GROUNDWATER-DEPENDENT ECOSYSTEMS

AI and satellites unlock secrets of Kruger's hidden water lifelines

Study leverages the power of remote sensing and machine learning to analyse groundwater-dependent ecosystems in the Kruger National Park (KNP). Article by Jorisna Bonthuys.

The Kruger National Park's ephemeral river drainage systems, or seasonal rivers, play a vital role in its biodiversity. These rivers only flow during the rainy season, drying up during the drier months. Although their existence is temporary, they have a significant impact on the landscape. During the rainy season, their waters carve out channels, deposit nutrient-rich sediments, and recharge underground water sources.

The interaction between ephemeral rivers, groundwater, and soil moisture is crucial for understanding the link between hydrology and groundwater-dependent ecosystems and for ensuring informed water management in the park. However, studying these ecosystems is challenging because of the park's vast size, its highly dynamic hydrological processes, and the limited availability of data. These factors make it difficult to fully grasp how water moves through the landscape and sustains the diverse life dependent on it.

Recently, Prof Timothy Dube and collaborators used machine learning and remote sensing to enhance their understanding of groundwater-dependent ecosystems in the park. Dube, the Director of the Institute for Water Studies at the University of the Western Cape (UWC), worked with Dr Tatenda Dalu from the University of Mpumalanga and Dr Mbulisi Sibanda from UWC on this project. Their research, funded by the Water Research Commission (WRC), demonstrated how advanced geospatial techniques can help decode the connections between groundwater resources and biodiversity in the KNP and other dryland regions.

Robust framework to assess ecological health

Using advanced geospatial methods, the scientists mapped groundwater-dependent ecosystems in the southern region of the KNP. They combined spatial data, satellite imagery, and machine learning algorithms to delineate these areas accurately. Unlike other parts of the park, which receive ample surface water from rainfall, the southern region, especially around Pretoriuskop, is characterised by deep sandy soils, low rainfall, and limited surface water. Here, groundwater is crucial for supporting many plants and the animals that rely on them.

The researchers carried out an extensive review of existing literature alongside field surveys to collect real-world data on vegetation and soil moisture. This on-site data was essential for developing, calibrating, and validating the estimates generated from satellite observations. Additionally, the team studied how fluctuations in water availability impact local macroinvertebrate populations, which serve as important indicators of ecosystem health.

To understand future risks, they developed and tested predictive models to assess how groundwater-dependent ecosystems might respond to different climate change scenarios and environmental stresses. This comprehensive approach allowed for a deeper understanding of the complex interactions between water resources and biodiversity in the region. Together, these efforts allowed the team to create a comprehensive framework for monitoring groundwater-dependent ecosystems in the study area.

By integrating remote sensing technologies with field data, this framework provides a robust way to assess ecological health. It utilises satellite-based spatiotemporal models to enhance understanding and support informed decision-making for effective ecosystem management.

The team's project report, titled *Remote sensing of groundwater-dependent ecosystems in the Kruger National Park, South Africa* (**WRC report no. 3214/1/25**), emphasises the critical role that satellite-based monitoring can play in conservation efforts both within the park and in other dry or semi-arid regions. The document details how combining advanced remote sensing technologies with field data enables more accurate and timely assessment of groundwater-dependent ecosystems, which are often difficult to monitor using traditional methods due to their ephemeral nature and the vast scale of the landscapes involved.

By providing continuous, large-scale insights into changes in vegetation health, soil moisture, and hydrological dynamics, satellite monitoring offers a powerful tool for detecting early signs of ecological stress and guiding adaptive management strategies. The findings underscore the potential for this approach to improve water resource management, preserve biodiversity, and enhance resilience against the impacts of climate change in vulnerable environments.

The framework allows the researchers to accurately estimate and delineate water availability as well as groundwater-dependent ecosystems, particularly in non-perennial rivers that only flow intermittently. Achieving approximately 85% accuracy in these assessments is a significant breakthrough, especially in

semi-arid and dry regions where traditional monitoring techniques, such as manual water sampling or short-term field observations, frequently fail to capture the full picture due to the variable and often unpredictable nature of water sources.

"This level of precision provides a reliable means of identifying critical water-dependent habitats, tracking changes over time, and informing more effective conservation and water management strategies," Prof Dube says. "As a result, the framework not only enhances scientific understanding of these fragile ecosystems but also helps land managers and policymakers make better decisions to safeguard water resources and biodiversity in challenging environments."

The project team worked closely with scientific teams from the KNP, which played a crucial role in fostering strong social capital both within and surrounding the park. The project's spatial data for the study area were, for instance, sourced from the KNP.

Using technology to gain a new understanding

Groundwater-dependent ecosystems are increasingly under pressure from human-wildlife and climate-related stresses, including changes in hydrology, rising temperatures, and shifts in land use. Unfortunately, effective management and conservation of these ecosystems are often hindered by a lack of comprehensive data regarding their condition, structure, function, and resilience. "At this stage, our understanding of the spatial distribution, vegetation composition, soil moisture dynamics, and water quality of these ecosystems, particularly in Africa, remains insufficient," says Prof Dube.

The researchers say recent advancements in geospatial artificial intelligence, which combine spatial analysis with artificial intelligence and medium-resolution satellite data, can, however, help bridge current knowledge gaps about groundwater-dependent ecosystems. Integrating remote sensing – using satellite or aerial imagery – provides almost the necessary scale and precision needed to map the connections between groundwater flow and dependent ecosystems in the park and beyond.

"Increasingly, technological advancements allow us to respond to environmental changes in real-time, optimise water usage, and develop predictive models for better resource planning
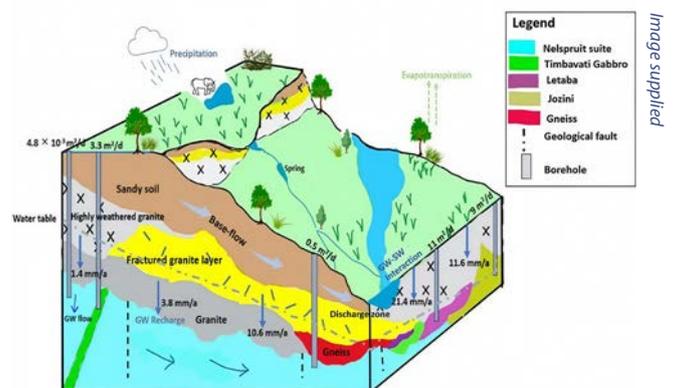
A hydrogeological conceptual model of the southern granite supersite in the Kruger National Park.

Lani van Vuuren

The windmills and borehole-dependent reservoirs dotted around the Kruger National Park are a reminder of the park's high dependence on groundwater.

in dryland regions," Prof Dube explains. These advancements are transforming the collection and analysis of biodiversity and freshwater data, he points out.

With remote sensing, researchers can detect whether groundwater-dependent ecosystems are expanding or shrinking over time. The effectiveness of remote sensing in mapping these ecosystems, however, depends on the spatial and spectral resolution of the imagery used, which is particularly important since small wetlands may cover less than one hectare.

The researchers highlight that advancements in data analytics, particularly through cloud computing platforms, present significant opportunities to improve data collection and analysis for monitoring groundwater-dependent ecosystems via remote sensing technologies. Notably, Google Earth Engine offers a wealth of readily available geospatial data archives, including Sentinel-2 satellite data, along with advanced computational resources that researchers can use in the local context.

When combined with hydrogeological approaches, advanced geospatial techniques enhance the ability of resource managers and policymakers to make actionable data-driven decisions regarding biodiversity conservation in these ecosystems.

"While many remote-sensing studies have mapped groundwater-dependent vegetation at regional scales, few have incorporated ground-truth validation, limiting confidence in their accuracy," Prof Dube explains. "Earlier approaches often treated groundwater and surface water as separate systems, thereby oversimplifying hydrological dynamics. In contrast, this study demonstrates their continuous exchange, providing a more integrated and realistic understanding of groundwater–surface water interactions and their role in sustaining groundwater-dependent ecosystems."

This study advances groundwater-dependent ecosystem science by providing the first integrated framework for identifying and monitoring groundwater connections in ephemeral systems. "To the best of our knowledge, no study has mapped groundwater-dependent ecosystems in South Africa using geospatial techniques," Prof Dube points out.

Collecting data with field surveys

The researchers conducted a field survey in September 2022, during the late dry season when most of the pans in the southern KNP were dry. Some inundated pans were found in the Makuleke section of the park.

The analysis made use of the medium-resolution Sentinel-2 satellite dataset, focusing on imagery collected in 2018, 2019, and 2022. These selected years were particularly relevant because the rainfall in the park was consistently below the long-term average annual precipitation.

By examining data from these comparatively drier years, the team was able to better understand how reduced rainfall impacts water availability and groundwater-dependent ecosystems. This approach provided valuable insights into the resilience and vulnerability of the region's ecosystems under conditions of drought and water stress, which are expected to become more frequent with ongoing climate change.

A total of 23 study plots were used to sample vegetation data in the Makuleke and Letaba regions. Twelve natural pans from the Makuleke wetland system, located in the Pafuri area, were sampled, while the second set of plots was sampled in the Letaba region. The researchers employed machine learning predictions to identify groundwater-dependent vegetation potential zones along the Makuleke and Letaba regions. It demonstrated a connection between species diversity and changes in water levels.

The results confirmed that remotely sensed soil moisture data is effective for assessing soil moisture patterns within the KNP.

It also showed that macroinvertebrate communities in the study area were influenced by seasonal patterns of water level fluctuations, known as hydroperiods. These hydroperiods refer to the duration and timing of flooding or water presence, as well as the geological types in the pans. Notably, the results indicated that the duration and frequency of inundation in the study area have a significant impact on macroinvertebrate diversity. Specifically, low hydroperiods tend to result in a decline in biodiversity within pan wetlands.

Furthermore, sediment chemistry, influenced by geological types, affected the nutrient content and substrate features essential for macroinvertebrate habitats. The quality of water was another crucial factor for groundwater-dependent ecosystems, with parameters such as pH and nutrient concentrations directly affecting the diversity, abundance, and health of macroinvertebrates in the study area.

New knowledge generated

The project demonstrated that freely available satellite data, such as Landsat and Sentinel, combined with advanced machine learning techniques, can effectively map groundwater-dependent ecosystems across large protected areas. Prof Dube says that the methodologies and insights developed in this study offer a scalable approach that can be adapted to other vulnerable ecosystems, thereby supporting conservation efforts and facilitating data-driven decision-making.

The findings highlight the importance of machine learning techniques and multi-source remote sensing data in identifying potential groundwater zones. "This project represents a significant step towards developing smart technologies that provide essential and timely information for resource managers, enabling them to make informed field decisions," Prof Dube states. "Additionally, it helps scientists make recommendations for the sustainable management of conservation areas."

These findings are critical as they establish robust methodologies for geolocating these systems, ultimately enhancing the protection of groundwater-dependent ecosystems in semi-arid regions.

By evaluating the interactions among geological, hydrological, and biological factors, the researchers provided a model for sustainable ecosystem management in climate-sensitive regions. As such, this research offers a replicable framework for understanding groundwater-dependent ecosystems in other semi-arid environments. "The methodology combining moderate-resolution satellite data, targeted field measurements, and machine learning integration makes this approach accessible across resource-limited regions," Prof Dube points out. "Recent advancements in cloud computing and open-access satellite platforms mean these techniques can be applied in other dryland areas."

Next steps

According to Prof Dube, there remains much to learn about aquifer recharge dynamics in the study area in relation to climate variations and the long-term impacts of human activities on aquifer sustainability. The team recommends using high-resolution data to capture extremely dry periods, enabling better identification of green areas that may represent potential zones for groundwater-dependent vegetation.

Image supplied

Among others, the research team studied how fluctuations in water availability impact local macroinvertebrate populations, which serve as important indicators of ecosystem health.

Groundwater-dependent ecosystems

What are groundwater-dependent ecosystems?

Groundwater-dependent ecosystems consist of communities of plants, animals, and microorganisms that rely on available groundwater to sustain their structure and function. These are ecosystems that have access to subsurface water on which they depend for their survival. The alluvial floodplains, especially around the Limpopo, Levuvhu and, to a lesser extent, Shingwedzi rivers, are good examples of such systems in the Kruger National Park.

Groundwater-dependent ecosystems, such as wetlands and riparian zones, depend heavily on underground water, especially during dry periods. If the groundwater level drops, these unique ecosystems become stressed and may be threatened. Consequently, these ecosystems face substantial threats from changes in water cycles, rising temperatures, and alterations in land use.

The researchers also emphasise the need to expand future studies by integrating machine learning techniques, diverse spatial datasets, and groundwater hydrogeological modelling. They believe this combined approach will significantly improve the accuracy and detail of mapping groundwater-dependent ecosystems.

In addition, they highlight the importance of evaluating high-resolution satellite data for accurately delineating soil moisture within these ecosystems. "Such advancements will deepen our understanding of the abundance, diversity, and distribution of plant and animal species that rely on groundwater, ultimately supporting more effective conservation and management efforts," Prof Dube says.

Future research should incorporate the use of stable and radioactive isotope tracers in combination with advanced geospatial modelling techniques to better identify and understand the unique geological interactions related to groundwater throughout the year. "These isotope tracers would provide valuable information about the origin, movement, and age of groundwater, allowing scientists to trace water sources and flow paths with greater precision," Prof Dube says.

When integrated with a geographic information system (GIS), this approach can reveal spatial patterns and seasonal variations in groundwater dynamics that are otherwise difficult to detect. "Such detailed analysis will help confirm the presence and extent of groundwater-dependent ecosystems by providing direct evidence of how groundwater supports the flora and fauna in these areas," he adds. "Ultimately, this enhanced understanding will strengthen efforts to monitor, protect, and sustainably manage groundwater resources and the ecosystems that rely on them."

Future studies could also investigate the use of waterborne invertebrates to determine if certain pools are dependent on groundwater and to monitor their conditions over time. Additionally, researchers could examine how different growth stages of plants in the study area relate to climate change. This could involve analysing geological type, water availability, sediment chemistry, and water quality to develop targeted conservation and management plans for groundwater-dependent ecosystems.

Lastly, a comprehensive assessment of water quality is necessary, including how variations in chlorophyll levels correlate with species diversity in these ecosystems. (Chlorophyll levels indicate the amount of algae and cyanobacteria in a water body, with levels correlating to water quality.)

The research underlines the need for using conservation methods and other arid regions that are specifically adapted to individual situations instead of using a generic approach (a one-size-fits-all strategy). "Understanding the complex interactions between geological type, hydroperiod, sediment chemistry, and water chemistry necessitates the implementation of site-specific and hydroperiod-specific conservation and management strategies," Dube says. "This, for instance, provides wetland managers with proactive solutions to protect groundwater-dependent systems, ensuring the sustainable existence of diverse macroinvertebrate populations and the overall health of pan wetlands."

The researchers note that the methodology developed in this study holds promise for future studies wanting to gain insights applicable to various global ecosystems, particularly those reliant on groundwater. "This study offers a step toward developing smart technologies that provide essential and timely information for resource managers to make in-field decisions and for scientists to offer recommendations for the sustainable management of conservation areas in South Africa. Ultimately, it contributes to a broader understanding of groundwater-dependent dynamics and enhances strategies for preserving these vital ecosystems in the face of global environmental change," they conclude.

To download the report, *Remote sensing of groundwater-dependent ecosystems in the Kruger National Park, South Africa* (**WRC report no. 3214/1/25**), visit: https://www.wrc.org.za/wp-content/uploads/mdocs/3214%20final.pdf