PHOTOGRAPHED BY GUERCHOM NDEBO FOR *NATURE*

Residents of Goma in the Democratic Republic of the Congo are flanked by Nyiragongo volcano and Lake Kivu, both of which pose threats.

HOW DANGEROUS IS AFRICA'S EXPLOSIVE LAKE KIVU?

An unusual lake in central Africa could one day release a vast cloud of greenhouse gases that suffocates millions of people. But researchers can't agree whether the threat is getting worse. **By Nicola Jones**

On 22 May, one of Africa's most active volcanoes, Mount Nyiragongo, started spewing lava towards the crowded city of Goma in the Democratic Republic of the Congo (DRC). The eruption destroyed several villages, killed dozens of people and forced an estimated 450,000 people to flee their homes.

The volcano has since calmed and the immediate humanitarian crisis has eased. But government officials and scientists have another worry on their minds: something potentially even more dangerous than Mount Nyiragongo.

Goma sits on the shore of Lake Kivu, a geological anomaly that holds 300 cubic kilometres of dissolved carbon dioxide and 60 cubic kilometres of methane, laced with toxic hydrogen sulfide. The picturesque lake, nestled between the DRC and Rwanda, has the potential to explosively release these gases in a rare phenomenon known as a limnic eruption. That could send a huge pulse of heat-trapping gases into the atmosphere: the lake holds

the equivalent of 2.6 gigatonnes of CO_2, which is equal to about 5% of global annual greenhouse-gas emissions. Even worse, such a disaster could fill the surrounding valley with suffocating and toxic gas, potentially killing millions of people. "It could create one of the worst, if not the worst, natural humanitarian disasters in history," says Philip Morkel, an engineer and founder of Hydragas Energy, based in North Vancouver, Canada, who is attempting to get funding for a project to remove and utilize gas from the lake.

The 2021 volcanic eruption didn't trigger a mass release of gases from the lake, and on 1 June, the Rwanda Environment Management Authority (REMA) said there was no imminent risk. But, the authorities do think that lava flowed through underground fractures beneath the city of Goma and Lake Kivu itself. A day after the eruption, a tremor seems to have triggered part of a sandbar by the lake to collapse, which might have caused a small release of gases in that spot: some people reported that waters offshore from a prominent hotel looked like they were boiling.

For now, the lake is stable. Although it contains a lot of gas, the concentration would have to double in the region with the most gas for it to reach saturation point. But a strong earthquake or volcanic eruption could potentially trigger a gas release by disrupting the lake's layered structure or increasing the gas concentrations. And some researchers worry that a disaster might be brought on by human activity, too.

Methane is already being pumped from the lake's depths and burnt to create much-needed electricity, which most people agree is both a sensible use of local natural resources and a way to make the lake safer by removing some of its gas. The stakes are high: researchers have estimated that the methane in Lake Kivu could be worth up to US$42 billion over 50 years.

But researchers disagree about which method of gas extraction is best, and whether such efforts might eventually disturb the lake in ways that elevate the dangers rather than subduing them. The debate rages even while efforts to harvest methane are expanding — plans are in place to bump up electricity generation more than fivefold in the coming years or decades.

"A lot of scientists don't agree," says biochemist Eric Ruhanamirindi Mudakikwa, head of Rwanda's Environment Analytics and Lake Kivu Monitoring Division. "What we are doing on the lake is really new," he says. "We don't know how it can behave."

Under pressure

Lake Kivu is the largest of only a handful of lakes in the world thought to be capable of limnic eruptions. Two, much smaller, such lakes lie thousands of kilometres west, in Cameroon; and another, Lake Albano, is in Italy.

These lakes all sit above tectonically active regions, where volcanic gases such as CO_2 seep upwards from deep within Earth. The lakes are deep, and their waters do not mix top to bottom with seasonal temperature swings. Instead, the dissolved gas accumulates in denser bottom layers, capped by a 'cork' of pressure from the waters above. If the gases accumulate to such an extent that they form bubbles, these lakes can literally explode like a champagne bottle. An external event can also 'pop the cork' — a drought could lower lake levels and reduce pressure on the gassy waters below; a landslide, earthquake or lava erupting into the bottom of the lake could shift the water layers or add enough heat to cause gas to bubble out.

"You have a gas-rich lake sitting next to a volcano; you have a potential for many triggers."

The violent potential of these lakes became clear in August 1986, when Lake Nyos in Cameroon erupted with a blast that some locals mistook for the testing of a nuclear weapon. As much as 1 cubic kilometre of heavier-than-air CO_2 flooded low-lying regions, suffocating more than 1,700 people and 3,500 livestock.

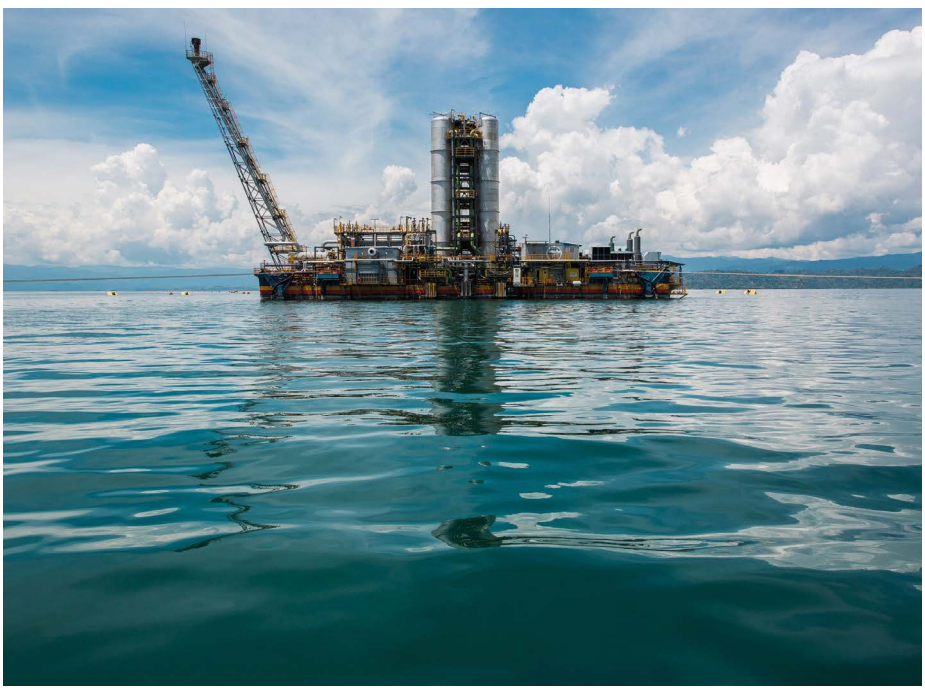
After the blast, a project was initiated to ensure this wouldn't happen at Lake Nyos again: in 2001, physicist and engineer Michel Halbwachs, then at the University of Savoie in Chambéry, France, and his team inserted a pipe into the lake from a floating dock and siphoned up deep, gassy waters. This created a self-powered fountain, allowing gas to vent in a tiny, controlled version of a limnic eruption. The team added another two pipes in 2011; by 2019, Halbwachs and his colleagues considered Lake Nyos "quite totally emptied of hazardous amounts of dissolved carbon dioxide"[1].

Halbwachs then tackled Nyos's little sibling, Lake Monoun, which had experienced a much smaller eruption in 1984. After the venting pipes were installed, the lake was considered degassed by 2009.

Halbwach's company, Limnological Engineering, has just secured a $5-million contract to degas CO_2 from the Gulf of Kabuno, a small offshoot at the north end of Lake Kivu, which has high concentrations of CO_2 at shallow depths. The company has had a pilot project under way since 2017.

But the vastly larger Lake Kivu presents a different problem. Lake Kivu is geologically older than Lake Nyos, and the soil surrounding it is richer in organic matter. Unlike at Lake Nyos, this has led to substantial amounts of methane in Lake Kivu, says biogeochemist George Kling at the University of Michigan in Ann Arbor, who studies limnic eruptions. Microorganisms digesting organic matter produce methane, and volcanically produced methane or hydrogen could be seeping directly into the lake from the rocks below. Methane is much less soluble than CO_2, and so is much closer to bubbling out. "It's the methane that's the problem. It's not like Lake Nyos," says Alfred Johny Wüest, a lake physicist at the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) in Kastanienbaum.

Although the lake contains a lot of CO_2, it



RACHEL COUCH

The KivuWatt project generates electrical power by extracting methane gas from the lake.

could safely hold much, much more if the methane wasn't adding to the gas pressure. Extract the methane for fuel use, and the CO_2 becomes a non-issue, scientists say.

Gas mysteries

Despite the threat that Kivu potentially poses, there is considerable disagreement on basics, such as the source of the gases, whether amounts are increasing, and even whether Lake Kivu has erupted before. Robert Hecky, a retired lake ecologist at the University of Minnesota Duluth, who has studied Lake Kivu, says that although there are 9 brown layers in the sediments, showing mixing events in the past 2,000 years, he has found no evidence of any events in the past 12,000 years violent enough to be called a limnic eruption[2]. Others interpret the evidence as signifying at least one eruption 4,000 years ago[3].

Some facts are clear. The lake's surface waters are fresh and filled with fish. Around 260 metres down, there's a dramatic shift to waters that are much warmer and saltier, thanks to hydrothermal springs. These are the deep 'resource waters' flush with dissolved gas (see 'Deep gas').

In 2005, a paper[4] by EAWAG environmental scientist Martin Schmid and his colleagues, including Halbwachs, compared gas levels in that deep layer with measurements taken in 1975, and suggested that methane concentrations had increased by 15%. If that trend were to continue, the deeper layers would reach saturation by 2090, triggering an eruption. In 2020, however, data in another paper[5] – with Schmid as co-author – suggested the gas levels had not increased after all.

This reassured many researchers, but the findings remain controversial. For one thing, the gas-measurement technique had changed from one data set to the next. "From a methodological standpoint, they are mostly comparing apples to oranges," says Kling. And the errors on such measures can be large, he says. From Kling's perspective, the 2020 paper doesn't prove there has been no change over time, but rather that a change can't be detected one way or another. "That is a very different thing," he says.

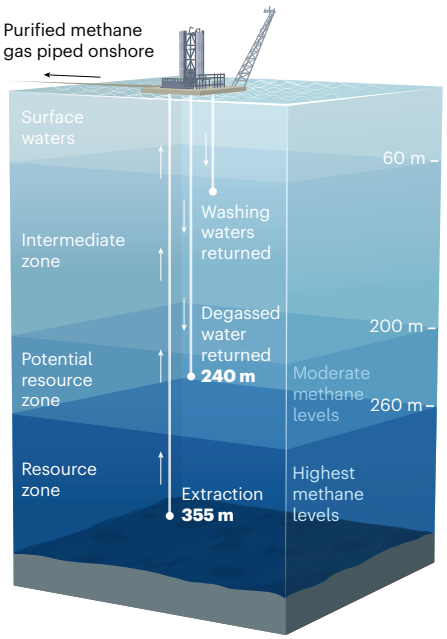
Whether gas levels have gone up or not, their future is also uncertain – and concentrations could still rise dramatically without warning. "The underground plumbing of the volcanic system of the rift that surrounds Lake Kivu is very poorly understood," says Kling. "It is quite possible that changes in gas inputs could increase dramatically, due to a rise in subterranean volcanic or geologic activity."

Those same volcanic eruptions and earthquakes could also theoretically trigger an eruption. "You have a gas-rich lake sitting next to a volcano; you have a potential for many triggers," says Hecky. The question is how big they would have to be. "The lake is exceptionally stable; it would take an enormous amount of energy to overturn it," he says. Dario Tedesco, a volcanologist at the Luigi Vanvitelli University of Campania, Italy, who works in Rwanda, says his data show that the 2021 volcanic eruption didn't release gases from fissures around Goma or the lake: magma was either not present underground, he says, or its flows were so small or deep that they had no impact.

Yet most of the dozen or so scientists contacted by *Nature* remain concerned about the lake's methane levels, given the area's geological activity. Efficiently extracting 90% of the methane over some 50 years, argues Morkel, could reduce the likelihood of a limnic eruption by 90% in the first 10 years. "In the best case, it will never happen," he says.

DEEP GAS

Lake Kivu in central Africa is stratified and holds vast amounts of dissolved methane and carbon dioxide below a depth of 260 metres. The KivuWatt energy project pipes up deep water, and methane bubbles out. The methane is purified by washing it with surface waters and then pumped to an onshore power plant. Both the degassed water and the washing waters are returned to the lake.



Tapping the methane

People have been pumping methane from Lake Kivu on a small scale for decades to make use of it for energy. But efforts ramped up seriously when KivuWatt, run by London-based ContourGlobal, began operation in 2016. The $200-million project is currently providing 26 MW of electrical power, and it has a contract to increase that to 100 MW. This will add considerably to Rwanda's baseline installed grid capacity of about 200 MW.

For now, KivuWatt's withdrawals are minor in terms of the lake's stock: at the current rate of extraction, the company will remove less than 5% of the methane in the lake in 25 years. "For sure, this speed cannot be considered sufficient to really decrease the risk of limnic eruption," says Francois Darchambeau, a limnologist at KivuWatt. "So, we need to expand to more capacity." But expansion plans are on hold until electricity demand catches up with supply, the company says. KivuWatt is also considering options for removing CO_2 from the lake and selling it as a commercial product.

Meanwhile, Rwandan company Shema Power Lake Kivu has bought a tiny pilot plant, KP-1, that started pulling methane from the lake in 2006. The firm is currently constructing a facility planned to deliver 56 MW. The company's website says it expects to have construction finished in early 2022, but Shema Power's project director Tony de la Motte declined to answer *Nature*'s questions about the plant's schedule or details of its operation.

The general principle of all such projects is to pull up deep water so the methane bubbles out and can be purified and pumped to a power plant. The degassed water is then returned to the lake. Questions surround how best to do this; plans vary, depending on the company and the proposal.

The degassed water still contains high levels of nutrients and toxic hydrogen sulfide, so returning it too near the surface could kill fish and lead to harmful algal blooms, say some researchers. It is also salty and laden with CO_2, making it relatively dense. So, if released into the lake at too shallow a depth, the degassed water would sink, potentially disturbing the main density gradient, 260 metres deep, that keeps the gassy waters of the resource zone trapped below. "It wouldn't necessarily blow up, but it would be more prone to blow up," says Morkel.

Pushing the main gradient upwards could also be problematic, because it would reduce the pressure on the gassy waters. And diluting the resource layer with degassed water might lower gas concentrations enough that commercial extraction would no longer be possible. If that happened, it would leave a lot of dangerous gas in the lake, with no good way to remove it other than venting it to the surface – an approach that could both release potent greenhouse gases and contaminate surface waters.

In 2009, an international group of researchers, including Morkel, Wüest and Schmid, published 'management prescriptions' (MPs) outlining best practices for extracting the lake's methane. The majority of the experts favoured a strategy called the density zone preservation method, which involves controlling the density of degassed waters by managing the amount of CO_2 they contain, so they can be carefully returned to the lake without causing mixing. This is technically difficult to do, but would largely maintain the current structure of the lake.

KivuWatt opted for an alternative strategy,

in which degassed waters are released just above the main gradient. This is simpler to accomplish and should avoid diluting the resource layer, but is expected to alter the structure of the lake.

Darchambeau says KivuWatt monitors the surface waters daily, and does weekly profiling to get a robust data set regarding the lake's stability. He says that after five years of operation, the firm did start to see, as expected, a weakening of lake stability – but not by much. "If we pursue the gas extraction as we do, during 50 years we will reduce the lake stability by 1%," he says. This is well below the MPs' guideline, which is that the stability – expressed in terms of the energy needed to completely mix the lake – must not be reduced by more than 25%.

Some argue, however, that KivuWatt's approach is problematic. "That is the way to disaster," says Finn Hirslund, an engineer with consultancy firm COWI, based in Lyngby, Denmark, who was part of the group that wrote the MPs and who has published peer-reviewed papers about Lake Kivu. Hirslund argues that the project will "destroy the main gradient", and worries that continuing and scaled-up extraction from the lake using similar methodologies might have long-term consequences that only become apparent after decades[6].

Morkel, too, is critical of KivuWatt's approach. He argues that the company's degassed water has too much CO_2 and is too dense, which he thinks will punch a hole through the main gradient. Morkel advocates taking water and returning it to different depths from those chosen by KivuWatt. He thinks that would better preserve the lake's layering while extracting gas for energy. He continues to try to raise funding for his approach.

Others are not concerned, however. "In terms of safety, I'm absolutely confident," says Wüest, who also serves on KivuWatt's independent expert advisory group. "I have a really positive view on the whole thing," says Bertram Boehrer, a physicist at the Helmholtz Centre for Environmental Research in Magdeburg, Germany, who has worked on the lake. "If something goes in an unexpected way, there's enough time to act."

Future forecasts

Perhaps the only way to resolve debate about how these operations might affect the lake is to track whether and how the density layers are changing. Rwanda's lake-monitoring division surveys the depths and inspects the gas-extraction companies, and Mudakikwa says its weekly profiling shows the lake remains stable for now. "The main gradient is not changing," he says. "If there is a lake instability, we will be the first ones to be concerned."

KivuWatt says it is required to and does comply with the guidelines set out by the monitoring division, and that the company's independent expert advisory group (including Hecky and Wüest) has access to its data and reviews its annual report to the government of Rwanda.

"We are very open to science," Darchambeau says, although some information – such as the design of KivuWatt's bespoke gas concentration sensors – remains proprietary. "Everyone wants the data from KivuWatt," says Priysham Nundah, director of KivuWatt. "I cannot give a competitor things," he says, "But what we are supposed to give [to the monitoring division] contractually and based on our obligation, we are doing."

Some researchers contacted by *Nature* complained that they have had trouble getting access to such data. "In our [MP] guidelines we stated very clearly that this data has to be public," says Wüest. "To my knowledge, the government of Rwanda never lived up to that." Mudakikwa says that data relating to the gas-extraction companies are confidential, but lake-profile data can be obtained if researchers write a letter to the director-general of REMA explaining what they need and why they need it.

The monitoring programme only recently moved under the remit of REMA; until April, it was under the Rwanda Energy Group, which is also the country's national energy utility company. The programme's new website hasn't yet been set up. The authority is currently revising the MPs, Mudakikwa says, in part to better outline its data-sharing policies.

PHOTOGRAPHED BY GUERCHOM NDEBO FOR *NATURE*

A gas eruption from Lake Kivu could threaten millions of people living in the region.

"The underground plumbing of the volcanic system of the rift that surrounds Lake Kivu is very poorly understood."

Augusta Umutoni, who headed the monitoring programme until this April, says she is proud of the technical team she helped to set up, and thinks the Rwandan government is committed to keeping the monitoring effort going. But, she adds, governments sometimes find their budgets stretched thin, or become bogged down in bureaucracy. "The governments and operators will have to work together," she emphasizes. The MPs also recommended the creation of a bilateral regulatory authority shared by Rwanda and the DRC; this has not yet happened, confirms Mudakikwa.

The combination of Lake Kivu's monetary value, its potential explosive capacity, and the huge range of opinions about how to best deal with it, makes emotions run high among the scientists who work there. "It has become an obsession for me to understand what's going on in this lake," says Hirslund. "When you start working with Lake Kivu, you get passionate," agrees Umutoni.

Taking gas out of the lake should be making it safer, says Mudakikwa, but there are some things – such as a volcanic eruption – that no scientist, company or regulatory authority can counter or prevent. "If it's Mother Nature, you can't fight Mother Nature."

Nicola Jones is a science journalist based in Pemberton, Canada.

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Correction

This feature misspelt Francois Darchambeau's name. It also erroneously referred to the Lake Kivu Monitoring Program, which no longer exists. The programme's tasks have been taken up by the new Rwanda Environment Management Authority's Environment Analytics and Lake Kivu Monitoring Division.