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Performance Evaluation and Optimization of Haffir Water Harvesting Systems for Domestic and Livestock Water Supply in Arid Central Sudan version

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ABSTRACT

In arid and semi-arid regions of Sub-Saharan Africa, rainwater harvesting (RWH) is a key source for sustaining agro-pastoral communities during dry periods. This study evaluates and optimizes El Wali Haffir in El Managil Locality, Central Sudan. By integrating four months of daily water abstraction data across domestic and species-specific livestock users with climate parameters, a modified water balance framework was applied alongside statistical analysis. Results show an average daily water consumption of 51.8 m3/day, with domestic human demand accounting for 17.6 m3/day (34%) and evaporation representing the largest loss at 23.7 m3/day (45.8%). Total daily livestock water demand was significantly driven by camel, sheep, and cattle consumption, which demonstrated strong positive correlations with total depletion ($r = 0.67$, 0.56, and 0.45, respectively). Cattle water consumption showed high seasonal variability ($p < .001$) due to late dry-season transhumance, while donkey abstraction spiked in November ($p < .001$) driven by crop harvest transportation needs. To overcome evaporation and siltation challenges, the study provides an optimized multi-sectoral storage design model (V_total) that accounts for seepage, siltation margins, and targeted species-specific trough allocations.

KEYWORDS:

Haffir optimization, rainwater harvesting, water balance, livestock water requirement, evaporation suppression, semi-arid hydrology

1. Introduction:

In arid and semi-arid regions of Sub-Saharan Africa, rainfall variability, shortened growing seasons, and prolonged dry-season durations pose critical threats to rural livelihoods, livestock production systems, and overall water security (Lombe et al., 2024). These regions are characterized by highly variable precipitation, in which the bulk of annual rainfall is concentrated into a short wet season of three to four months, followed by dry period of near-zero effective precipitation during which evapotranspiration demand substantially exceeds available surface and soil moisture. Under climate change, this mismatch between water supply and demand is expected to widen further, increasing the frequency of droughts and increasing pressure on already fragile water-dependent livelihood systems (Assan, 2022; Anuta et al., 2025). In these water-scarce regions, Rainwater Harvesting (RWH) is considered as an adaptive strategy for freshwater supplies, buffering inter-annual and intraseasonal variability, and meeting rapidly rising domestic, agricultural, and industrial demands (Umukiza et al., 2023; Abd-Elaty et al., 2024). RWH systems function as a low-cost storage infrastructure that captures runoff during periods of surplus and releases it during periods of scarcity, thereby smoothing the temporal distribution of water availability relative to the natural hydrological cycle.

In Sudan, where large rural communities rely heavily on agropastoral production systems, integrating livestock rearing with rain-fed and irrigated cropping, surface water harvesting is essential not only for household consumption and animal watering, but also for groundwater recharge and supplementary crop irrigation during dry spells (S. Mohamed-Ali et al., 2012; Bushara et al., 2021). Reliance on surface-stored water is particularly important in areas where there is no piped water networks or where groundwater is deep, saline, or otherwise inaccessible, making surface reservoirs the primary source of water for both human and animal populations during the dry season.

Among RWH infrastructure in Sudan, Haffirs (excavated earthen reservoirs designed to intercept and store seasonal rainfall runoff from natural catchments) serve as the primary source for the dry season across Sudan (Ezzat et al., 2016). These structures typically operate as open, unlined excavations that rely entirely on direct rainfall-runoff capture and diversion from ephemeral watercourses khors (Vetter and Rieger, 2019), with storage volumes and inflow rates governed by catchment characteristics, soil moisture, and rainfall intensity-duration relationships. Despite their socio-economic role, Haffars' efficiency and long-term sustainability are compromised by a combination of design, hydrological, and management deficiencies. Current systems frequently suffer from inadequate volumetric sizing relative to actual multi-sectoral demand, excessive evaporation losses driven by high temperatures of semi-arid climates (Aminzadeh et al., 2018; Chapman, 2024), rapid siltation and sedimentation resulting from poorly managed catchment erosion (Sichingabula, 2019; Osei, 2024), and unmanaged abstraction of domestic, livestock, and supplementary irrigation users. These abstractions progressively reduce effective storage capacity and shorten the lifespan of Haffirs, often resulting in premature depletion well before the onset of the next rainy season.

Compounding these physical constraints is a persistent knowledge gap regarding the quantitative water-use behavior of the different consumer groups sharing a single Haffir. Domestic consumption, livestock watering requirements - which vary substantially by species, and ambient temperature (Assan, 2022; Tulu et al., 2024) - and potential irrigation demand each impose distinct and temporally variable draw-down patterns on stored water volumes. Aggregated of these demand components, will facilitate accurately size storage infrastructure, anticipate seasonal shortfalls. Ensuring reliable multi-sectoral water access therefore requires an accurate understanding of daily consumption dynamics across domestic households and diverse livestock species, balanced against climate-driven hydrological losses of evaporation and seepage, within a coherent water-balance framework to evaluate and optimize the Haffir water harvesting

This study aims to evaluate and optimize El Wali water harvesting Haffir in El Managil Locality, Central Sudan. By integrating daily field-monitored abstraction and climate data with parametric statistical modeling (ANOVA and Pearson correlation) and a modified water balance framework. Specifically, this research aims to quantify seasonal water-balance components, factoring in water evaporation and species-specific livestock water requirements; characterize multi-sectoral and inter-species abstraction patterns under varying climate constraints; and optimize Haffir storage capacity and design parameters to improve domestic and livestock supply reliability.

Methodology:

Study Area

El Managil region is situated on the southwestern plateau of Gezira State near Sennar State (coordinates 14.12°N to 13.45°N and 33.24°E to 32.55°E) (Figure 1) (Ahmed, 2020). Lying outside the gravity-fed canal network of the Gezira Scheme, El Managil receives low and highly erratic annual precipitation ranging between 150 mm and 250 mm (Bashir et al., 2023). Consequently, rural communities, seasonal pastoralists, and their livestock herds rely on Haffirs during the dry period.

Data Collection

Field observations and hydrological monitoring were conducted at El Wali Haffir in El Managil region. The study monitored daily water abstraction across four continuous dry months (November, December, January, and February 2018–2019), comprising 117 days.

Data collection included household demographic counts, livestock headcounts by species (cattle, camels, sheep, goats, donkeys), daily volumetric abstraction estimates, and evaporation. Daily water abstraction was calculated based on the total number of water consumers. Evaporation loss was estimated by multiplying the daily evaporation rate retrieved from CLIMWAT by the surface area of the Haffir. Human domestic consumption was benchmarked against World Health Organization (WHO, 2017) rural standards, using an average daily allocation of 50 liters/person/day (0.050 m3/person/day) to cover drinking, cooking, sanitation, and hygiene needs.

Daily voluntary livestock water intake was estimated using tropical livestock unit (TLU) coefficients adapted to Sahelian climatic conditions across a representative temperature average of 27°C, following Pllas (1986)

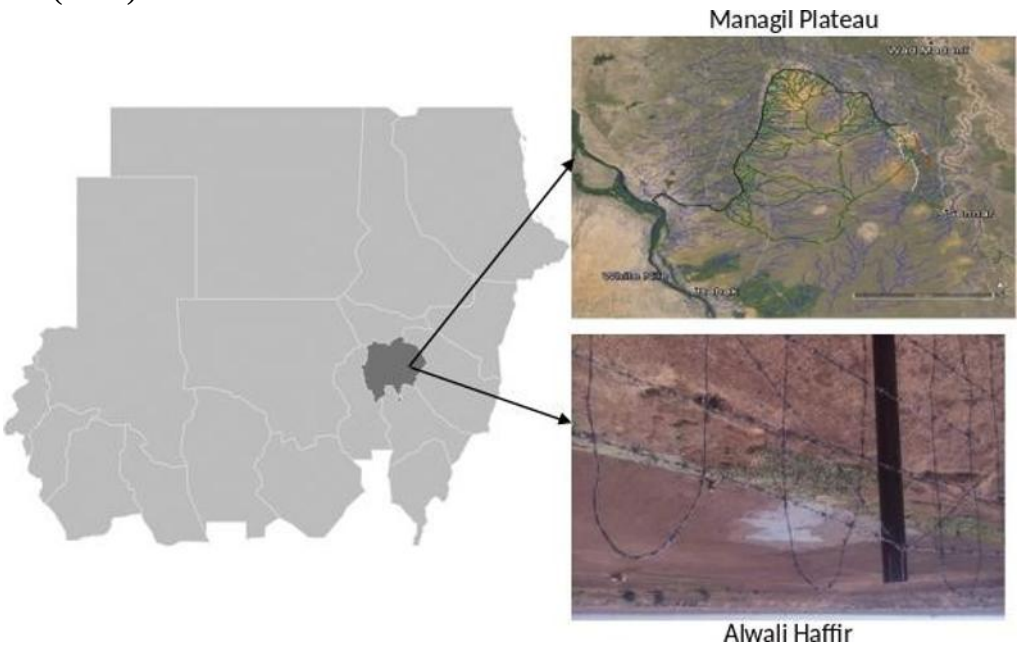


Figure 1. El Managil location, including El Managil Plateau catchment and El Wali Haffir.

Conceptual Framework

El Wali Haffir is treated as a single well-mixed storage element whose state variable, S(t), is the volume of water held at time t. Figure 2 summarizes the system as a set of inputs (hydrological and data inflows that add to storage) and outputs (physical losses and consumptive withdrawals that deplete storage), linked through the water balance
Water balance = Inflow − Evaporation − Seepage − Siltation – Σ Abstraction.

On the input side, the Haffir receives water directly from catchment rainfall-runoff and from diversion structures (guide bunds) that route flow from the khor during rainy season. On the output side, water leaves the system through three climate- and soil-driven physical loss pathways (evaporation, seepage, and silt accumulation) and through three consumptive withdrawal pathways (domestic abstraction, species-specific livestock abstraction, and supplementary irrigation releases if needed). However, there is irrigated area around the Haffir to be supplemented, and therefore supplementary irrigation is considered zero.

A fourth, cross-cutting analytical layer (descriptive statistics, one-way ANOVA, and Pearson correlation) is used to attribute the variance in total abstraction to specific species and months, and its outputs feed back into the sizing of V-total and into the design of species-specific trough infrastructure.

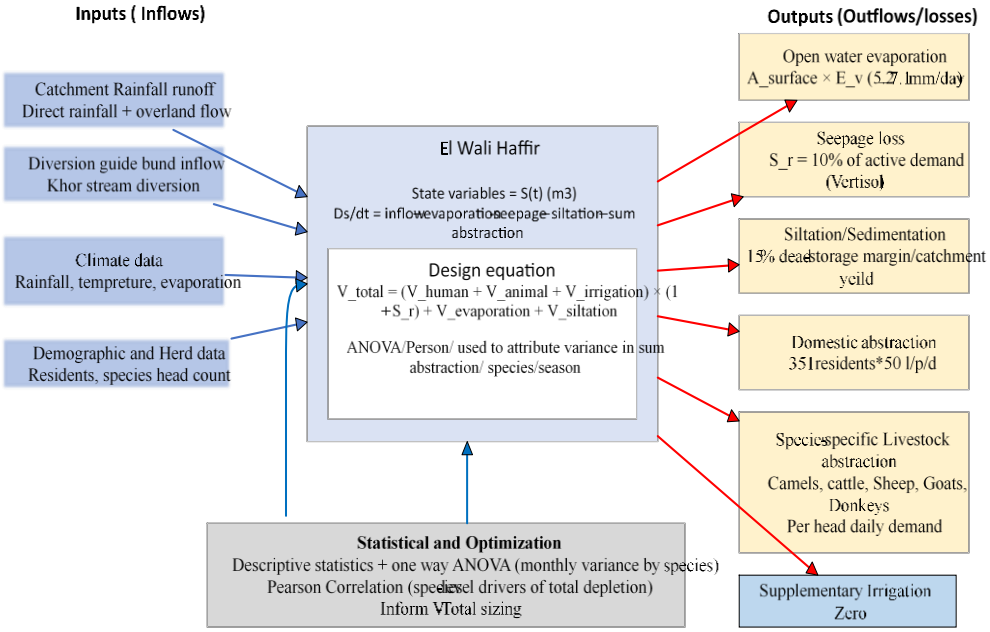


Figure 2 Conceptual inputs–outputs schematic of the *El Wali Haffir* water-balance system

The Haffir Water-Balance

To determine the total storage capacity required (V_total) for sustainable Haffir design, a modified water-balance equation was applied, combining the multi-sectoral demand as follows:

$$V_total = (V_human + V_animal + V_irrigation) \times (1 + S_r) + V_evaporation + V_siltation$$

Where the water balance components were defined and explained in table 1.

Table 2. Water balance model definition and computation

Term	Definition	Computation
V_human	Total domestic (human) water demand accumulated over the operational period	$P \times C_human \times T \times 10^{-3}$ (m^3); P = 351 residents, C_human = 50 L/person/day, T = 117 days
V_animal	Cumulative livestock demand across n = 5 animal classes (camels, cattle, sheep, goats, donkeys)	$(\Sigma_{i=1}^{n} N_i \times C_i) \times T \times 10^{-3}$ (); N_i = species headcount, C_i = species-specific daily per-head consumption
V_irrigation	Optional supplementary crop-irrigation allocation drawn from surplus active storage	irrigation $\times T \times 10^{-3}$ (m^3); set to zero when no irrigation allocation is designed
S_r	Seepage loss factor, applied multiplicatively to the active (consumptive) demand subtotal	Fixed at 0.10 (10%), reflecting the high clay content and low saturated hydraulic conductivity ($K_sat < 10^{-7}$ m/s) of Gezira Vertisols
V_evaporation	Cumulative water evaporation loss from the exposed Haffir surface over the operational period	A_surface × E_v × T; A is the surface area (3915 m^2). E_v = daily estimated evaporation rate, ranging from 5.2 to 7.1 mm/day across the monitored months
V_siltation	Dead-storage allowance reserved for sediment ingress from catchment runoff over the design horizon	0.15 × [(V_human + V_animal + V_irrigation) × (1 + S_r)]; a 15% safety margin applied to the active capacity subtotal

Statistical Analysis

Descriptive statistics (means, standard deviations, confidence intervals, and ranges) were used for daily species-specific and total consumption across the 117 days dry season. A one-way Analysis of Variance (ANOVA) was used across the four operational months, with month treated as the categorical factor, to evaluate whether mean daily abstraction differed significantly by season for each species and for total consumption. Bivariate Pearson correlation matrices were calculated to identify the species-level drivers of total reservoir depletion and to examine inter-species abstraction relationships.

Results and discussion

Field surveys at El Wali Haffir reported a permanent human population living in El Wali village of 351 residents, alongside an average daily livestock visiting population of 2,920 animal units (144 cattle, 79 camels, 256 sheep, 309 goats, and 9 donkeys) (Figure 3). All households depend on the Haffir for domestic water use and livestock production, without any alternative water source during the dry season.

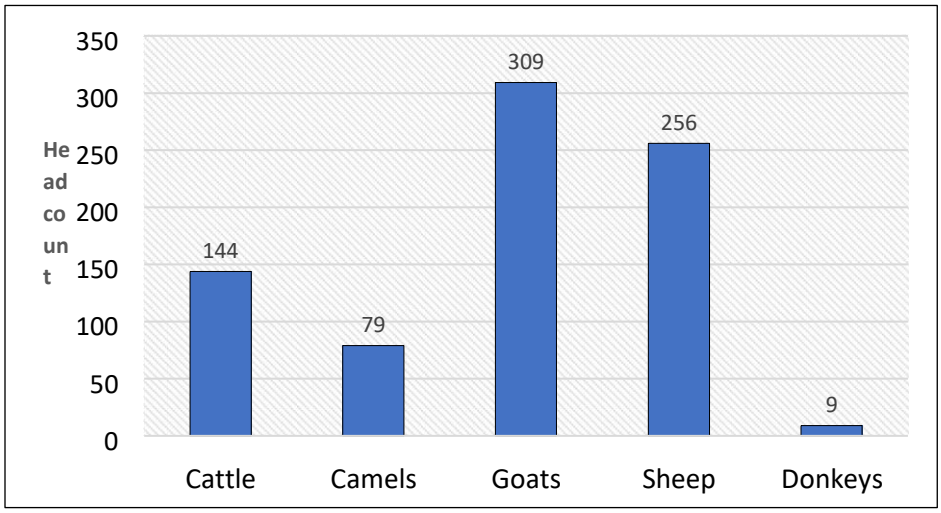


Figure 3. Average daily livestock population visiting the *Al Wali Haffir*.

Table 2 summarizes the daily water demand across user categories. Human domestic consumption accounts for 17.6 m^3/day (34.0% of total daily depletion). The populations depend on the Haffir for both domestic water use and livestock production. This aligns with broader evidence that Haffirs anchor rural settlement and animal breeding decisions in dryland Sudan (Mekuria et al., 2026; Ahmed, 2024). Climate-driven evaporation loss represents the single largest volumetric drain at 23.7 m^3/day (45.8% of total daily depletion) (Figures 4 and 5). This proportion is consistent with international evidence that small, shallow, open-water reservoirs in arid climates can lose up to half of their stored volume due to evaporation alone (Aminzadeh et al., 2018; Nevermann et al., 2024). Among the livestock, cattle and camels represent the largest volumetric consumers at 4.3 m^3/day (8.2%) and 3.2 m^3/day (6.2%) of total daily depletion, respectively. This finding contributes to the broader literature on the interaction between climate variability, reservoir management, and agricultural water demand in water-stressed basins (Almahawis et al., 2026).

Although goats and sheep together account for nearly 85% of total livestock headcount, their combined daily water footprint (2.8 m^3/day) is only slightly higher than that of the 144 cattle (4.3 m^3/day): a single head of cattle requires roughly 8 to 10 times the daily water volume of an individual goat or sheep. This ratio is consistent with comparative livestock water-requirement studies (Araújo et al., 2010). The small cattle population therefore exerts a disproportionately heavy demand on the localized Haffir relative to its numerical share of the herd.

The heavily skewed herd structure (dominated numerically by goats (average 309 head) and sheep (256 head) is typical of dryland and pastoral production systems in which forage and water availability are variable and unpredictable. Small ruminants require lower absolute water volumes per head and are physiologically and behaviorally better adapted to survive on erratic supply schedules than cattle (Akinmoladun et al., 2019; Tulu et al., 2024). Camels and donkeys (88 animals combined) provide essential transport and draught power while maintaining high water use efficiency and drought tolerance (Pearson et al., 2023), even though camels register the single highest per-head volumetric requirement of any species monitored.

Table 2. Daily water demand structure at *El Wali* Haffir.

Category/consumer type	Headcount (N)	Unit requirement (L/head/day)	Daily demand (m^3/day)	%
Residents	351	50.0	17.6	deleted
Evaporation (fixed loss)	—	—	23.7	deleted
Cattle	144	30.0	4.3	deleted
Camels	79	40.0	3.2	deleted
Goats	309	5.0	1.5	deleted
Sheep	256	5.0	1.3	deleted
Donkeys	9	20.0	0.2	deleted
Total active demand	—	—	51.8	deleted

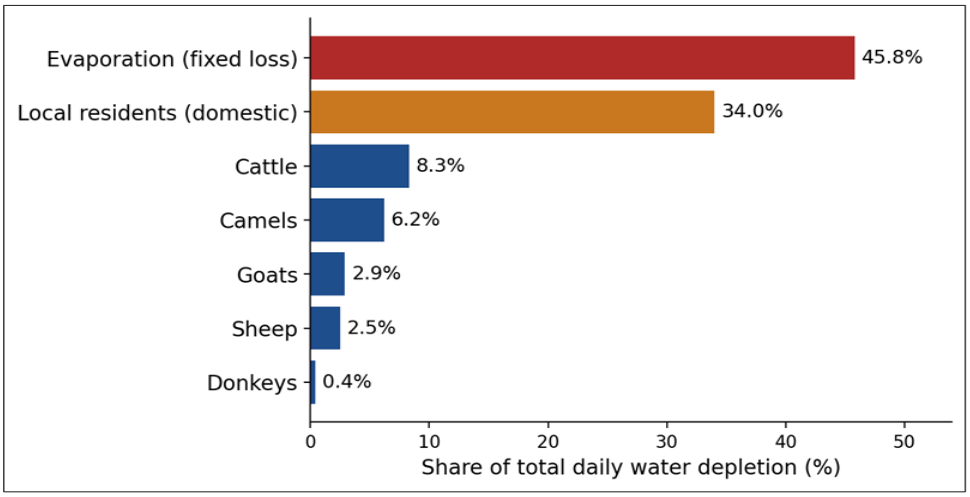


Figure 4. Share of total daily water depletion.

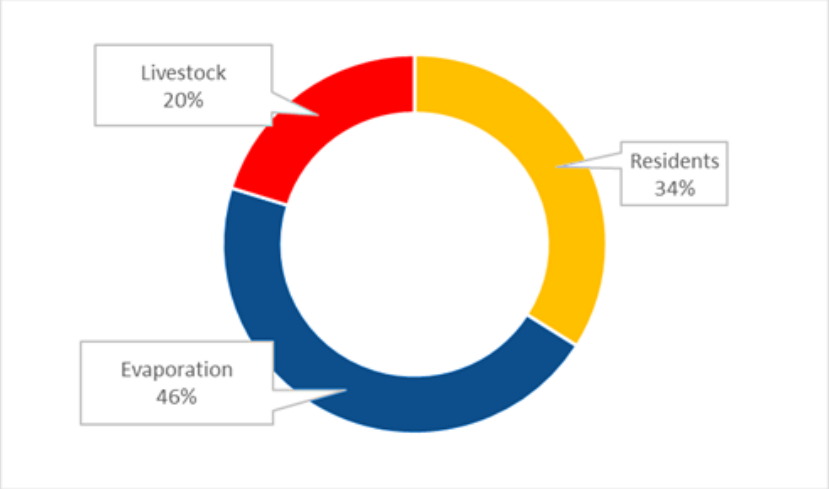


Figure 5. Percent share of total daily water demand by consumer category.

Seasonal and daily livestock consumption

Across the 117 days, total daily consumption averaged 55.15 m^3/day (SD = 1.14), ranging from 51.70 m^3/day in February to 57.50 m^3/day in November (Table 3). Total consumption peaked in November (55.64 m^3/day), remained stable through December (55.04 m^3/day) and January (55.23 m^3/day), and reached its minimum in February (54.62 m^3/day) (Table 3).

Animal types analysis reveals distinct seasonal behaviors. Cattle water requirements dropped sharply from 1.35 m^3/day in December to 0.74 m^3/day in February, reflecting seasonal pastoral transhumance, whereby herds migrate south toward Sennar State in search of dry-season grazing and temporarily reduce the resident cattle population at the Haffir. Donkey consumption spiked in November (0.21 m^3/day) relative to the remaining months (0.12–0.13 m^3/day); this surge corresponds closely with the timing of agricultural harvest, durin which donkeys are intensively utilized for crop transport, illustrating how non-physiological, labor-driven demand spikes can transiently dominate an otherwise stable animal type signal. Camels maintained the highest single volumetric requirement throughout the period (2.11 m^3/day average), peaking in February (2.27 m^3/day). This result is consistent with camels' which are comparatively greater physiological tolerance of progressively drier and hotter late-season conditions. Goat consumption remained uniform across months (1.47–1.61 m^3/day). These findings collectively confirm that livestock water demand is a highly species- and context-specific characteristic rather than a generic function of herd size alone (Sileshi and Tsadik, 2003; Assan, 2022).

Table 3. Monthly means and standard deviations for daily livestock water consumption (m^3/day).

Category	Nov	Dec	Jan	Feb	Overall mean	Overall SD	Range (Min-Max)
Goats	1.61	1.47	1.5	1.52	1.53	0.23	0.60-2.70
Sheep	1.43	1.13	1.3	1.23	0.54	0.20-2.30	
Cattle	1.34	1.35	1.27	0.74	1.19	0.56	0.20-2.50
Camels	2.11	1.99	2.07	2.11	0.79	0.30-3.40	
Donkeys	0.21	0.13	0.12	0.12	0.14	0.08	0.00-0.50
Total consumption	55.64	55.04	55.23	54.62	55.15	1.14	51.70-57.50

ANOVA and Pearson correlation analyses

The one-way ANOVA (Table 4) shows significant monthly variation for specific animal species and for total consumption, but not uniformly across all groups. Goat consumption showed no significant monthly variation ($F = 1.939$, $p = .127$), confirming stable, near-constant demand year-round. Sheep showed a statistically significant monthly effect ($F = 3.334$, $p = .022$), consistent with moderate seasonal grazing flux. Cattle showed a highly significant monthly effect ($F = 8.943$, $p < .001$), driven by late-dry-season transhumance. Camels showed no significant monthly variation ($F = 0.583$, $p = .627$), consistent with high physiological tolerance to fluctuating dry season conditions. Donkeys registered the strongest F-ratio of any species ($F = 12.697$, $p < .001$) alongside the lowest within-group variance, reflecting a sharp, narrowly timed harvest-labor spike rather than gradual seasonal drift. Total consumption varied significantly across the four months ($F = 4.183$, $p = .008$), a signal jointly shaped by the cattle, sheep, and donkey fluctuations rather than by any single species acting alone.

Table 4. One-way ANOVA for water consumption across months (α = 0.05).

Variable	F-statistic	Significance (p-value)
Goats	1.939	.127
Sheep	3.334	.022 *
Cattle	8.943	.000 **
Camels	0.583	.627
Donkeys	12.697	.000 **
Total consumption	4.183	.008 *

*** Significant at the 0.05 level; ** significant at the 0.01 level.**

The Pearson correlation matrix (Table 5) identifies which of these species-level signals actually drive variation in total Haffir depletion, as opposed to simply varying independently in time. Camel consumption shows the strongest positive correlation with total consumption ($r = .666$, $p < .001$), followed by sheep ($r = .562$, $p < .001$) and cattle ($r = .453$, $p < .001$); goat consumption shows a weak but still significant positive correlation ($r = .197$, $p = .033$), while donkey consumption is not significantly correlated with total depletion ($r = .118$, $p = .204$) despite its own strong monthly ANOVA indicating that the donkey spike, while statistically significant in isolation, is too small in absolute volume to meaningfully move total Haffir depletion. Cross-correlations among livestock species themselves are generally weak and non-significant (e.g., cattle–camel $r = −.085$, $p = .361$; cattle–sheep $r = .054$, $p = .561$), suggesting that the different species draw on the Haffir in a largely independent, rather than jointly reinforcing, manner. This result is encouraging for species-specific trough infrastructure design, since it implies that abstraction by one species is not simply displacing abstraction by another within the same day.

The ANOVA and correlation results together show that camels, sheep, and cattle jointly explain the majority of variance in total daily water consumption at the El Wali Haffir. Accordingly, they should receive design priority in the Haffir sizing, management, and monitoring efforts, even

though camels and cattle are numerically a small minority of the total herd. Table 5. Pearson correlation matrix (coefficients).

	Total	**Goats**	**Sheep**	**cattle**	**Camels**	**Donkeys**
Total	1	.197*	.562**	.453**	.666**	.118
Goats		1	.140	-.042	-.088	.103
Sheep			1	.054	.058	.110
Cattle				1	-.085	.073
Camels					1	-.063
Donkeys						1

Evaporation

At 23.7 m^3/day, unmitigated evaporation constitutes a larger single loss than any consumptive category. Sun Z et al., (2021) found that the evaporation loss of stable isotopes in surface water was 70.98% for desert areas. International experience with small and medium reservoirs in arid and semi-arid climates indicates that physical evaporation barriers can suppress evaporative losses substantially (Aminzadeh et al., 2018). Small agricultural reservoirs support local water demands, but high evaporation rates, particularly in dry regions, undermine their storage effectiveness (Aminzadeh et al; 2025). Khalid et al., (2017) reported that the main problems associated with water uses in Sudan are limited water storage capacity, evaporation from large water bodies (reservoirs, Haffirs, irrigation and drainage networks), and sedimentation accumulation in dams and irrigation canals. More recent cost-effectiveness assessments caution that evaporation-suppression retrofits should be evaluated on a unit-reference-value basis rather than adopted on efficiency grounds alone (Chapman, 2024). El Wali community, which managed the Haffir, suggests that partial, targeted interventions (e.g., shaded trees) to reduce evaporation are likely to offer a more favorable cost-to-benefit ratio than full-surface coverage.

Siltation and the lifespan of the Haffir

Siltation permanently and cumulatively reduces the storage capacity of the Haffir. Bathymetric surveys of small reservoirs in sub-Saharan Africa have documented sediment accumulation rates sufficient to eliminate the entire designed dead storage and shorten reservoir lifespan and, in most cases, cause seasonal reservoirs to dry prematurely (Sichingabula, 2019). Sediment yield is closely linked to catchment land-use and the intensity of upstream soil erosion. The 15% siltation margin adopted here in this research is the first-order design allowance rather than a guarantee of long-term capacity retention. It is advisable complements to the sizing model rather than substitutes for it (Chapman, 2024; Aminzadeh et al., 2018). Anibi et al., (2024) confirmed that sediment assessment is important for the suitability of construction materials and contributes to informed decision-making for reservoir/Haffir management.

Supplementary Irrigation

Because El Managil lies outside the Gezira Scheme's canalization network, crop farming in the locality relies entirely on seasonal rainfall. Seasonal dry spells, however, frequently coincide with critical growth stages of staple crops such as sorghum, causing severe and recurrent yield reductions even in years with adequate cumulative seasonal rainfall (Adimassu et al., 2024). By incorporating supplementary irrigation (V_irrigation) into the Haffir design equation, harvested water can be reserved and allocated during these dry spells rather than left to unplanned abstraction. Field trials in Sudan and comparable semi-arid settings indicate that applying 50–100 mm of supplementary irrigation at critical sorghum growth stages, particularly flowering, can stabilize and increase grain yield relative to purely rain-fed production (Abdalla et al., 2010; Abubaker et al., 2017), with reported yield gains of up to 180% under combined supplementary irrigation and soil-fertility management in comparable semi-arid rain-fed systems. The surplus storage remaining - after domestic, livestock, seepage, and siltation demands are met - can be converted into an equivalent irrigation depth (mm) over a specific command area. In this study, the haffir depleted in four months without any surplus water for supplementary irrigation. However, supplementary irrigation can be planned and added to the capacity and design of Haffirs without compromising the community's core domestic and livestock supply.

Conclusion:

Camel, sheep, and cattle water consumption are the primary drivers of total daily water consumption at El Wali rural Haffir. Cattle transhumance, harvest-season labor demand, and species-specific physiological tolerance jointly significantly influence daily water demand. Evaporation (23.7 m^3/day) and progressive siltation represent the primary bottlenecks constraining Haffir lifespans to approximately three to four months following the rainy season. The modified water balance framework developed here provides an evidence-based basis for sizing future Haffirs. The findings jointly motivate the multi-sectoral, loss-explicit sizing framework model, and they inform the design and policy recommendations for future water management in arid zones.

Policy and Implications

Future Haffirs construction in Gezira and other similar regions should incorporate siltation, evaporation covers, or shaded trees. and partitioned livestock trough infrastructure proportioned to camel, cattle, and sheep requirements rather than to raw headcount. Local water committees should implement staggered livestock watering schedules to prevent overcrowding and to manage peak demand periods, particularly around the November harvest time when donkey and general activity-driven demand is highest. Sizing Haffirs using the complete multi-sectoral water-balance model (V_total) and re-testing that sizing periodically against updated bathymetric and herd-count data enables dual-purpose allocations that support both community survival and, where surplus capacity allows, supplementary crop irrigation to strengthen regional food security.

Because camels, sheep, and cattle account for the majority of variance in total daily water consumption, water management strategies and off-take trough design at *El Managil Haffir* should

prioritize capacity and monitoring effort for these three species, while recognizing that goats contribute comparatively little to the variability.

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Conflict of Interest

The Authors declared no conflict of Interest

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