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Southern African Science Service Centre for Climate Change and Adaptive Land Management
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POLICY BRIEF

With funding from the:
Federal Ministry of Research, Technology and Space

Issue 12 / May 2026

SECURING THE INVISIBLE RESOURCE: LEVERAGING MACHINE LEARNING TO ADDRESS GROUNDWATER DEPLETION IN THE UPPER ZAMBEZI RIVER BASIN

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KEY MESSAGES

- **A declining trend:** Satellite data reveals a consistent decline in groundwater storage across the Upper Zambezi Basin from 2009 to 2023, with severe drops during El Niño cycles.
- **The 614mm "Tipping Point":** Groundwater recharge is compromised when seasonal rainfall falls below 614mm, serving as a critical early-warning threshold for disaster management.
- **Precision management:** Advances in **machine learning** now allow for **5km-resolution monitoring**, enabling authorities to manage specific "hotspots" like Lukulu and Mongu rather than relying on broad regional estimates.
- **Economic risk:** Without improved monitoring, the basin faces "**governance blindness**," threatening multibillion-dollar investments in hydropower, irrigation, and regional water security.

EXECUTIVE SUMMARY

Groundwater is the hidden foundation of the Upper Zambezi River Basin's economy, supporting hydropower stability, large-scale agriculture, and rural water security. However, data reveals a systemic decline in storage, with "hotspots" of depletion emerging in Western Zambia. Current ground-based monitoring is insufficient to manage this risk.

By integrating machine learning with satellite data, we can now monitor groundwater at a 5km local scale. This brief calls for the immediate institutionalization of these tools to prevent a "blind" water crisis and to secure the region's climate-resilient future.

THE CRISIS: WHY WATER SECURITY IS AT RISK

The Upper Zambezi River Basin is a complex hydrological system where groundwater behaviour is dictated by diverse geological formations. Despite its importance, it remains the least-monitored resource in Southern Africa.

- **The data gap:** Traditional observation wells are too sparse to capture local changes. Policymakers are currently making billion-dollar decisions on agriculture and energy based on incomplete data.
- **Climate sensitivity:** Groundwater storage is no longer a "buffer" that can be ignored; it responds rapidly to climate shocks, particularly during El Niño cycles.

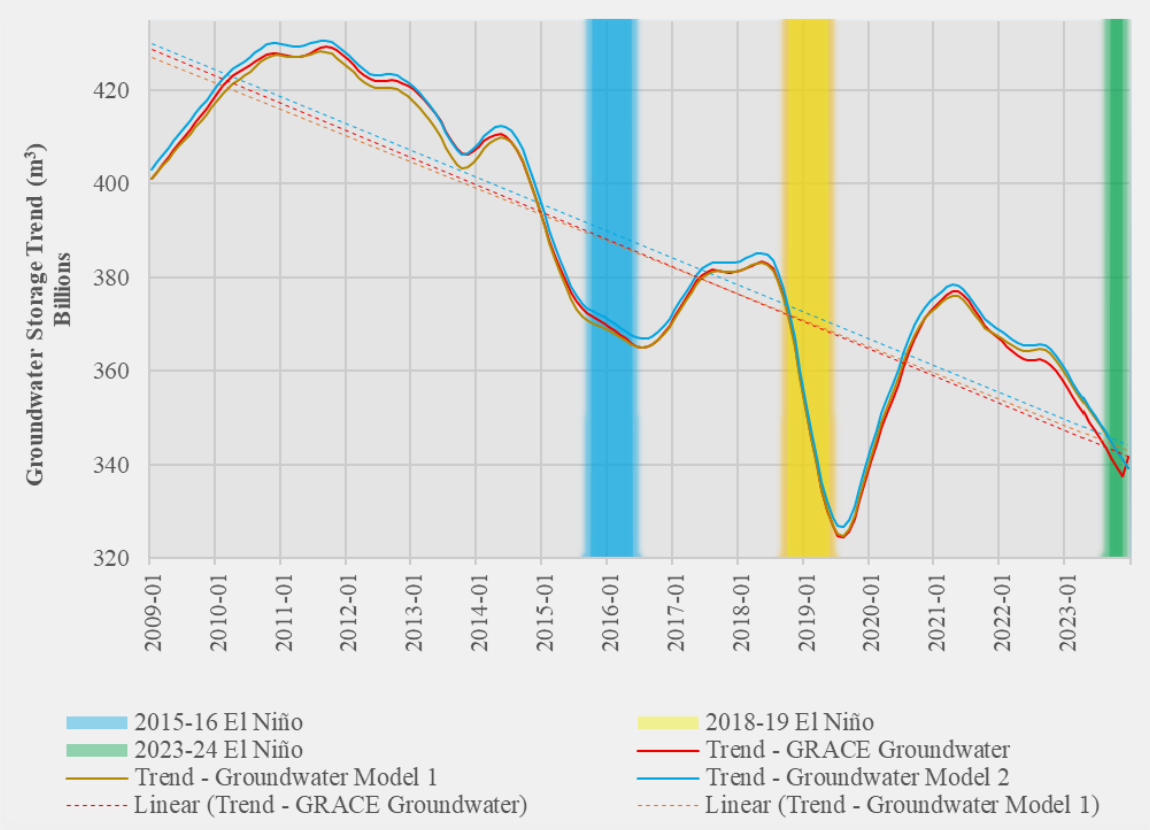

FIGURE 1: GROUNDWATER STORAGE TRENDS 2009–2023) (Shilengwe et al., 2024)

This graph clearly shows the downward trajectory of storage, highlighting sharp "dips" during the 2015-16, 2018-19, and 2023-24 El Niño periods. This demonstrates that groundwater resources in the basin are highly vulnerable to climate variability and prolonged drought conditions associated with climate change.

EVIDENCE FROM MACHINE LEARNING AND SATELLITE DATA

Recent advancements under the SASSCAL 2.0 Tipping Points Explained by Climate Change (TIPPECC) project have used machine learning to downscale Gravity Recovery and Climate Experiment (GRACE) satellite data (Shilengwe et al., 2024). The findings are clear:

1. **Systemic decline:** Between 2009 and 2023, the basin has seen a steady loss in groundwater volume, totalling billions of cubic meters in storage loss.
2. **Spatial variability:** Depletion is not uniform. While some areas show recharge, others are in a state of chronic decline.
3. **Local vs. Regional:** While regional data may look stable, sub-catchment data reveals "hidden" droughts that ground-based systems fail to detect.

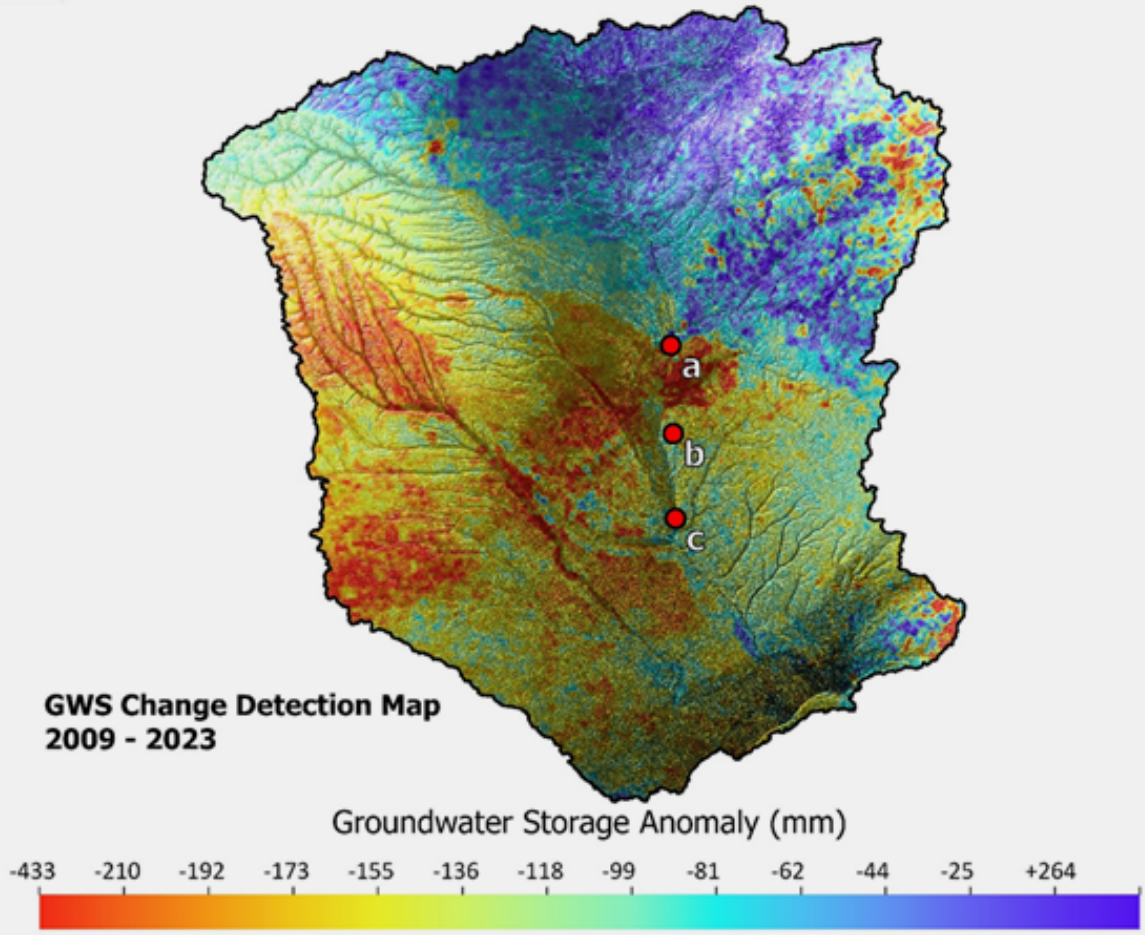

FIGURE 2: Groundwater Storage (GWS) (Shilengwe et al., 2024).
This map shows the "Red-Orange" hotspots of depletion focused around (a) Lukulu, (b) Mongu, and (c) Senanga.

POLICY IMPLICATIONS: THE COST OF INACTION

1. **Weak economic governance**
   Without 5km-resolution data, water authorities cannot accurately license large-scale irrigation. This leads to potential over-allocation and "stranded" agricultural assets.
2. **Increased disaster vulnerability**
   Reliance on surface water leads to a false sense of security. When groundwater depletion goes unmonitored, the "early warning" window for drought is lost.
3. **Transboundary friction**
   The Upper Zambezi River Basin is shared by multiple states. Data gaps create "information asymmetry," which can lead to disputes over shared aquifers and hinder regional cooperation.

RECOMMENDATIONS: A PATH TO RESILIENCE

- **Mandate machine learning integration:** Formally adopt downscaled satellite products as a standard tool for national water accounting.
- **Establish "Red Flag" indicators:** Integrate the **614mm rainfall threshold** into National Early Warning Systems. When forecasts fall below this level, authorities should trigger conservation measures.
- **Decentralize water management:** Develop **Sub-catchment management plans** specifically for hotspots like Mongu and Senanga to regulate localized abstraction.

CONCLUSION: DATA-DRIVEN DIPLOMACY

Investment in machine learning-based monitoring is not just a scientific endeavor; it is a strategy for national security and regional stability. By making the invisible resource visible, the Upper Zambezi River Basin countries can ensure that water remains a catalyst for growth rather than a source of conflict.

REFERENCES & FURTHER READING

Shilengwe C, Banda K, Nyambe I. Machine learning downscaling of GRACE/GRACE-FO data to capture spatial-temporal drought effects on groundwater storage at a local scale under data-scarcity. Environ Syst Res 2024;13:38. https://-doi.org/10.1186/s40068-024-00368-1

ACKNOWLEDGEMENTS

This work was supported by the **Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL)** through the TIPPECC project, funded by the German Federal Ministry of Research, Technology and Space (BMFTR).

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