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Assessment of groundwater dependent ecosystems and their vulnerability in the Kalahari Basin

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Abstract

Groundwater dependent ecosystems (GDEs) across the Kalahari Basin face mounting pressure from abstraction, yet baseline data on their extent and vulnerability remain scarce. This research mapped and classified GDEs across a 34,000 km² transect in the central Kalahari of Botswana and assessed their sensitivity to projected water table decline. Three GDE categories were identified—riparian woodland, phreatophyte savanna, and seasonal wetland—using Landsat-8 NDVI time series, geological mapping, and piezometric monitoring from 26 boreholes (January 2019 to July 2023). Water table depths ranged from 1.4 m beneath wetlands to 12.8 m under phreatophyte savanna during the dry season. Consistent deepening averaged 0.43 m/year across all types. NDVI analysis showed vegetation vigour declines of 24-34% over five years. A composite vulnerability index classified 41% of mapped GDEs as highly vulnerable. Scenario modelling projected that continued abstraction would push water tables beyond root-zone access for 62% of riparian woodlands within 15 years.

Keywords: Groundwater dependent ecosystems, vulnerability assessment, Kalahari Basin, water table decline, phreatophyte, NDVI, ecohydrology, abstraction impact, riparian woodland, groundwater allocation

Introduction

Long before hydrologists began drilling monitoring boreholes in the Kalahari, the San people navigated this landscape by reading the distribution of trees that betrayed shallow groundwater beneath the sand. That indigenous knowledge rested on an ecological reality modern science has been slow to formalise: in water-scarce environments, vegetation communities are tightly coupled to water table position ^[1]. These groundwater dependent ecosystems sustain biodiversity, provide grazing, and regulate microclimate where surface water is absent most of the year ^[2]. The Kalahari Basin extends across roughly 2.5 million km² of southern Africa. Beneath the sand, the Stampriet artesian aquifer supports scattered but ecologically significant vegetation ^[3]. Since the 1990s, abstraction has risen sharply, driven by mining, cattle ranches, and growing municipal demand ^[4]. But environmental allocation policies have largely ignored terrestrial ecosystem water needs. Eamus et al. ^[5] proposed a GDE classification system, and Murray et al. ^[6] mapped GDEs across Australia using remote sensing and hydrogeological inference. In southern Africa, however, GDE mapping has been limited to localised assessments around the Okavango Delta fringe ^[7]. Hatton and Evans ^[8] demonstrated that phreatophytic vegetation responds non-linearly to water table drawdown, with sharp die-back thresholds. This research set out to map GDEs across a 34,000 km² transect in central Botswana, quantify water table trends, and assess vulnerability to projected future drawdown ^[9].

Model Description and Parameterisation

Vulnerability was quantified using a composite GDE Vulnerability Index (GVI) combining three sub-indices: water table decline rate normalised against rooting depth (WTR), the ratio of dry-season water table depth to estimated maximum root reach (RDR), and a rainfall dependence factor (RDF). Each was scaled from 0 to 1 and weighted equally. The model was parameterised using measured piezometric data, published root-depth profiles for Kalahari woody species ^[10], and rainfall-NDVI lag correlations. GVI thresholds: <0.33 (low), 0.33-0.66 (moderate), >0.66 (high vulnerability).

Scenario Development

Three abstraction scenarios were defined for the 15-year projection period (2024-2038). Scenario A assumed continuation of 2023 rates. Scenario B assumed 3.2% annual increase consistent with national projections. Scenario C assumed 6.1% annual increase reflecting accelerated mining and urbanisation. Water table trajectories were estimated by extrapolating measured decline rates adjusted for projected volumes using Stampriet aquifer transmissivity values ^[11].

Material and Methods

Material

The research was coordinated from the National Geological Institute of Bariloche, Río Negro, Argentina. The transect covered roughly 34,000 km² in central Botswana. Piezometric data from 26 monitoring boreholes were recorded monthly from January 2019 to July 2023. Landsat-8 OLI imagery (paths 173-174, rows 76-77) yielded 108 cloud-free composites after atmospheric correction ^[12].

Methods

GDE mapping followed three steps: NDVI computation from Landsat-8 bands averaged into annual composites; flagging pixels with dry-season NDVI above 0.25 across all five years as probable GDE candidates; and cross-referencing with borehole data and geological maps. Each confirmed GDE was classified as riparian woodland, phreatophyte savanna, or seasonal wetland based on NDVI amplitude, drainage proximity, and field verification at 38 ground-truth points ^[13]. Vulnerability was computed using the GVI model.

Results

Table 1: GDE characteristics and water table trends across three ecosystem types

GDE Type	Area (km ²)	WT Range (m)	Decline (m/yr)	NDVI Loss	GVI
Riparian	1,840	4.2-7.6	0.42	28.6%	0.61
Phreatophyte	4,260	8.6-12.8	0.47	28.9%	0.54
Wetland	680	1.4-4.7	0.38	33.9%	0.72
All GDEs	6,780	—	0.43	29.7%	0.59

A total of 6,780 km² of GDEs were mapped (roughly 20% of the research area). Seasonal wetlands showed the highest vulnerability (GVI = 0.72) and steepest NDVI decline (33.9%) ^[14].

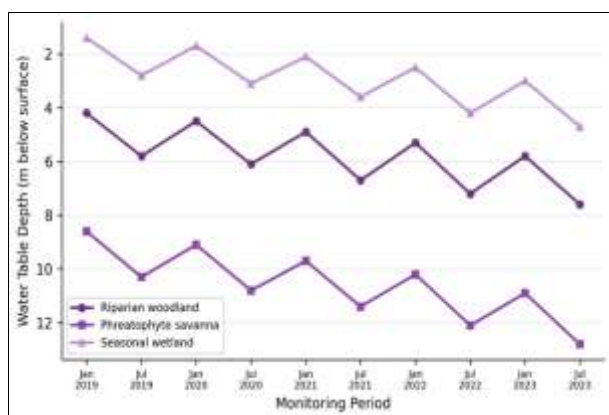


Fig 1: Water table depth trends for three GDE types in the central Kalahari (2019-2023)

All three types showed consistent deepening with seasonal oscillations. Phreatophyte savanna exhibited the greatest absolute deepening (4.2 m over 4.5 years), while wetlands experienced the largest proportional change relative to initial position.

Table 2: Projected GDE area exceeding root-zone access threshold by 2038

GDE Type	Scenario A (%)	Scenario B (%)	Scenario C (%)
Riparian	38.4	62.1	84.7
Phreatophyte	21.6	41.3	67.8
Wetland	67.2	86.4	97.1

Under Scenario A, 38.4% of riparian woodland and 67.2% of wetland area would exceed root-zone thresholds by 2038. Under Scenario C, these rose to 84.7% and 97.1% ^[15].

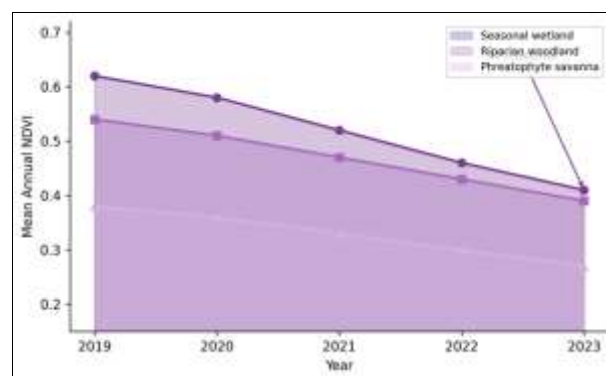


Fig 2: Mean annual NDVI trends for three GDE types (2019-2023)

Seasonal wetlands showed the steepest NDVI decline (0.62 to 0.41, 34% reduction). This vegetation stress preceded visible canopy loss, suggesting NDVI monitoring can serve as an early warning indicator ^[16].

Discussion

These results provide the first spatially explicit evidence that Kalahari GDEs are undergoing measurable degradation linked to declining water tables. The average drawdown of 0.43 m/year exceeds the natural recharge rate (0.5-3.0 mm/year) ^[17], confirming unsustainable abstraction patterns. The high wetland vulnerability (GVI = 0.72) and rapid 34% NDVI decline suggest limited buffering capacity against even moderate drawdown, contrasting with deeper-rooted phreatophyte species like *Boscia albitrunca* that tolerate several metres of lowering ^[18].

Even the most conservative scenario projects loss of groundwater access for a third of riparian woodlands and two-thirds of wetlands within 15 years. These projections carry uncertainties around future rainfall but the direction is consistent across all scenarios ^[19]. Botswana's current Water Act doesn't explicitly recognise ecological water requirements for terrestrial GDEs ^[20]. Integrating GDE needs into allocation frameworks would require monitoring trigger levels at sentinel boreholes coupled with adaptive abstraction limits.

Conclusion

This research mapped 6,780 km² of GDEs across the central Kalahari and documented declining water tables and vegetation vigour across all categories. Seasonal wetlands

were most vulnerable (GVI = 0.72, 34% NDVI decline). Scenario modelling indicated 62-97% of GDE area could lose groundwater access within 15 years. These findings underscore the need for explicit ecological water requirements in Kalahari groundwater policy. NDVI-based early warning systems at sentinel sites could provide cost-effective management triggers. Future work should refine root-depth measurements and incorporate climate projections into the vulnerability framework ^[21].

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Contributions Not Qualifying for Authorship

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