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Quantitative Assessment of Groundwater Resources using a Water Balance Approach: A Case Study from the Ummdukhun Locality, Central Darfur, Sudan

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Abstract:
Groundwater is the primary source of water in semi-arid regions like Central Darfur, yet its sustainable management is often hindered by a lack of quantitative assessments. This study provides a comprehensive estimation of the groundwater budget for the Ummdukhun locality, an area experiencing water scarcity and perceived overuse. Using a water balance approach, key inflow and outflow components were quantified. The primary input is direct recharge from surface water (precipitation, flooding, and run-off), calculated using the Water Table Fluctuation (WTF) method, which yielded 475.42 × $10^6 m^3$/year. Lateral subsurface inflow contributes a further 6.4 × $10^6 m^3$/year. The total groundwater output, comprising abstraction (52.45 × $10^6 m^3$/year), evapotranspiration (22.15 × $10^6 m^3$/year), and lateral subsurface outflow (3.21 × $10^6 m^3$/year), amounts to 77.81 × 10^6^ m³/year. The resulting positive groundwater balance of 404.01 × $10^6 m^3$/year indicates that the aquifer system is not currently experiencing significant depletion, despite intensive abstraction. This surplus is attributed to the high storage and recharge capacity of the wadi alluvium aquifers. The findings are critical for sustainable water resource planning and demonstrate that future development should focus on managed abstraction from the alluvial systems.
Keywords: *Groundwater Balance, Water Resources Management, Arid Region, Alluvial Aquifer, Darfur, Sustainable Abstraction.*

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I. Introduction

Water scarcity poses a critical challenge to populations in semi-arid and arid regions, where climate variability and increasing demand exert immense pressure on limited resources (Messaoudi et al., 2024; Rohde et al., 2015; Wang et al., 2025). In these areas, renewable groundwater resources are vital, providing a dependable water supply during extended dry periods (Gomaa et al., 2016). Effective management of these resources hinges on a clear understanding of the hydrological system, particularly the groundwater balance. According to the law of conservation of mass, the rate of change in water storage within a defined boundary over a specific period must equal the difference between inflow and outflow (Byeon, 2014). Quantifying these components through a water balance equation is therefore a fundamental tool for evaluating the availability and sustainability of a water supply (Kresic, 2006).

In Darfur, Sudan, the issue of groundwater depletion has garnered significant attention from humanitarian partners and local authorities, primarily due to high demand in areas with apparently limited reserves (Ali, 2021). This has prompted the need for new Integrated Water Resources Management (IWRM) strategies. A cornerstone of such strategies is the estimation of a groundwater budget, which provides a quantitative basis for evaluating the status of aquifer systems, determining safe yield, and informing future development plans (Chatterjee & Ray, 2014; Şimşek et al., 2020).

While the general hydrogeology of the region is known, a detailed, quantitative groundwater budget for the Ummdukhun locality has been lacking. This gap impedes the ability of local authorities to make evidence-based decisions regarding water allocation and future development. Therefore, the primary objective of this study is to construct a comprehensive groundwater budget for Ummdukhun locality by:

1. Quantifying the major inflow components, including direct recharge and lateral subsurface flow.
2. Quantifying the major outflow components, including abstraction, evapotranspiration, and lateral subsurface flow.
3. Assessing the net change in groundwater storage to determine the sustainability of current abstraction rates.

Study Area

The Ummdukhun locality in Central Darfur State (Figure 1 a&b) is a region frequently afflicted by water shortages and a lack of safe drinking water. Centered at approximately 22.96° E longitude and 11.14° N latitude, the locality lies about 200 km south of Zalingei, the state capital. The topography is characterized by flood plains of seasonal streams, with elevations ranging from 500 m in the southwest to 800 m above mean sea level. This topographic gradient promotes surface runoff, which can reduce potential infiltration. A network of seasonal drainage channels, primarily flowing from the northeastern highlands to the southwest, dissects the area. Khor Kaily, the main watercourse, is a critical source of annual recharge for Ummdukhun town and surrounding villages. Geologically, the area is underlain by the Precambrian basement complex, interspersed with patches of Syn-late granitic intrusions and superficial deposits (Figure 1c). The most productive aquifers are the shallow alluvial deposits within the wadis, which are the primary source for most water facilities. Fractured and weathered zones within the basement complex also provide localized groundwater sources.

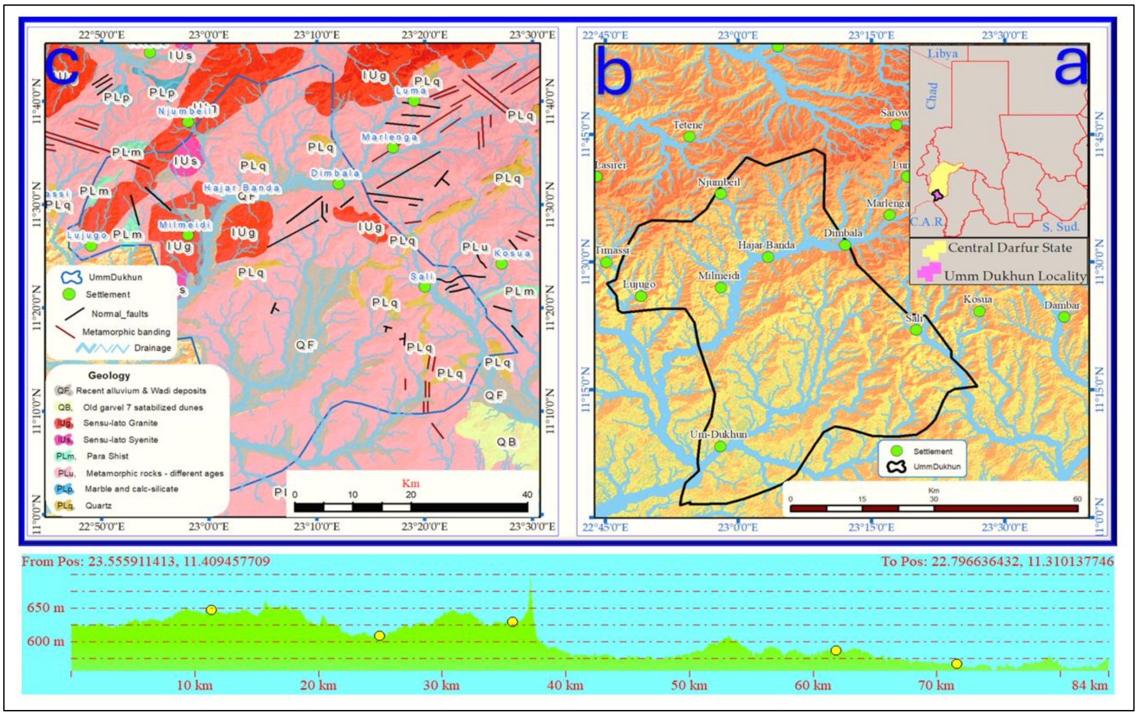

Figure 1. a) Location map of Sudan highlighting Darfur and the study area, (b) Detailed map of Ummdukhun locality showing topography from SRTM DEM, major towns, and the network of seasonal streams (Khors), (c) Geological map of the same area.

Methodology

A multi-faceted methodology was employed to achieve the study objectives, integrating field data, remote sensing, and established hydrogeological techniques. The conceptual workflow is summarized in (Figure 2).

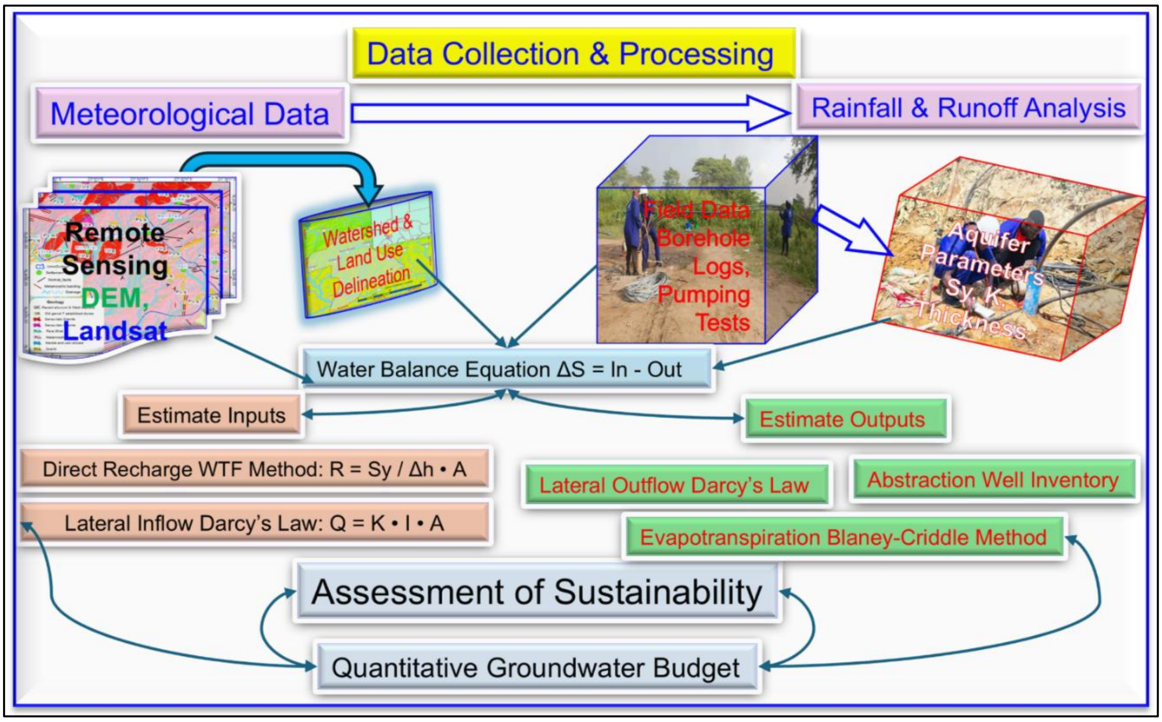

Figure 2. Conceptual Workflow of the Groundwater Budget Assessment Methodolog

1.1 Data Collection and Processing

Data were collected from various sources, synthesized in (Table 1). Fieldwork provided lithological logs and water level measurements from boreholes. Meteorological data (rainfall) were obtained from the Ummdukhun meteorological station, and surface runoff data were acquired from stream gauge stations. Secondary data included published and unpublished reports, geological and topographical maps, a 30m Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM), and medium-resolution Landsat imagery.

Table 1 Summary of data sources and their application.

Data Type	Source	Application
Meteorological	Ummdukhun Station	Precipitation analysis
Hydrological	Stream Gauge Stations	Runoff estimation
Hydrogeological	Borehole logs & water levels	Aquifer parameters, WTF method
Pump Test Data	Musa (2021) (A., 2021)	Specific Yield (S~y~), Hydraulic Conductivity (K)
Spatial Data	SRTM DEM, Landsat	Watershed delineation, land use/cover
Geological Maps	Published sources	Geological unit classification

1.2 Water Balance Framework

The general water balance equation was applied:

$$Input - Output = \Delta S \qquad (1)$$

where ΔSis the change in groundwater storage.

1.3 Estimation of Inflow Components

Direct Recharge: The Water Table Fluctuation (WTF) method was used, as it is well-suited for unconfined aquifers with pronounced seasonal water level changes (Healy & Cook, 2002; Lerner, 2020). The annual recharge R was calculated as:

$$R = S_y \times \Delta h \times A \qquad (2)$$

where S_y is the specific yield (0.17, from pumping tests (A., 2021)*),Δhis the annual water table fluctuation (5.9 m, derived from seasonal measurements), and A is the surface area of the alluvial aquifer (474 km²).*

Lateral Subsurface Inflow: Darcy's Law was applied to estimate groundwater flow from adjacent aquifers

$$Q = K \times I \times A_c \times 365 \qquad (3)$$

whereKis hydraulic conductivity (30.24 m/d [(A., 2021)*]),I is the hydraulic gradient (0.0038), and A_c is the cross-sectional area perpendicular to flow.*

1.4 Estimation of Outflow Components

Lateral Subsurface Outflow: Calculated using Darcy's Law, with parameters consistent with the inflow calculation but applied at the downstream boundaries.

Groundwater Abstraction: Estimated based on an inventory of 1,774 production wells, assuming an average discharge rate of 8.1 m³/h for 10 hours per day.
Evapotranspiration (ET): Estimated using the Blaney-Criddle method (Blaney & Criddle, 1962), adapted with crop coefficients and meteorological parameters from the hydrologically similar Wadi Azum area (A., 2021), scaled to the land cover area of Ummdukhun.

II. Results

2.1 Groundwater Recharge (Inflow)

The total groundwater inflow was estimated at 481.82 × 10^6 m³/year. Direct recharge from surface water, confined to the alluvial aquifers, was the dominant component, contributing 475.42 × 10^6 m³/year (Table 2). The spatial distribution of this recharge across the four main aquifer zones (Str.1-Str.4) is detailed in (Table 2). The water table fluctuation between dry and wet seasons, which is the basis for this calculation, is illustrated in a representative hydrograph in (Figure 3 a & b). Lateral subsurface inflow from adjacent basement aquifers was a minor component, contributing 6.4 × 10^6 m³/year.

Table 2 Calculated annual direct recharge of alluvial aquifers in Ummdukhun locality

Streams	Surface Area Km^2	Water table fluctuation, m	S_y	Groundwater recharge ×10^6 m^3
Str.1	209	5.9	0.17	209.63
Str.2	214	5.9	0.17	214.64
Str.3	23	5.9	0.17	23.07
Str.4	28	5.9	0.17	28.08
Total	474			475.42

2.2 Groundwater Discharge (Outflow)

The total groundwater outflow was estimated at 77.81 × 10^6 m³/year. Groundwater abstraction for water supply was the largest outflow component at 52.45 × 10^6 m³/year. Evapotranspiration losses were estimated at 22.15 × 10^6 m³/year, while lateral subsurface outflow from the alluvial system was 3.21 × 10^6 m³/year (Table 3).

Table 3. Summary of the groundwater budget in Ummdukhun locality.

Input components	Groundwater Input Volume ×10^6 m^3/year	Outputs components	Groundwater Output Volume ×10^6m3/year
Direct recharge from surface water	475.42	Lateral Subsurface Outflows	3.21
Lateral Subsurface Inflows	6.4	Groundwater Abstraction	52.45
		Evapotranspiration	22.15
Total	481.82		77.81
Input – Output	404.01 × $10^6 m^3$/year		

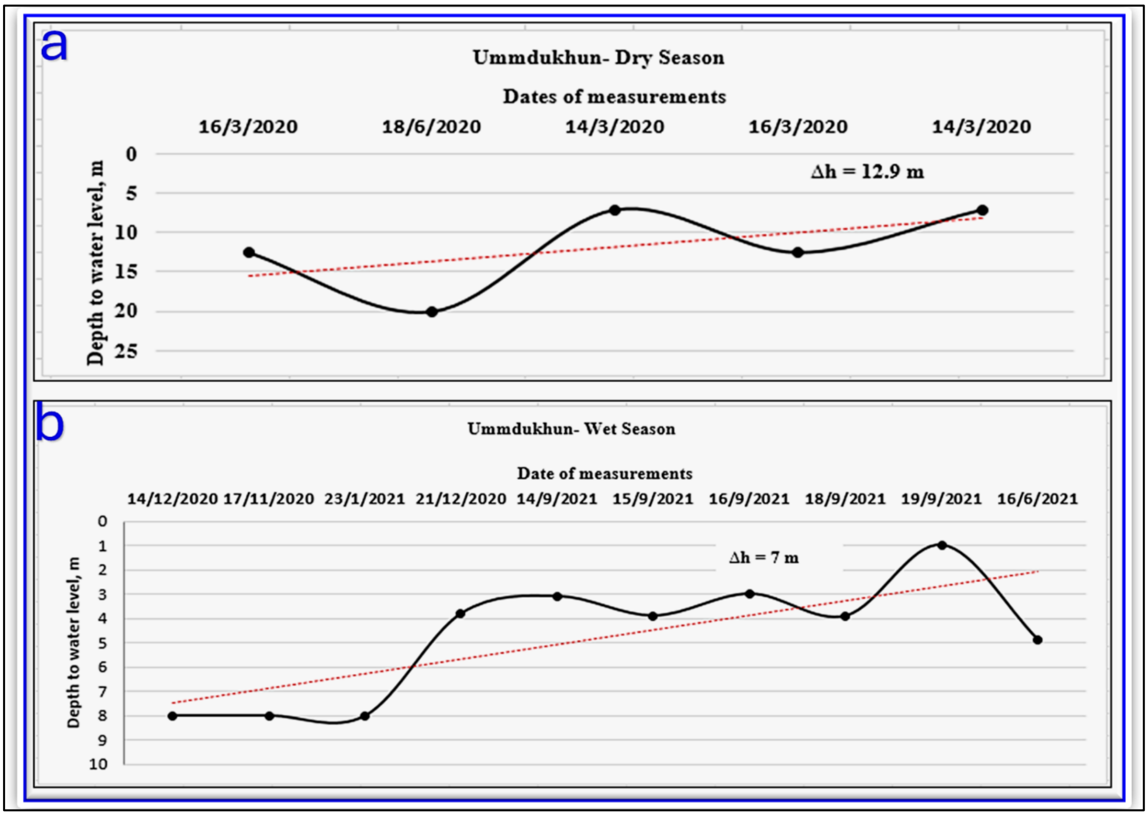

Figure 3. (a) Water table variation during Dry season, and (b) in Ummdukhun Locality

III. Discussion

3.1 Interpretation of the Water Balance

The groundwater budget for Ummdukhun reveals a significant positive balance, with an annual surplus of 404.01 × 10^6 m³ . This finding indicates that the groundwater resources in the locality are not currently experiencing significant depletion, despite the intensive abstraction from over 1,700 wells. The sustainability of the system is primarily due to the high recharge capacity of the wadi alluvium aquifers, which effectively capture and store water from seasonal precipitation and flooding. The dominance of direct recharge (98.7% of total inflow) underscores the critical importance of these alluvial deposits for the regional water supply.

3.2 Implications for Water Resources Management

The results have direct implications for water management strategies in Central Darfur. The positive balance suggests that there is potential for further controlled development of groundwater resources, particularly within the defined alluvial aquifers. Future water supply projects should be strategically located to maximize yield from these high-potential zones (Figure 4). However, management must remain vigilant; the current abstraction, while sustainable, is concentrated. Localized over-exploitation could still occur if well density becomes too high in specific areas. The budget serves as a regional tool, and local monitoring should accompany any new development.

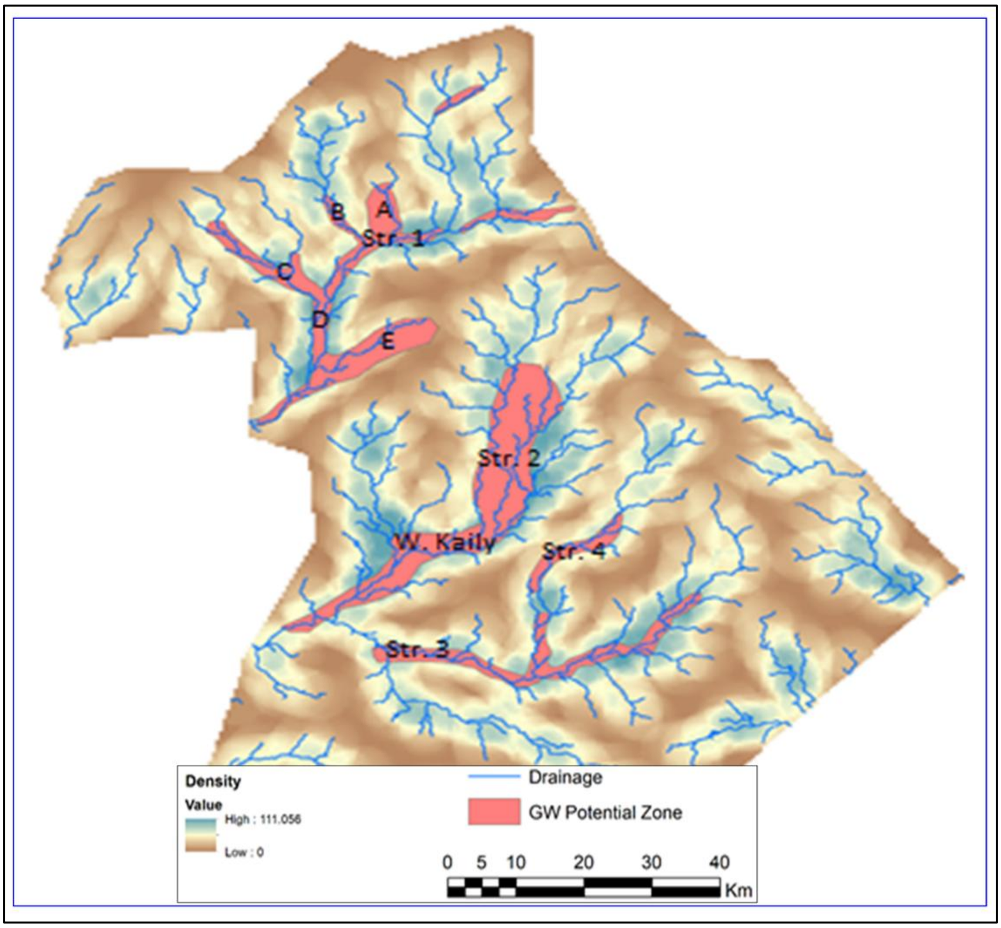

Figure 4. Groundwater potential zones at Ummdukhun locality

3.3 Uncertainty and Limitations

While the results are robust, several sources of uncertainty must be acknowledged. The evapotranspiration estimate carries significant uncertainty as it was derived from a neighboring area (Wadi Azum) due to a lack of local data. The WTF method assumes that water table rises are solely due to recharge, potentially overlooking the effects of lateral flow during the measurement period. Furthermore, the specific yield (S~y~) value, while derived from local tests, is applied uniformly across the alluvial aquifer, which may not account for spatial heterogeneity. Future work should prioritize the installation of continuous water level loggers and the collection of local climatic data to refine these estimates.

IV. Conclusion

This study successfully established a quantitative groundwater budget for the Ummdukhun locality, providing a critical evidence base for sustainable water resource management. The key conclusion is that the aquifer system is in a state of positive water balance, with a substantial annual surplus of approximately 404 million cubic meters. This surplus is overwhelmingly driven by high direct recharge into the wadi alluvial aquifers, which effectively mitigates the current levels of abstraction.

The findings indicate that the perceived threat of widespread groundwater depletion in Ummdukhun is not supported by the quantitative data at a regional scale. Consequently, future water development should be strategically focused on the prolific alluvial aquifers, supported by managed abstraction plans. To reduce uncertainty in future assessments, it is recommended to establish a dedicated monitoring network with continuous data loggers and to initiate studies on the water quality of these vital aquifers.

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Statements & Declarations

1. Author Contribution Statement

All authors contributed equally to the conception and design of the study.

2. Conflict of 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.

3. Funding Statement

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