand throughout the dry season. See sections 11 and 12 of the ESM, which provide monthly water storage and water demand data for the selected sites.

4.4. Dry season water balance

The dry season water balance analysis (April to October) showed that combined abstraction and seepage were the main water fluxes. The second-largest flux was upstream longitudinal flow, especially at Nathi, Pangamano, and Tadla, where combined abstraction and seepage were also notably higher than at other locations (Table 8). While the relative impact of abstraction vs. seepage

Table 6
Throwback length, sand accumulation area, and maximum storage volume.

Sites		Maximum throwback length (m)	Sand storage area upstream of site (m^2)	Maximum storage (m^3)	Ratio of surface area to storage
Sand dam	Mzingwane	131	1754	1250	1.4
	Nathi	672	17058	11,400	1.5
	Pangamano	483	17255	9300	1.9
	Tadla	170	2193	1560	1.4
	Tshaheyi	118	1433	780	1.8
Natural	Mawane - Zhokwe	564	8381	2230	3.8
	Nsimbi	137	435	150	2.9

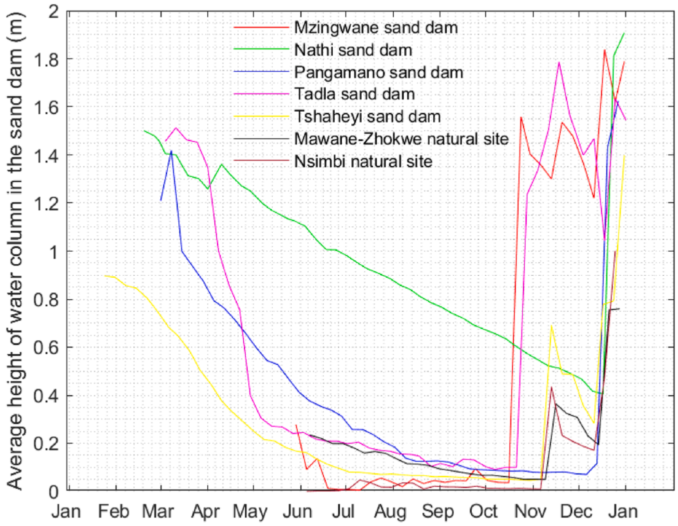

Fig. 6. The average water level across the selected sites.

on the water balance could not be conclusively determined due to the inability to monitor the dispersed, evolving number of scoop-holes, a preliminary, "back-of-the-envelope" calculation of water demand for large dams like Nathi suggested that seepage is significantly greater than abstraction during the dry season. Further research can be conducted to pinpoint the relative contribution of each factor.

5. Discussion

Sand dams are valuable sources of water for rural communities. Their decentralized design provides access for communities located far from the main water supply infrastructure. Although over 30 sand dams have been built in the Shashe catchment of the Limpopo River basin, a lack of clear understanding of their water storage capacity and its spatial and temporal variability hampers effective water resource planning and management. This study addressed this knowledge gap by examining the spatiotemporal dynamics of water storage in seven sites: five sand dams and two natural sites. The analysis has produced at least five key findings.

5.1. Sand dams provide more storage than natural sites

Confirming a growing number of sources (Maddrell and Neal, 2012; Ritchie et al., 2023; Ryan and Elsner, 2016), sand dams indeed offer important benefits to rural communities. Our analysis clearly indicates that sand dams increase water storage per unit of surface area. This additional storage provides significant benefits for the communities that rely on these dams. Natural sites without sand dams have limited water storage, leading communities that rely on them to face extended periods of water scarcity. Evidence of this impact underscores the value of sand dams in sustainable water management and climate adaptation strategies.

5.2. The benefits of sand dams are site-dependent

The level of benefits realized at particular sites is driven by their physical characteristics. Key physical factors include river width, thickness of sediment accumulation, sediment characteristics, sand accumulation area, and catchment area. While assertions about the importance of some of these factors have been made (e.g., Hussey, 2007), they were not based on systematic cross-site assessment, as used in this study. Now rigorously substantiated, these four criteria – catchment size, river size, and sediment volume and coarseness, can play a crucial role in guiding sand dam and catchment planning to enhance water availability by maximizing sand dam impacts.

5.3. Greater storage capacity enhances dry season water availability

Sand dams in large rivers with significant sediment buildup, like the Nathi sand dam, can retain water year-round. Smaller natural rivers, such as the Nsimbi, often face longer water shortages due to their limited storage capacity. This finding aligns with research by Ngugi et al. (2020), who also emphasizes the importance of a large catchment area to generate sufficient runoff to recharge the sand dams. While sediment characteristics are generally important, since fine sediments reduce water storage due to smaller voids, they were not the main driver of variability in our study, as sediments were mostly similar across sites. In our case, the CV for porosity and specific yield across sites is below 10 %, indicating high consistency in sediment properties. Therefore, the main reason for differences in dry season water availability was the interaction among the dam's physical size, seepage, and water-extraction rates.

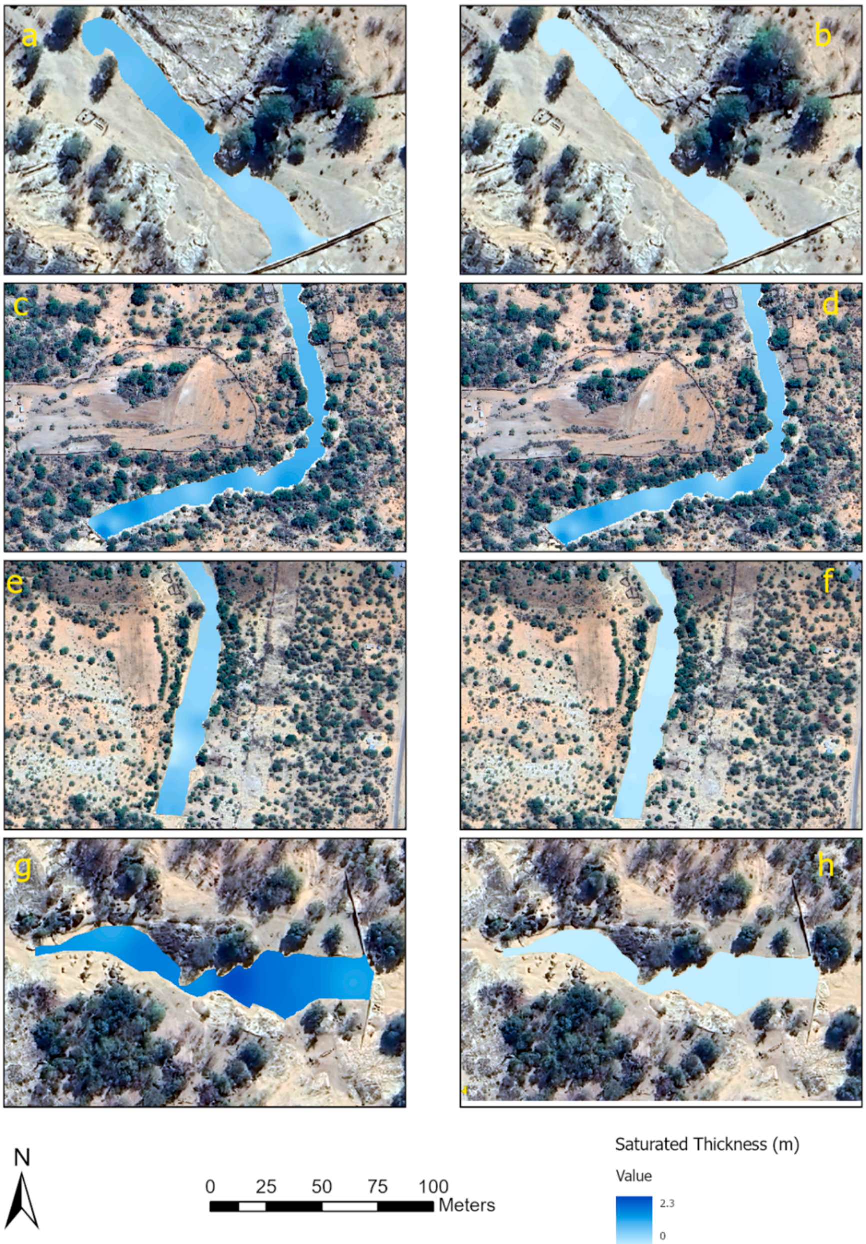

Fig. 7. The spatial distribution of saturated thickness for Mzingwane (a, wet season and b, dry season), Nathi (c, wet season and d, dry season), Pangamano (e, wet season and f, dry season), and Tshaheyi (g, wet season and h, dry season).

5.4. Comparing water availability trends in sand dams with those of the other notable option (groundwater) suggests potential for a conjunctive approach

A combined approach that uses both sand dams and groundwater is a highly effective water management strategy (Ebrahim et al., 2024). During the rainy season and early stages of the dry season, communities can depend on sand dams. As the dry season continues and water levels in the sand dams naturally decline, they can switch to groundwater from boreholes. In cases where communities prefer the taste of sand dam water, the borehole water can be allocated for other purposes, such as irrigation or watering livestock, allowing the higher-quality sand dam water to be reserved for drinking. This integrated method optimizes resource use, providing a more sustainable and reliable water supply, particularly during droughts.

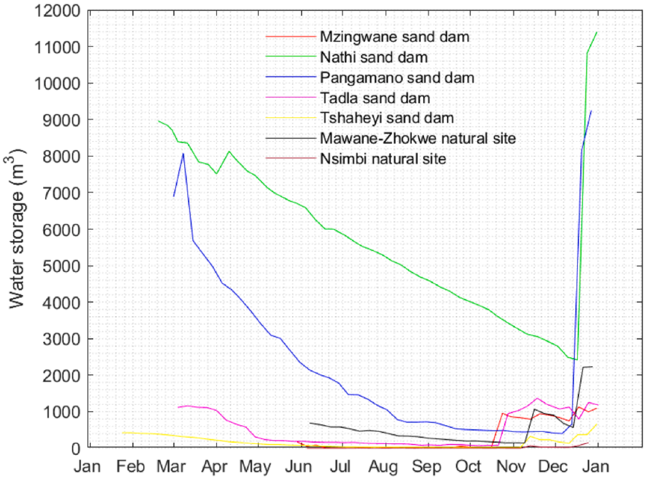

Fig. 8. water storage in sand dams and natural sites.

Table 7
Dry months' water storage in cubic meters.

Sites		May	Jun	Jul	Aug	Sep
Sand dam	Mzingwane	169	38	19	23	34
	Nathi	6875	6189	5518	4896	4269
	Pangamano	2959	2001	1386	816	602
	Tadla	198	161	135	102	88
	Tshaheyi	98	60	36	31	28
Natural	Mawane-Zhokwe	-	911	710	485	329
	Nsimbi	-	0.3	5	5	4

Table 8
dry season sand dam water balance (April to October).

	Sand dam					Natural site
	Mzingwane	Nathi	Pangamano	Tadla	Tshaheyi	Mawane-Zhokwe
Catchment area (km^2)	12	242	331	17	8	198
Sand dam area (m^2)	1754	17058	17255	2193	1433	8381
Dates (day/month)	29/05–16/10	15/04–28/10	12/04–25/10	22/04–07/10	17/04–30/10	29/05–26/10
Initial storage (m^3)	170	7903	4335	590	137	690
Rainfall (m^3)	11	359	574	17	48	20
Surface inflow (m^3)	0	0	0	0	0	0
Upstream longitudinal flow (m^3)	13	15097	2592	1368	137	138
Abstraction & Seepage (m^3)	172	19960	7197	1974	337	852
Evaporation (m^3)	0	198	0	0	0	0
ΔS calculated (m^3)	-148	-4702	-4032	-588	-152	-543
ΔS direct (m^3)	-148	-4476	-3848	-510	-133	-543
Error (%)	0	5	5	13	12	0

Note: Nsimbi was excluded from the calculation because of unreliable data.

5.5. Sand dams contribute to groundwater levels in surrounding areas

While the degree of water level decline attributable to abstraction vs. seepage is unclear, it seems clear that some portion of the water level change is due to seepage, and that seepage contributes to water levels in adjacent areas. This finding aligns with Ritchie (2024), who reported that lateral seepage is the dominant water-loss mechanism (responsible for 57–97 % of total loss) across all sites. The increase in groundwater recharge is evidenced by the visible growth of vegetation near the sand dams. These structures function as Managed Aquifer Recharge (MAR) (Quinn et al., 2019), greatly increasing the low-yielding hard rock aquifer that the community depends on for water when the sand dams run out. To confirm the impact of the sand dam on aquifer recharge, it is recommended to monitor both the sand dam's water levels and groundwater levels in the vicinity.

Before concluding this discussion, it is important to note some limitations of this study. The known limitations in the present analysis include: 1) the increasing number of scoop holes after instrumentation may influence the nearby water levels, 2) the analysis year (2024) experienced below-average rainfall. The notable lack of precipitation in February and March highlights the potential impact of interannual climate variability and may reduce water storage capacity. Multi-year monitoring is necessary to comprehensively understand how interannual rainfall variability affects sand dam water storage. 3) Evaporation losses from the sand dams were estimated using a simple empirical approach. 4) Specific yield and hydraulic conductivity values were estimated using empirical formulas. Because these formulas are based on general relationships, the calculated values may not accurately reflect the true properties of the local sediments, potentially leading to overestimation.

6. Conclusions and Recommendations

While the benefits of sand dams are gaining increasing recognition as a key tool for rural water supply and climate adaptation, guidance on their optimal roll-out has been scarce. This study represents the first systematic monitoring of water levels in sand dams and natural sites to estimate and compare their storage capacities, thereby enhancing water resources planning by optimizing the roll-out of sand dams. Weekly water level measurements were taken from January to December 2024 at five mature sand dams and two natural sites in the Shashe Catchment. The monitoring period for each sand dam ranged from 6 months to 1 year. The study highlights significant spatiotemporal variability in water storage across sand dams in the Shashe catchment. Our findings indicate that sand dams constructed on larger rivers are more effective in sustaining water availability throughout the dry season, whereas many others do not retain sufficient water to meet community needs and livestock watering. Furthermore, the results demonstrate that sand dams have greater storage capacity per unit of surface area than natural sites. The water balance assessment indicates that abstraction and seepage contribute to reduced water levels during the dry season. Seepage is vital for recharging hard-rock aquifers and increasing groundwater availability.

Looking forward, five recommendations are proposed to promote the benefits of sand dams in the Shashe catchment and other regions:

Strategically expand sand dams. This study has shown that vital benefits can be provided to rural communities through the construction of sand dams. Given the relatively limited number of sand dams, one recommendation is to increase their number. Geographic information system multi-criteria analysis supports the identification of potential sites by integrating topographic layers and other spatial criteria maps.

Consider four criteria – namely, Catchment size, river size, and sediment volume and coarseness – in order to maximize the benefits of sand dams. Sand dam benefits vary, and at least four factors have been identified to affect that variance. There is a key opportunity to leverage this knowledge to improve on-the-ground outcomes.

Integrated sand dam planning and management with other storage options. A conjunctive water management strategy is recommended to enhance drought resilience by utilizing sand dams during the rainy season and transitioning to groundwater in the dry season.

Understand and maximize the positive externalities of sand dams, such as the impact of seepage on groundwater levels. Secondary impacts of sand dams may be considerable. One such secondary impact, seepage on groundwater levels, has not been substantially explored but highlights an additional impact of sand dams that can be accounted for and harnessed.

Future studies should prioritize two areas to improve the sand dam's water balance: systematic assessment of various abstractions and enhanced hydrological monitoring. Because there is limited systematic data on water abstractions for different uses (domestic, livestock, irrigation, and brick molding) served by the sand dams, the relative contributions of seepage versus abstractions are currently unknown. Therefore, additional research should focus on a detailed assessment of all water uses and on better monitoring of both the sand dam water levels and the surrounding groundwater levels to create a reliable and accurate water balance model.

CRediT authorship contribution statement

Girma Yimer Ebrahim: Conceptualization, Methodology, Investigation, Software, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Jonathan F. Lautze:** Conceptualization, Project administration, Writing – review & editing. **Matthew McCartney:** Conceptualization, Project administration, Writing – review & editing. **Fortune Batiya:** Data curation. **Stephen Hussey:** Writing – review & editing. **Joyce Dube:** Writing – review & editing.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.ejrh.2025.103102.

Data availability

Data will be made available on request.

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