WATER ECOSYSTEMS

The slow death of Lake Sibaya

Why is the water level dropping steadily in one of South Africa's most valuable freshwater lakes? And what can be done to stop it from drying up further? Article by Tony Carnie.

Lake Sibaya, named after the Zulu word for ***cattle kraal***, is the country's largest coastal freshwater lake.

With a surface area of more than 60 km^2 and a water depth of 41 m at the deepest point, it has been estimated that Sibaya can hold more water than all three large dams in the uMngeni River system (Midmar, Albert Falls and Inanda dams) or about 44% of the Pongolapoort Dam.

The lake was once an ancient river estuary, before it was cut off from the Indian Ocean by the gradual formation of a coastal dune barrier. Located in the northern part of KwaZulu-Natal, about 60 km south of the Mozambique border, Sibaya lies on a flat coastal plain where most of the surrounding landscape rarely rises more than 100 m above sea level.

But beneath the region's largely infertile and sandy soils there is a vital groundwater aquifer which has helped to sustain local communities and the ecology around Lake Sibaya for millennia. As part of this aquifer, the lake is an almost direct reflection of the regionally-important groundwater table.

Now the lake is in peril, drying out rapidly due to drought, increasing human water demands and the thirsty roots of exotic timber plantations that have been dubbed "money trees".

During the severe 2014-2016 drought, Lake Sibaya's water level dropped quickly – along with that of several other lakes and

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dams in the region. But whereas Lake St Lucia and local dams have improved gradually since the drought, Sibaya has not risen – and is still dropping.

According to Van Rensburg, the level of the lake reached the lowest recorded level in 2014 and has continued to decline since then. Van Rensburg, the coordinator of the Grasslands-Wetlands-Forests Node of the SA Environmental Observation Network (SAEON), says the main section of the lake has dropped over five meters over the last decade when historic fluctuations were only between one and three meters. Because of the surface area of the lake, even a small drop in water level equates to a large volume of water lost.

Having separated from the main lake for the first time in living memory in 2015, the southern basin – which supplies Mbazwana and Sodwana Bay – has now dropped even lower than the main lake.

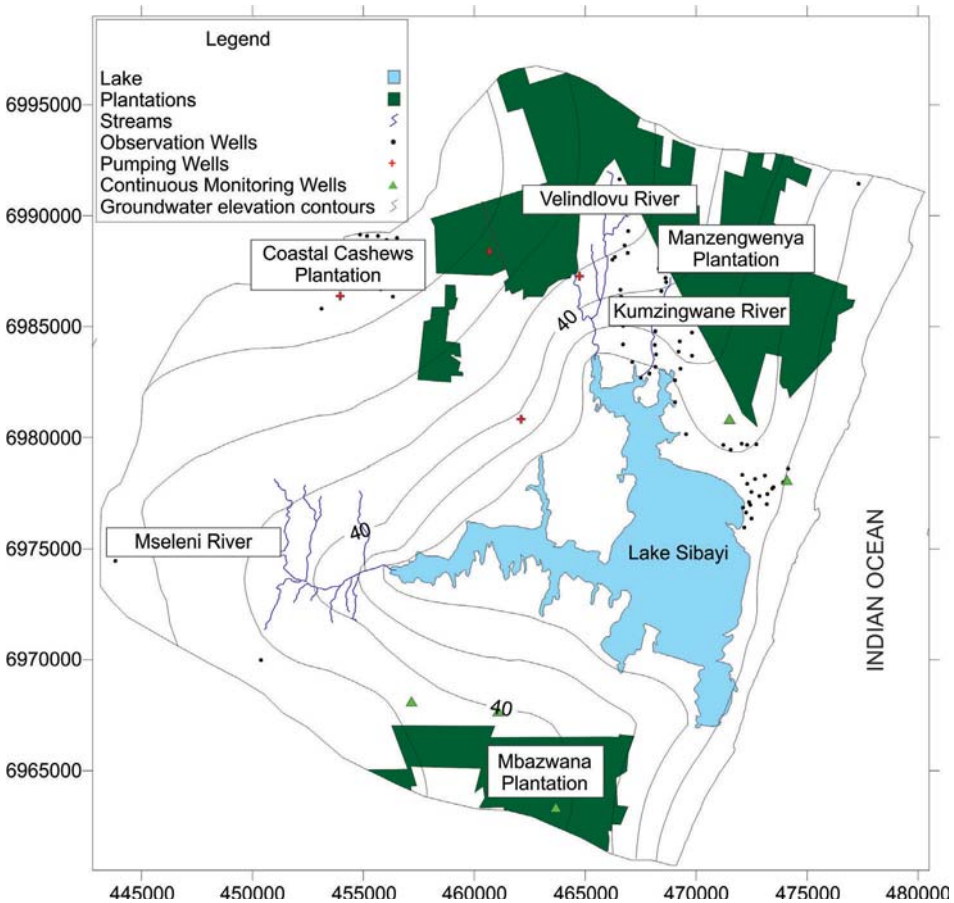
One of the main reasons for this, explains Van Rensburg, is because Sibaya is almost entirely dependent on local rainfall and groundwater recharge. Unlike open river estuaries (which receive both seawater inflow, and freshwater from surrounding rivers) Sibaya has no large perennial rivers that import water into the system from upper catchments. If it does not rain locally, there is no recharge to the system.

Located in quaternary catchment W70A, the total catchment area for the lake is estimated at 530 km^2, of which 60-70 km^2 is taken up by the lake itself. The surrounding human population has also increased significantly in recent decades, although recent studies by Prof Jeff Smithers of the University of KwaZulu-Natal suggest that water abstractions for human use are considered to be modest.

In a study published in 2017, Smithers et al. suggested that (other than drought) a major cause of Sibaya's recent water loss can be linked to depletion by water-guzzling gum and pine plantations.

The first State forestry plantations in the Sibaya area were established in the 1950s and now cover at least 23% of the catchment. Studies show that between 2001 and 2014, the level of Lake Sibaya dropped from close to 20 m above sea level to nearly 16 m above sea level – its lowest level since the commencement of record keeping more than 50 years ago and simulations going back to 1914.

Smithers and his colleagues also modelled the hydrology back to 1986. The results indicated that approximately 35% of the drop in lake levels since 2001 could be attributed to the impact of afforestation, although they noted that there was some uncertainty regarding the exact history, extent and impact of afforestation in the catchment. In contrast, the results indicated that the impact of domestic abstractions on lake levels had been 'negligible'.



Jannie Weitz

The first State forestry plantations in the Sibaya area were established in the 1950s and now cover at least 23% of the catchment. Hydrologists have suggested that at least 5km2 of plantations be removed to protect the lake's water resources.

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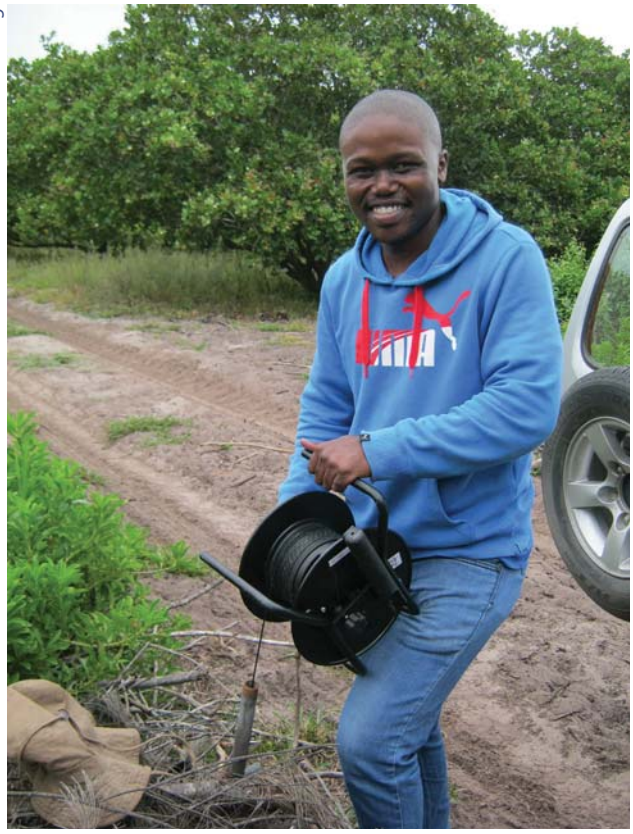
Sue van Rensburg



University of KwaZulu-Natal PhD student, Mlu Shabalala, onducting groundwater use management studies on early growth macadamia and eucalyptus plantations in relation to grasslands.

"The major cause of the drop in the level of Lake Sibaya since 2001 is postulated to be the 10-year period of significantly lower than average rainfall which lasted from 2001 to 2011," said Smithers. Subsequent analysis (Blamey et al) have shown that 2015/2016 was the driest year on record for the region.

A yield analysis demonstrated that at 2014 levels of water use from timber plantations and domestic abstractions, no sustainable additional yield was possible. The 2015/16 drought and subsequent erratic rainfall has exacerbated this situation.

Smithers suggested that at least 5 km^2 of forestry should be removed to provide for additional domestic abstraction. Several other studies in the region have also highlighted the significant impact of timber plantations on local water resources.

In 2018, Prof Molla Demlie of the University of KwaZulu-Natal (UKZN) reported that the large primary aquifer on South Africa's north-eastern coastal plain was under stress from domestic water abstraction, irrigation, commercial forests and reduced rainfall linked to climate change. Prof Demlie suggested that removing water-intensive commercial plantations from the recharge area of the catchments and halting over abstraction of the freshwater lakes were some of the solutions needed to avert serious environmental impacts.

Further studies by hydrogeologist Claudia Brites in the Nyalazi plantation near Lake St Lucia suggest that deep-rooted gum trees use more than twice as much groundwater compared to locally indigenous trees, while hydrologist Brian Rawlins reported that gum and pine plantations around St Lucia could reduce the lake's groundwater inflow by as much as 30% during periods of extreme drought.

More recent modelling studies by UKZN hydrologist, Jannie Weitz, warned that further severe depletion of groundwater around Sibaya could lead to salt-water intruding into the lake from the Indian Ocean.

SAEON's Sue van Rensburg has also voiced concern that climate change may be exacerbating the problem due to reduced rainfall in the catchment in recent years. Van Rensburg started visiting Sibaya regularly from 2014, capturing a set of time-series images which graphically illustrate the declining water level and gradual separation of the southern basin from the main lake.

Van Rensburg, a former regional ecologist for the Hluhluwe-Imfolozi Park who also spent two years working with communities around Serengeti National Park in Tanzania, is determined to help find a sustainable solution before it is too late: "Our job is to do science with and for society to ensure a more sustainable future"

She sees the emerging water crisis as an important research opportunity to understand the relative impacts of land-use, water abstraction, weather, climate change and sea-level change on one of the country's most important coastal aquifer systems.

Sue van Rensburg

SAEON technician, Siphiwe Mfeka, downloads groundwater data from a monitoring sensor. Working in collaboration with various stakeholders, SAEON has established a network of groundwater monitoring sites which it maintains to determine trends in ground water dynamics and how this links to lake level, climate and different land uses in the region.

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There is a very real need to provide economic opportunity in the region, she says, particularly in the north, where poverty levels are high. But she questions the sustainability of recent initiatives to reignite forestry expansion amid the alarming Sibaya water decline.

Over time, working with several collaborators including the Department of Water and Sanitation, commercial forestry and scientists, SAEON expanded its activities into the northern section of the coastal plain and from 2014 onwards, and has also provided logistical support to a Water Research Commission (WRC) project aimed at assessing the hydrodynamics of the Sodwana Bay system.

In 2015 node staff started working in the Vazi pans area, facilitated through a WRC project run by SAEON's Prof Colin Everson, which focuses on understanding alternative agroforestry systems and plant water use. "In May 2017, I called an informal meeting of invited experts in groundwater modelling who had insight into the Sodwana-Sibayi-Vazi-Kosi systems, including experts from the Department of Water and Sanitation," she notes. "The intention was to determine if there was consensus of what might be happening in the system and if there was a case for solid long-term observation by SAEON in the area."

But because of the extended drought and water loss, problems emerged in gathering reliable data after several monitoring stations and the only lake water level gauging station became stranded above the receding water line. SAEON has stepped in with temporary monitoring systems to help ensure a continued record.

Sue van Rensburg

Student, Josephine Magolego, and Sue van Rensburg of SAEON collecting water temperature samples from Lake Sibaya.

Van Rensburg notes that poverty levels around Sibaya are amongst the highest in the country and because the soils are poor for agriculture, there appear to be limited options for economic growth.

"It is therefore imperative when initiating work in the area to ensure there is community buy-in at the outset. The socio-economic context and concern regarding the potential impacts of alternative land uses such as forestry, which many see as the only major source of income, in my view necessitates a multi-disciplinary collaborative approach if we are to see traction in response to our work."

To this end, SAEON and the Isibusiso Esihle Science Discovery Centre (a home-grown science centre close to Vazi pans), hosted an informal workshop inviting relevant stakeholders and interested experts from different disciplines including hydrology, sustainability, resources economics and horticulture.

The workshop began by listening to the voices of community members and industry operating in the area and there was unanimous concern regarding the decline in the water table and the role that plantations may be playing in this in conjunction with the drought.

"The main request was for scientists to work together with industry and community members to understand trends, but more importantly, to provide guidance on alternatives: 'We know there is a problem, but we cannot remove the trees without alternatives being in place. Please work with us to find alternatives,' was the message that emerged."

Apart from the lake itself, impacts have also radiated out into the surrounding wetland areas, including dried-out pans where crocodiles, fish and hippo were once common.

"Changes in groundwater dynamics at a regional scale will consequently have impacts for both the wetland and the terrestrial systems. The vegetation is a rich mosaic of different grassland, forest, savanna and thicket communities and hosts a high number of endemics," she explains.

Large areas of unique peatlands have also dried out, with extensive fires adding to the damage. The peatlands in this section of Maputaland, estimated to be around 7 000 years old, play a vital role in retaining moisture from heavy rainfall and releasing it gradually. And as these unique, natural sponges and wetlands dry out, Van Rensburg says it becomes more difficult to map and accurately delineate buffer zones and land which should be off-limits to timber expansion.

While the National Water Act specifically details streamflow reduction activities, she believes these provisions do not cater adequately for impacts on groundwater-driven systems such as Sibaya. Ideally, she says, policies should be revised to take account of the unique hydro-ecological nature of coastal systems and climate change viability.

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Sue van Rensburg

This time-series sequence of images illustrates the rapid decline in water levels in the southern basin, Banda Banda Bay, of the lake since 2014

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Other potential solutions to land-use dilemmas, she suggests, could include greater community involvement in wildlife, marine and coastal tourism ventures. "Tourism will not make everyone rich. But it can provide a sustainable living for more people in the vicinity of the iSimangaliso Wetland Park World Heritage Site. This region has so much to offer and there is no reason why it should not become a rival to Kruger National Park."

According to the national Department of Environment, Forestry and Fisheries, the Mbazwana and Manzengwenya plantations are still classified as a State Forest but the biological assets were transferred to the Tembe, Mbila, Mabaso Development Trust by the Department of Agriculture, Forestry and Fisheries in April 2016.

The community trusts then formed Tembe Mbila Mabaso Forestry (TMM), to manage the plantations. TMM Forestry took over the management of the plantations and were currently carrying out all operations related to harvesting, silviculture and forest protection.

Responding to questions from ***the Water Wheel*** on what action had been since 2017 to implement the recommendation to remove at least 5km^2 of plantation forests from the Sibaya catchment, department spokesman Albi Modise said that TMM Forestry was well aware of the situation around Lake Sibaya.

"The plantations were established in the 1950s and the Department of Water Affairs and Sanitation are currently dealing with this issue . . .TMM is in the process of planting macadamia trees on 3 000 hectares of land as these trees use far less water than Eucalypts, hence the change in land use will be beneficial to Lake Sibaya."

He added that SAEON was also on board with TMM and had established a monitoring site on the first area planted with macadamias trees.

"They will establish the water use of the trees and try to provide an evidence-based approach to understanding trends to work out relative impacts of climate change. They will be establishing a site in new Eucalyptus plantings as well so that the water usage between the two different crops can be proved scientifically."

"TMM survives on timber sales and no grant funding is available to manage the plantations. For this reason, the company is intending to utilise all the available timber whilst managing the plantations in an environmentally sustainable manner."

Modise said the plantable area in the Manzengwenya plantation was 13 000 ha and that removal of 5 km^2 of timber would make this unit uneconomical for a timber plantation. TMM was also exploring alternative water-efficient crops, along with cattle farming and tourism.

Van Rensburg emphasises that Maputaland is a unique area requiring unique treatment and that part of the solution will depend on building a common vision, unlocking the region's ecotourism potential, combined with innovative, profitable, and climate-smart agricultural systems.

"We are moving into a new era where old rules, past trends and methodologies may no longer be appropriate. Exploring solutions as a collective with all parties represented and using social learning processes may be an important approach for ensuring long term success."

Sue van Rensburg

Banda Banda Bay, southern basin. Mlu Shabalala, UKZN PhD student on his first trip to the region gains an understanding of how important his work is to provide evidence-based decision support for water-wise land use for the region.

Sue van Rensburg

High and dry. A Department of Water and Sanitation gauging station at Banda Banda bay is now stranded above the receding water level.

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HYDRAULIC FRACTURING

Fracking and earthquakes: Taking stock of seismic risks in the Karoo

What does seismic risks and hydraulic fracturing have in common? The latest research in Leeu-Gamka in the Karoo provides some interesting results that should inform local shale gas development plans and practices, according to the scientist involved. Jorisna Bonthuys reports.

Efforts to extract shale gas resources in South Africa have been under intense public scrutiny in recent years.

The government has been looking into hydraulic fracturing or 'fracking' in the Karoo as a way to broaden South Africa's energy mix. This has been met with push-back from lobby groups and environmental organisations that are concerned about its impact on agricultural water resources and long-term socio-economic prospects in the region.

There are also concerns about the impact of such plans on the country's already high per capita carbon footprint in the context of the current climate crisis and South Africa's international obligations to reduce its fossil fuel dependency.

Government and energy companies are reportedly still contemplating their next moves in this regard. At the moment no applications for shale gas rights can proceed until the necessary technical regulations are promulgated by the Minister of Environmental Affairs, Janse Rabie, Agri SA's Head of Natural Resources, indicated.

And while legal battles were underway in 2019 about the Department of Mineral Resources' fracking regulations, a Cape

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Town researcher generated new knowledge about seismic risk and geohazards in the southern Karoo.

Melody Finn believes these results should be taken into consideration when future fracking plans are considered. Not only is the debate about fracking about the potential risks of groundwater contamination and the use of fossil fuels: there are seismic risks involved too.

Fynn received her Masters Degree in the Department of Geological Sciences at the University of Cape Town on this subject. Her study, titled ***Micro-seismic Observations in Leeu Gamka, Karoo, South Africa,*** has provided new insights into our understanding of microseismic activity in the interior of the country.

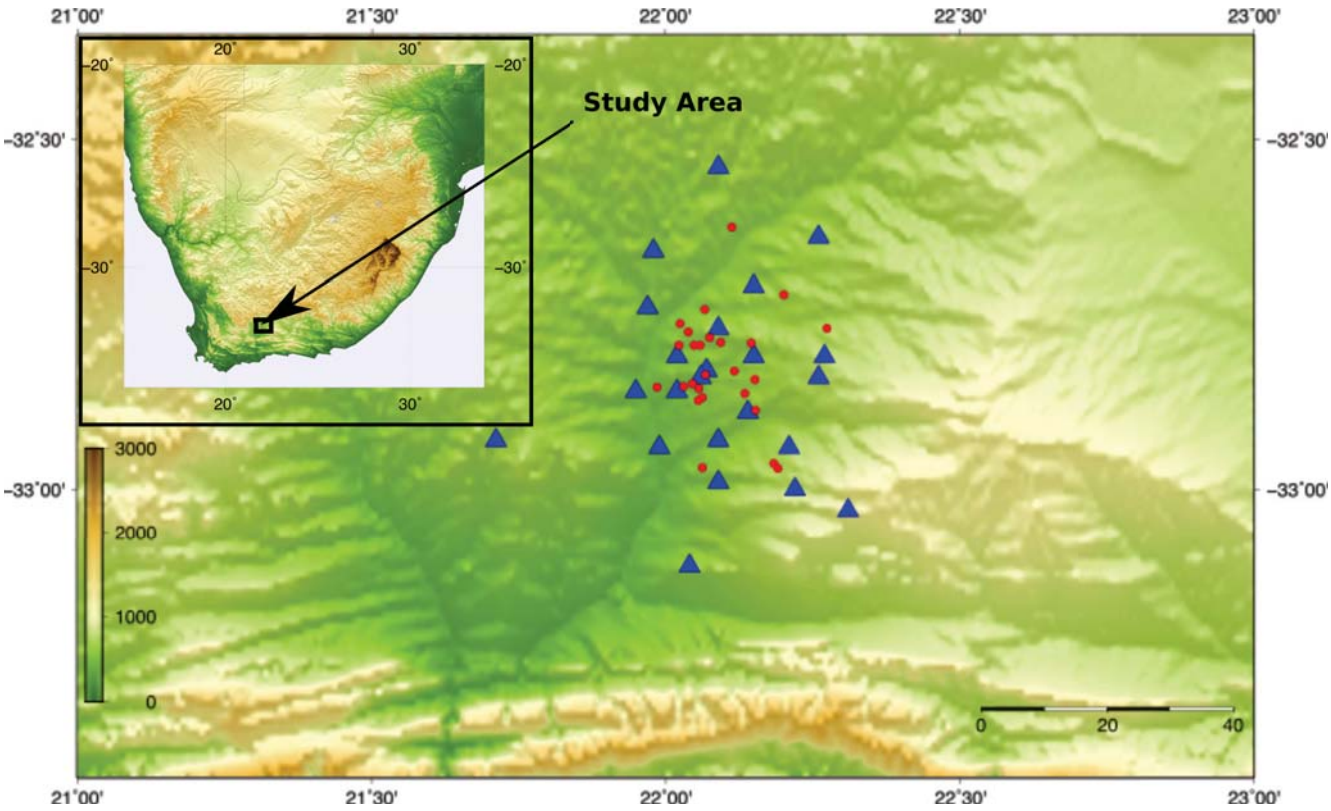
This study is important because the area she focused on is of economic interest to those interested in shale gas exploration.

Tectonic setting

The International Seismological Centre catalogue reported 27 localised anomalous seismicity in the Leeu-Gamka region between 2007 and 2013, with local magnitudes up to ML4.5. These small quakes occurred in a region that is considered as tectonically stable, and far from major tectonic plates. Leeu-Gamka's "seismic swarms" occur in a region which shows little evidence for previous earthquake activity or a fault segment that reaches the surface.

Fynn wanted to understand what caused these swarms. She also wanted to investigate the depth of the earthquake, the orientation of the structure along which the earthquakes are occurring and its source mechanism.

She deployed an array of seismometers in Leeu-Gamka, covering an area of 60 km x 65 km on private farm land based on the previous seismicity recorded in the region.



Melody Fynn

An illustration of the study area with the station locations as blue triangles .

These instruments were installed by digging a 30-50cm deep hole. After three months, the instruments were collected from the field. The data, which had been logged with GPS signals for accurate timing, were analysed.

Seismic swarms differ from earthquakes that are followed by a series of aftershocks in that there is no obvious mainshock in the sequence.

Fynn identified a total of 106 earthquakes from March-June 2015 in the Leeu-Gamka area. Interestingly, almost all of these events happened in the same small area (75% of the epicentres fall within a one square kilometre block).

She then calculated an average hypocentral depth of approximately 6km for the earthquakes, assuming a depth to the base of the Karoo of 5 km. This places the earthquakes just below the base of the Karoo, in the Cape Supergroup. The magnitudes of the earthquakes recorded range from -1.5<ML<0.4.

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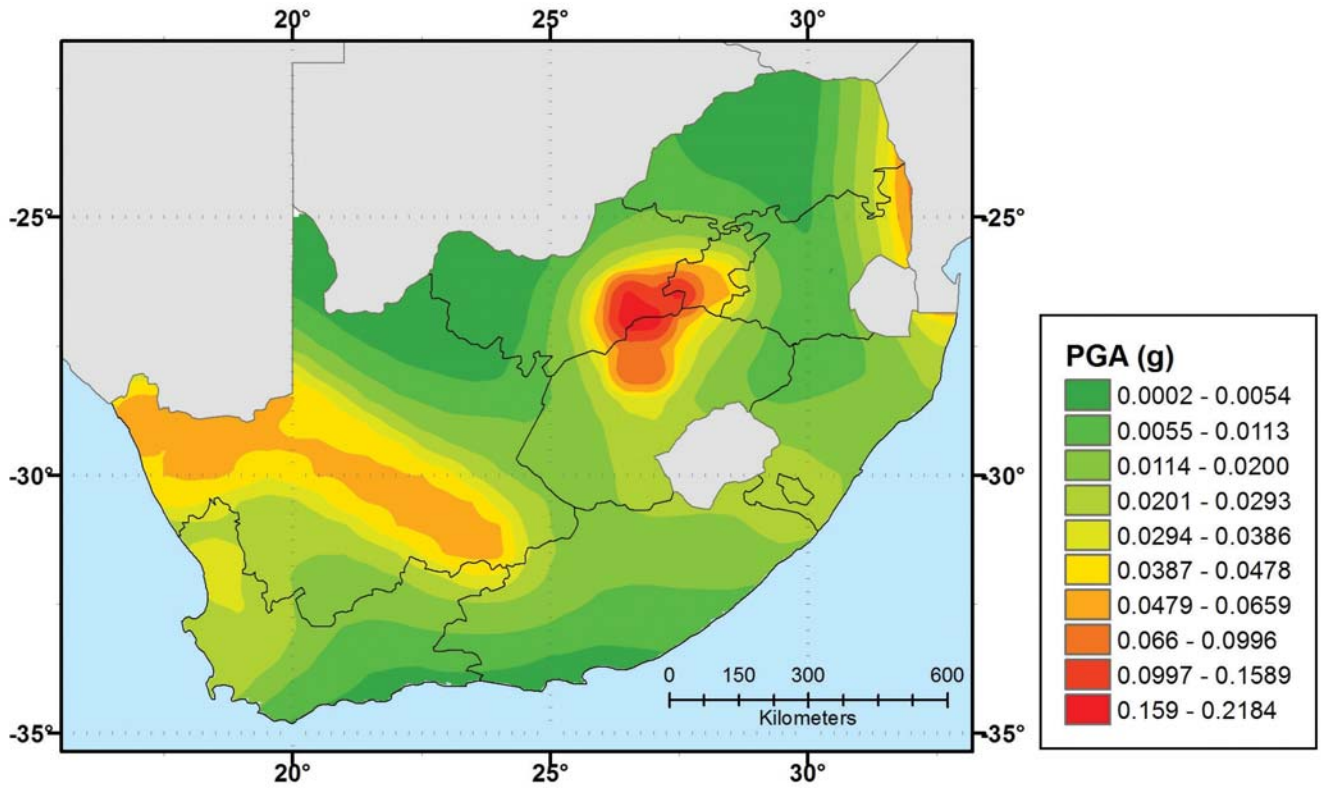
Fynn's work showed there is an active NW-SE strike-slip fault in this area, consistent with the distribution of the earthquakes. The presence of such a structure has implications for shale gas exploration in that wastewater pumping in an area with active faults could trigger larger and more frequent earthquakes, as seen in case studies in the central states of America, in particular, Oklahoma.

To understand this risk, we have to consider seismicity in the region.

Council for Geoscience)



Seismic hazard map of South Africa.

Spotlight on seismicity

Seismic stresses produced by relative tectonic plate motions result in frequent earthquakes at plate boundaries, where more than 90% of natural seismicity occurs. These are the most widely studied earthquakes and are relatively well-understood, Fynn points out.

"By contrast, large earthquakes in the interior of continents, known as intraplate seismicity, occur far from plate boundaries, are rare and are poorly understood. Surface evidence of ruptures is also generally absent during these quakes in the study area and makes them harder to study. South Africa falls within this region type."

Although far less common, earthquakes located far from plate boundaries are still capable of releasing large amounts of seismic energy and are often located on pre-existing structures. The potential energy that can be released on intraplate structures should not be underestimated, Fynn says.

"The essential concept of plate tectonics is that stress builds up on faults over time until the frictional strength of the clamping forces holding the fault together is exceeded, releasing energy in the form of an earthquake," Fynn explains. "It is, therefore, important to understand the conditions in which intraplate earthquakes might occur, especially those areas whose inherent stress conditions may be affected by human-induced activities."

Sporadic earthquakes sometimes occur as a single seismic event on an old fault that has not recently been active, she says. "This seems to be a characteristic that most stable continental regions share." This means that intraplate earthquakes can occur in regions where seismicity was not recorded before and no surface evidence for strain accumulation is observed.

The ML6.3 earthquake in Ceres-Tulbagh that occurred on 29 September 1969 is such an example. This event resulted in at least 12 deaths and considerable damage to infrastructure in the northern Boland. Interestingly, the towns of Ceres and Tulbagh have continued to experience regular seismicity after the quake and its aftershocks.

Southern Africa is generally classified as a stable continent region, bounded to the northeast by the East African Rift System (This is an active continental rift zone where the African plate is in the process of separating into two separate plates: The Nubian plate which is moving towards the west relative to the Somali plate, which is moving towards the east). Although this structure is not well defined, it is linked to much of the seismicity in Mozambique, Zambia, Zimbabwe, Namibia, Botswana and South Africa according to a recent article in the ***Journal of African Earth Sciences***.

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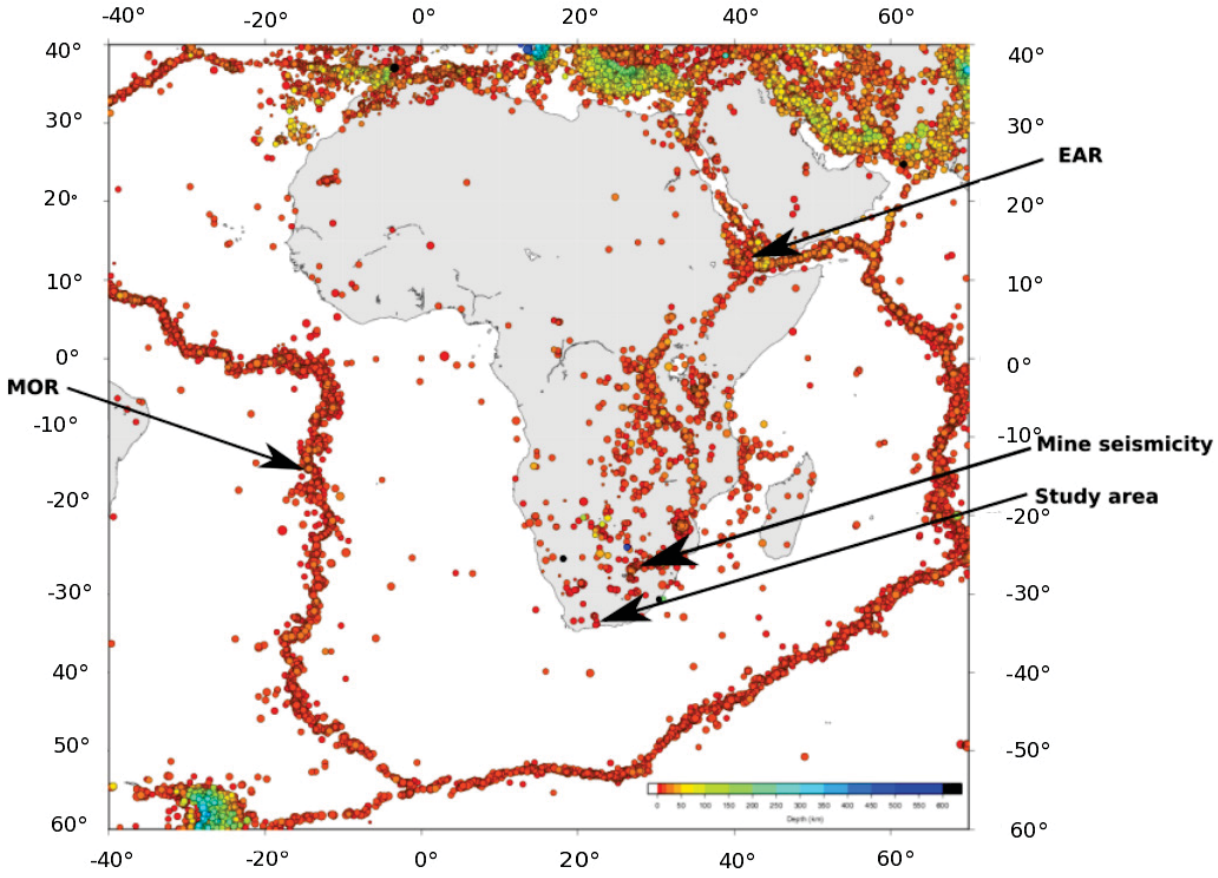

Melody Fynn

Map illustrating the plate boundaries.

Although massive earthquakes do not happen often in South Africa, it has happened according to geological evidence. The largest recorded earthquake in southern Africa is located at the southernmost extent of this system, in south-western Mozambique. The MW7 earthquake was recorded on 22 February 2006 and was unusually large considering that the earthquake occured at a divergent plate boundary, which typically produces events with smaller magnitudes.

"There are many, many smaller quakes and examples of rumblings underground – you just have to listen in the right place," according to Fynn. A total number of 22 089 earthquakes were recorded by the South African Network between 1996–2016.

Most of the seismicity recorded in South Africa is mining-related, but occasionally, clusters like the Augrabies cluster in the Northern Cape, the Drakensberg, Ceres-Tulbagh and quite unexpectedly in Leeu-Gamka, are observed and are of tectonic origin.

The stress region of the study region is according to Fynn influenced by the southern extension of the East African Rift System and the so-called Wegner Stress anomaly along the western coast of Southern Africa. These regimes are largely responsible for earthquakes of a tectonic source in South Africa and are mainly observed in the western regions of the country, including Ceres-Tulbagh and Augrabies.

Until the Tulbagh quake occurred, intraplate regions such as the Western Cape were conceived as effectively rigid and subject to no tectonic loading, except at distant boundaries.

The recurrence time for large earthquakes in individual parts of an intraplate seismic zone may be very long, measured on a scale of millennia rather than centuries, Hartnady says. "Consequently, the historical and instrumental seismic record yields an inaccurate view of the long-term seismicity, and seismic hazard analysis requires additional, scientific tools."

In the early understanding of the African plate, the Western Cape is far from an active plate boundary, explains Dr Chris Hartnady from Umvoto Africa. Hartnady, a former professor at the University of Cape Town, is involved in efforts to improve early warning systems for earthquake hazards in South Africa.

"It is, however, located close to the rifted ocean-continent margins that formed during the break-up of the Gondwanaland supercontinent, between 180 million and 135 billion years ago," he says. "So the western and southern parts of the province are riddled with major faults related to this episode of the supercontinent breakup."

In South Africa, the map of seismicity is dominated by mining regions due to two factors. "Firstly, natural or tectonic earthquakes are relatively rare in South Africa due to its location far from the plate boundary zones," Fynn says. "Secondly, seismic monitoring is concentrated around the mines due to the potential risk of earthquakes to mining." This means that more smaller earthquakes are recorded around the mines

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than elsewhere and this leads to an artificially high density of seismicity if all events are considered, she says. Fynn plotted all ML>4 earthquakes in southern Africa.

The largest mining-related earthquake to be recorded in South Africa was a ML5.5 and occurred near Orkney on 5 August 2014 in the KOSH ((including Klerksdorp, Orkney, Stilfontein and Hartbeesfontein) mining district. The region is quite active with more than 8 000 events recorded between 1971 and 2014 as well as about 150 events of magnitude greater than or equal to MW4.

Lessons from Oklahoma

Since the 1960s, the link between wastewater injection and seismicity has been documented.

This has been seen extensively in Oklahoma, also a previously seismically quiet region, where large earthquakes (>ML5) have been linked to the disposal of wastewater injection with the source locating within a few hundred meters of wastewater injection wells. In 2014, Oklahoma recorded more earthquakes than California, situated on a major active fault and known for its geohazards and seismic risks.

A relationship between increased seismicity and injection of wastewater has also been widely reported in Colorado, Ohio, Arkansas, Texas, New Mexico and China and seems to lead to larger magnitude earthquakes than those said to be related to fracking.

The pumping of wastewater, associated with the process of hydraulic fracturing, into a seismically active region can reactivate dormant faults, increase the seismicity on active faults or induce larger earthquakes than previously experienced or expected.

Research shows an increase in seismicity due to wastewater injection can happen because the pumped fluid causes an increase in pore-pressure which reduces the effective normal stress (or clamping forces) on the fault.

Seismicity can be triggered by changing the pore-fluid pressure at depth. "Faults usually remain locked by the pressure of an overlying column of rock and injecting fluids can counteract the pressure, making the frictional failure of rocks more likely," Fynn says.

A precautionary approach

Hartnady believes a prudent approach to groundwater-resource development requires micro-seismic monitoring in areas that undergo low levels of natural earthquake activity or if wellfield development has the potential to trigger induced seismicity.

Temporary deployments of seismic monitoring arrays have recently been undertaken in the Western Cape to demonstrate ongoing micro-earthquake activity following the 1969-1970 Tulbah-Ceres seismicity and the 2009-2011 Leeu-Gamka earthquake swarm.

Perturbations of stress may be a result of an increase in pore-pressure at earthquake source depths, or from local changes in secondary stresses, for example, surface loading and unloading. In the Karoo, these secondary stresses could originate from unloading caused by excessive borehole water extraction or in the case of possible fracking activities, the pore-pressure could be increased by waste-water injection.

It is also possible that natural seismic swarms can be attributed to fluid overpressure, Fynn points out. Some researchers argued that fluid pressure at depth plays a key role in earthquakes occurring by lowering effective stress on highly stressed fault segments close to shear failure.

Earthquakes can also be triggered by loading and unloading of the crust by surface or groundwater. Research showed that changing the local stress by extracting water from a shallow aquifer likely caused the ML5.1 earthquake near Lorca, Spain in 2011.

This is important for an area like Leeu-Gamka Fynn says. "Earthquakes greater than >ML3 associated with fluid injection are almost always associated with the injection of large volumes of wastewater, and not necessarily the deliberate, controlled formation of fractures to liberate the gas during the fracking process."

The depths of the earthquakes was a key research outcome, Fynn says. The location of the seismicity will prove to be important if fracking should start in the region, particularly if the wastewater produced is re-injected into the subsurface to a similar depth of the active fault.

Providing a baseline study of seismicity and identifying active faults in a region being considered for shale gas extraction is vital.

What this study has revealed, is that there is an active fault in the region with a NW-SE striking surface, capable of generating an earthquake of ML4.5, the largest observed within the period between 2007–2013. "I can say with some degree of confidence that the earthquakes in the Leeu-Gamka region are a consequence of reactivation along a pre-existing fault," Fynn says.

The active part of the fault identified starts at a depth of approximately 6 km, a critically stressed zone within the Cape Supergroup, and could further be exacerbated by wastewater injection near this depth if this method is adopted for disposal.

The disposal of wastewater produced by fracking merits further study, Fynn adds. Studies are also needed to examine earthquake swarm processes and their potential for reactivating inactive faults or unidentified faults in a particular region, she concludes.

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