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Swiss Federal Institute of Aquatic
Science and Technology

Methane Extraction from Lake Kivu

Scientific background

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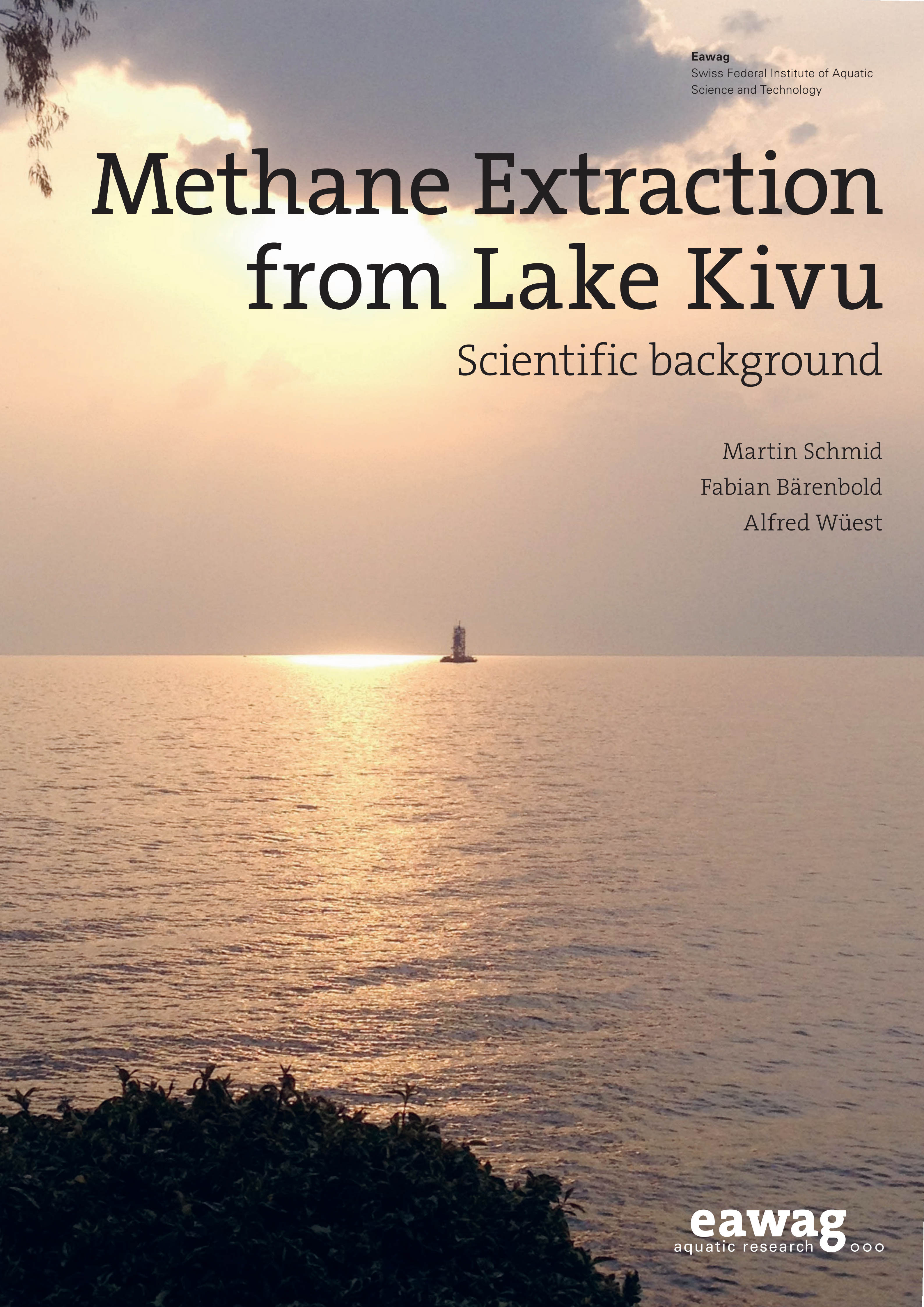

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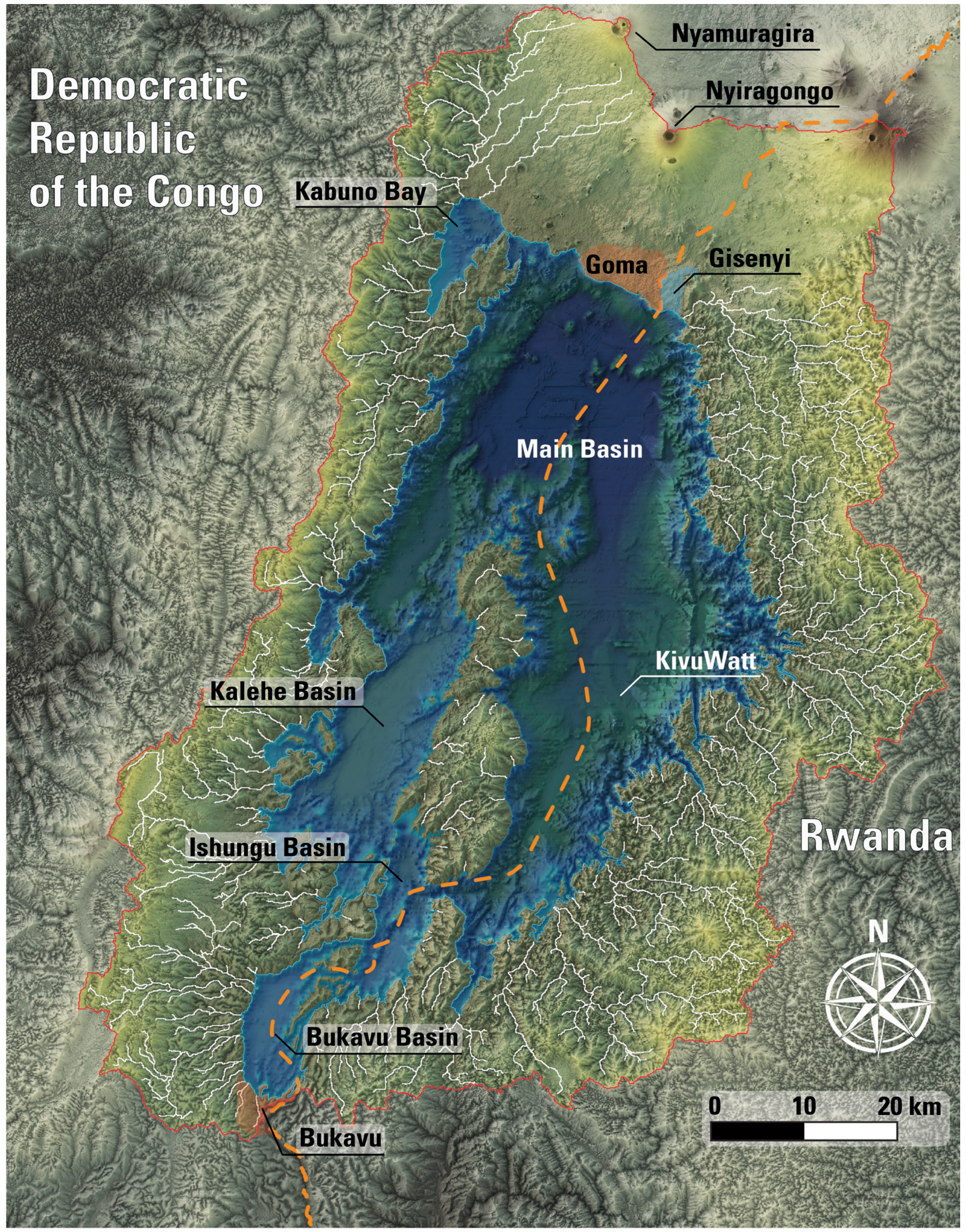
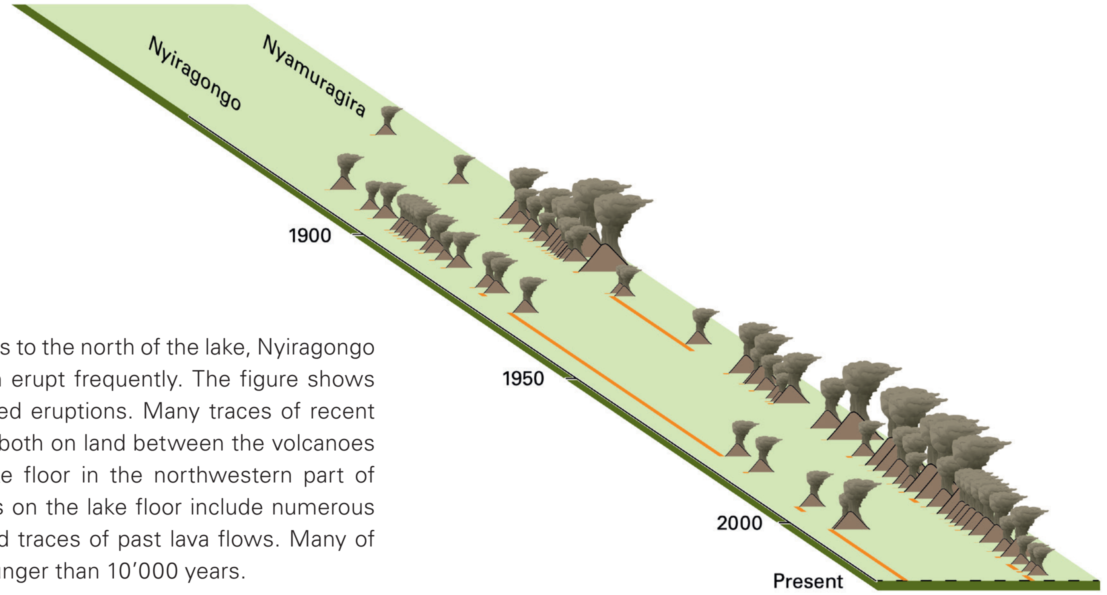
Lake Kivu – a special lake in an active volcanic region

The basins of Lake Kivu

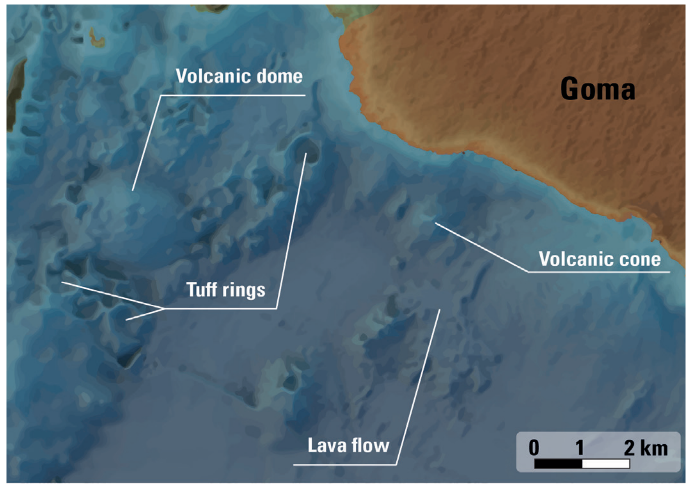
Lake Kivu consists of five basins. For the methane extraction, only the large **Main Basin** with a maximum depth of 485 m is important. The three basins in the west and southwest, **Kalehe Basin, Ishungu Basin,** and **Bukavu Basin,** are shallower and do not contain sufficient gas for commercial extraction. **Kabuno Bay** is a separate basin, connected to the main basin across a shallow sill. It contained carbon dioxide concentrations close to saturation at shallow depths but not enough methane for commercial extraction. To avoid the risk of a gas eruption, it is today artificially degassed using a syphoning system designed by the French company Limnological Engineering.





Volcanic activity

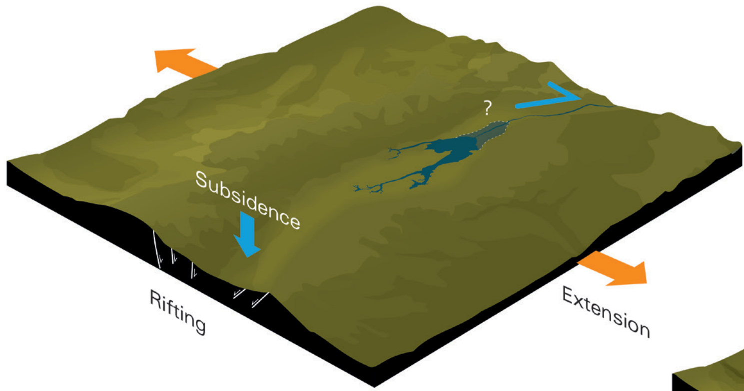
There are two active volcanoes to the north of the lake, Nyiragongo and Nyamuragira, which both erupt frequently. The figure shows the timeline of recent recorded eruptions. Many traces of recent volcanic activity can be seen both on land between the volcanoes and the lake, and on the lake floor in the northwestern part of the lake. Observed structures on the lake floor include numerous volcanic cones, tuff rings, and traces of past lava flows. Many of these structures are likely younger than 10’000 years.



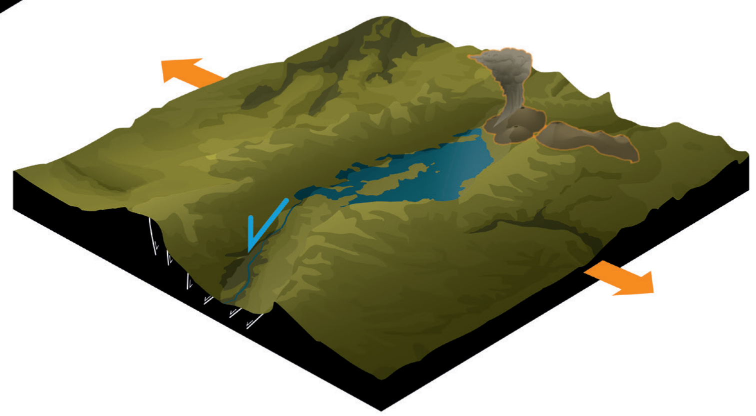
History of the lake

Lake Kivu is located in the Western Rift Valley of the East African Rift, which was formed by the divergence of two continental plates. Several large lakes have filled local depressions created by the subsidence in this valley. Until about 15’000 years ago, Lake Kivu’s water level was about 400 m below its current level. The outflow of the lake was directed to the north towards Lake Edward, and the southern branches of today’s lake were river valleys. The lake was then dammed by the rising volcanoes Nyiragongo and Nyamuragira. Its level rose, until the water found a new outflow towards Lake Tanganyika in the south around 10’000 years ago. The lake today has a surface area of 2’385 km², and a relatively small catchment of 5’100 km² with many small rivers feeding the lake.

Until 15’000 years ago



Present



The water cycle: a lake driven by subaquatic springs

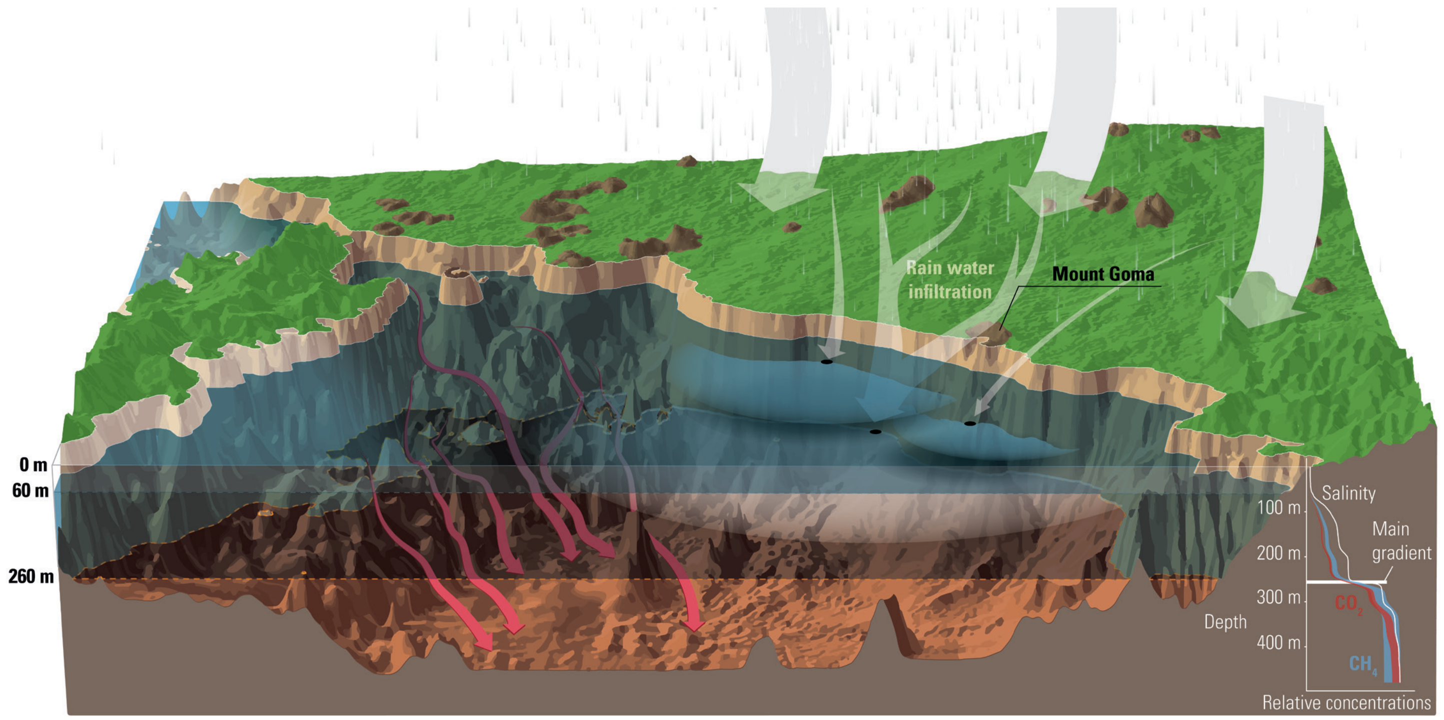
Vertical structure of the lake

Lake Kivu is vertically separated into three distinctively different water masses:

The **surface water** is in direct contact with the atmosphere. It is the only part of the lake that contains oxygen and thus is inhabited by fish, zooplankton and algae. It receives water from many small rivers, from rain, and from the upwelling water from below, and loses water by evaporation and to the outflow. Altogether, the water in this surface layer is replaced within 20 years. The lower boundary of the surface water at about 60 m depth is defined by the depth reached by seasonal mixing in the dry season (see page 6).

The **intermediate water** is located between 60 and 260 m depth. This water body consists mainly of “cool” groundwater, and the groundwater springs replace it in about 250 years.

The **deep water** is located below 260 m depth. It is warmer, more saline and much richer in nutrients and dissolved gases than the water above. Its properties are a result of the hydrothermal groundwater springs, which replace the water in this volume approximately every 1000 years.

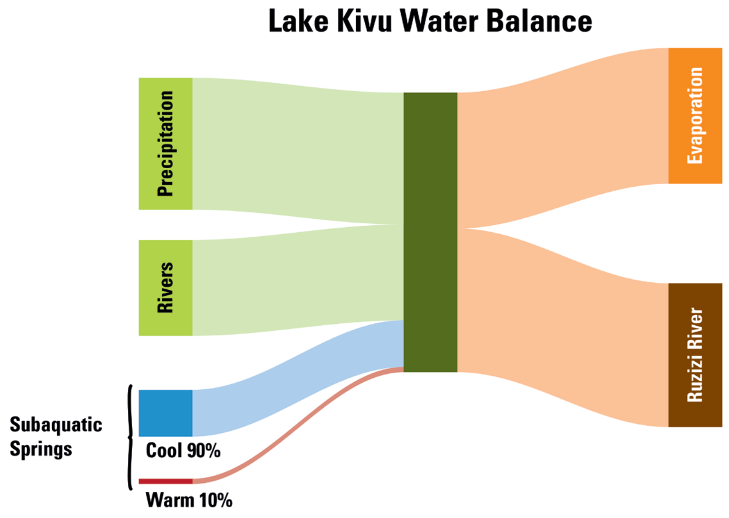


Hydrothermal groundwater springs

The hydrothermal groundwater springs discharge warm and saline water with high carbon dioxide (CO_2) content into the lake. These springs enter the lake at several locations in the northwestern part of the lake, and maybe also elsewhere. Because it has a higher density than the lake water, it flows downward along the topography and feeds the deep water of the lake, as depicted by the red arrows in the figure above. The hydrothermal springs contribute only a small fraction to the total water balance of the lake. Nonetheless, they are the reason why the deep water of the lake is saline and contains large amounts of CO_2.

Cool groundwater springs

Several relatively “cool” groundwater springs with low salinity enter the lake at the steep wall in the north of the lake close to Goma. We call them “cool” because the spring water is somewhat cooler than the lake water at the same depth. At least part of this spring water is likely rainwater infiltrating in the volcanic area around Goma, which is not drained by rivers. One large spring has been observed at the location where the volcanic cone of Mount Goma meets the steep wall at about 250 m depth. The cool groundwater mixes with the ambient water and spreads horizontally in the lake, as indicated by the white disks. The cool groundwater springs contribute about 90 % to the total groundwater discharge into the lake.

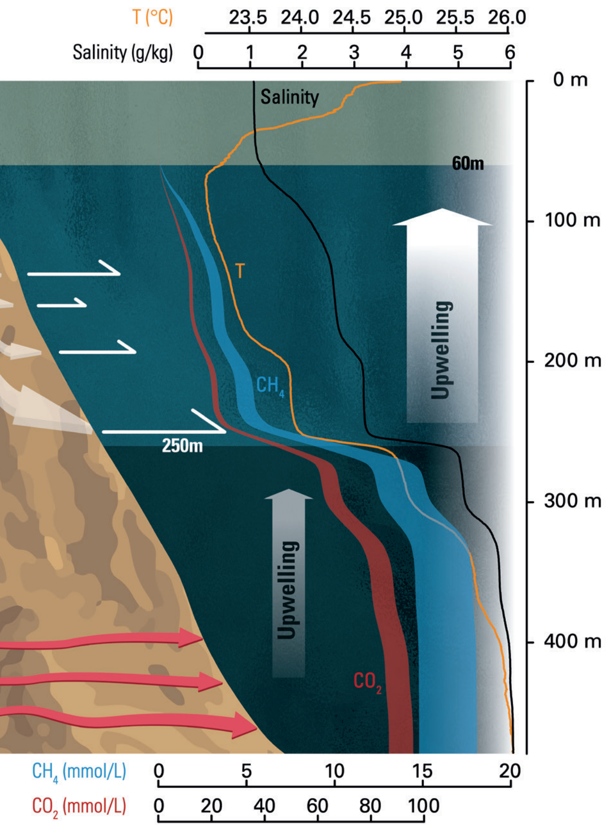


Upwelling

Because water from the groundwater springs enters the lake at depth and finally leaves the lake with the outflow at the surface, the entire water volume in the lake is slowly lifted upward. This process is called upwelling. It is a very slow vertical movement, with a speed that varies with depth between 15 cm (at 270 m depth) and 80 cm per year (at 120 m depth). This upwelling also transports nutrients and dissolved gases upward within the lake.

The main gradient

Between about 250 m and 270 m depth, the physical and chemical properties of the lake water change abruptly over a short vertical distance. This transition zone is called the main gradient or main chemocline. Two forces created the main chemocline and maintain it at its depth. The first force is the discharge of the hydrothermal groundwater springs below the gradient. This discharge adds water to the deep water and thus pushes to extend this layer by moving the gradient upward, although very slowly, at a speed of about 15 cm per year. The second force is due to the cool groundwater spring that enters the lake at about 250 m depth. It is cooler and less saline than the lake water at the same depth. Its inflow increases the differences in salinity and temperature between the top and the bottom of the gradient. It thus strengthens the gradient and maintains its upper limit at a constant level. The water above the main gradient is a mixture of cool and hydrothermal groundwater. Finally, there is a third force, diffusive transport, which would slowly eliminate the main chemocline in the absence of the two other forces. The system is in a dynamic balance, and changes to either of the processes mentioned above can result in a slow displacement or deformation of the main gradient.



Nutrients in Lake Kivu: continuous recycling

Seasonal mixing

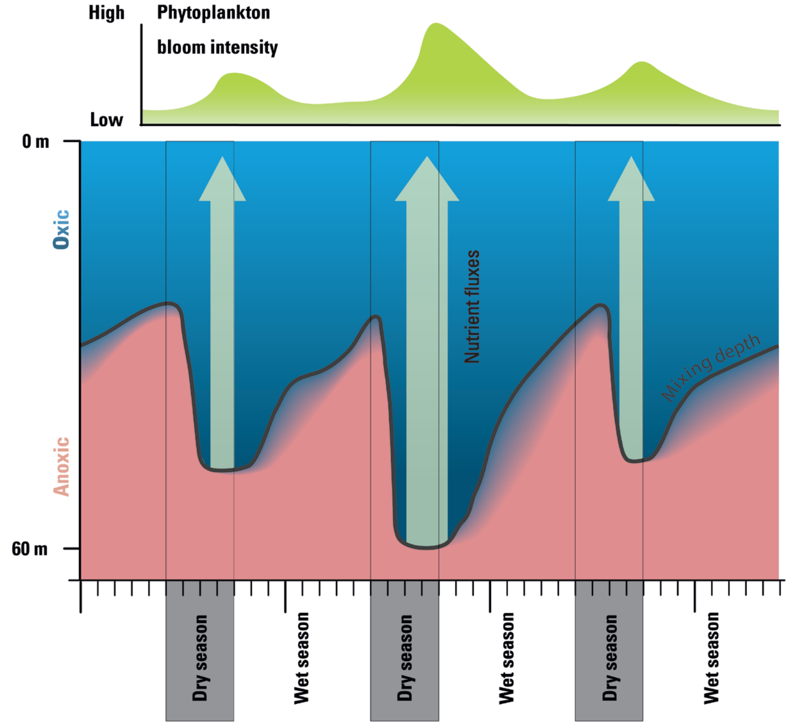
The seasonal dynamics in the surface layer of Lake Kivu is similar to many other tropical lakes. During the wet season, this layer is stratified, with warmer water on top and slightly cooler water underneath. During the dry season, the surface water cools down and mixes to the base of the surface layer. The intensity and exact depth of the mixing depend on the weather conditions and vary from year to year.

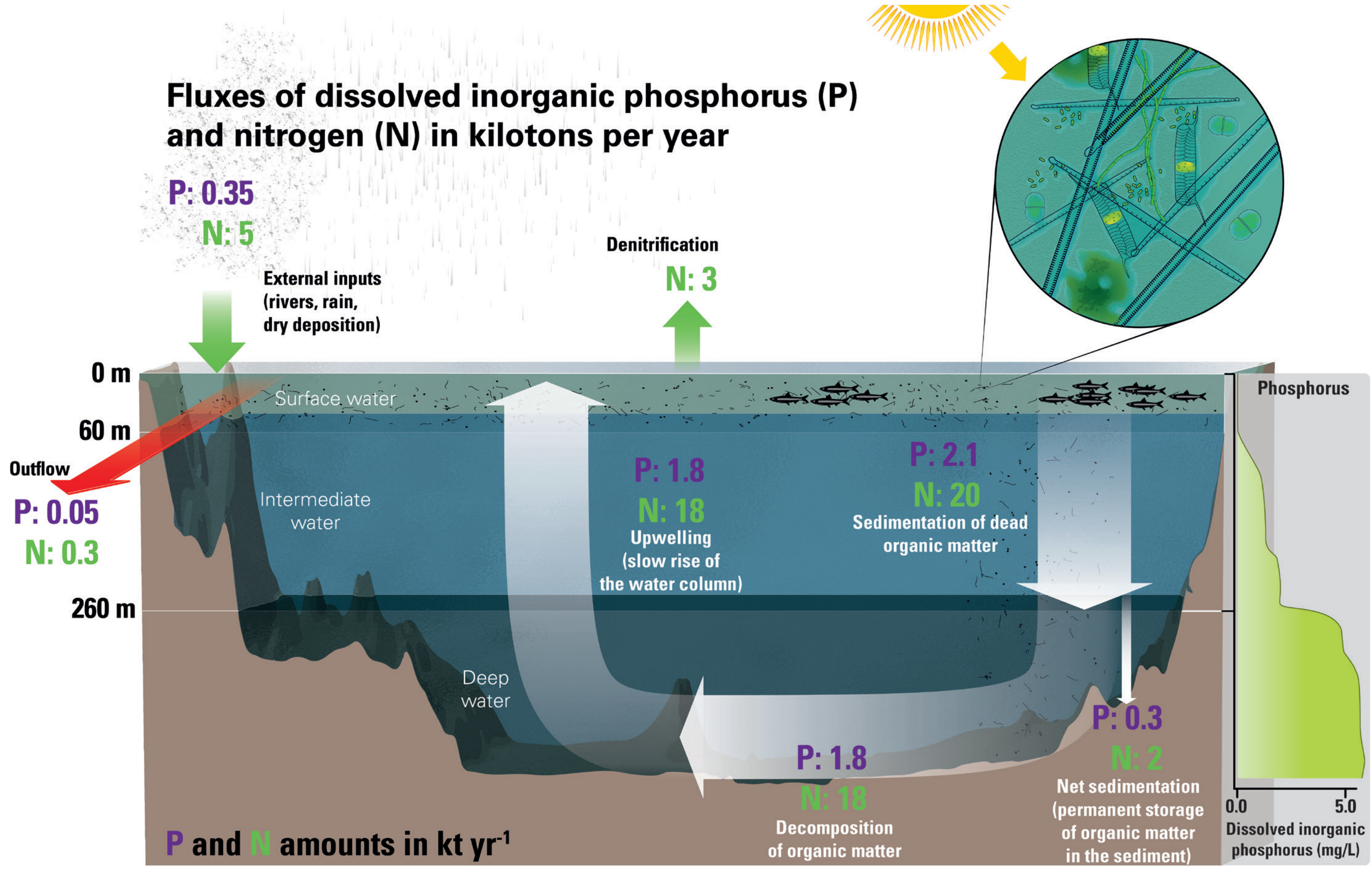
Oxygen dynamics

The seasonal mixing shapes the dynamics of oxygen in the surface layer. The top part of the surface layer always contains sufficient oxygen from the exchange with the atmosphere and from oxygen production by phytoplankton. In the lower part of the surface layer, oxygen is consumed by the decomposition of organic matter and the oxidation of substances (such as ammonium and methane) which are diffusing upward from the deep water. The boundary between the layer that contains oxygen and the layer that is free of oxygen moves slowly upward to about 30 m depth during the wet season. During the dry season, oxygen-rich water is mixed down to the base of the surface layer. Fish can only survive if there is sufficient oxygen. The living space for fish therefore reaches deeper during the dry season than during the wet season.

Nutrient and phytoplankton dynamics

The seasonal mixing entrains intermediate water into the surface water. As the intermediate water is rich in the nutrients phosphorus (P) and nitrogen (N), this entrainment supplies nutrients to the surface layer. The growth of phytoplankton in Lake Kivu is mainly limited by the availability of phosphorus, and to a lesser extent by the availability of nitrogen. The additional nutrient supply thus results in a peak in phytoplankton growth towards the end of the dry season. Averaged over several years, the amount of nutrients supplied by the seasonal mixing is equal to the amount of nutrients lifted upward from the intermediate water by upwelling. In an individual dry season, the nutrient supply and phytoplankton growth depend on the depth of mixing. Both are increased in years when the mixing reaches deep. In addition to this annual peak, there is permanent internal recycling of nutrients within the surface layer and nutrient input from the lake catchment. These supplies sustain a continuous, lower production of phytoplankton also during the wet season.





Nutrient recycling between the deep and the surface water

Organic matter, such as dead algae or faeces of zooplankton and fish, sinks into the oxygen-free zone of Lake Kivu. There, most of the organic matter is decomposed by microorganisms, producing carbon dioxide and methane (see next page), but also releasing the nutrients back to the water. Only a small fraction of the dead organic matter is permanently stored in the lake sediments. The nutrients have accumulated in the deep water over hundreds of years and thus reached unusually high concentrations. The nutrient-rich deep water is lifted upward by the inflows from the subaquatic springs (upwelling; see page 5). This results in a net flux of nutrients upward towards the surface layer. This flux is the main source of nutrients for the phytoplankton growth in the surface layer. For phosphorus, the main limiting nutrient, it is around five times as large as the external inputs from rivers and the atmosphere. However, the effective upward flux of nutrients into the surface layer varies from year to year around the average value, depending on the depth of seasonal mixing (page 6).

Consequences for lake management

An artificial increase of the flux of nutrients from the deep water to the surface water would have detrimental consequences for the lake. It would increase algae growth and could lead to harmful algal blooms and low oxygen concentrations in the lower part of the surface, reducing the habitable depth range for fish. These potential consequences must be considered in the design of the methane extraction plants.

The nutrients reaching the lake from rivers and the atmosphere do not have much direct effect on phytoplankton production in the lake. But they are, together with a poorly known potential input from the groundwater springs, the primary source of nutrients for the lake. In the long term, high nutrient inputs from outside will increase the nutrient content in the lake and would also have harmful consequences. It is therefore important to keep nutrient inputs from human activities, e.g. from sewage or erosion of agricultural soils, as low as possible.

Gases in Lake Kivu: risk and resource

How is the methane distributed in the lake?

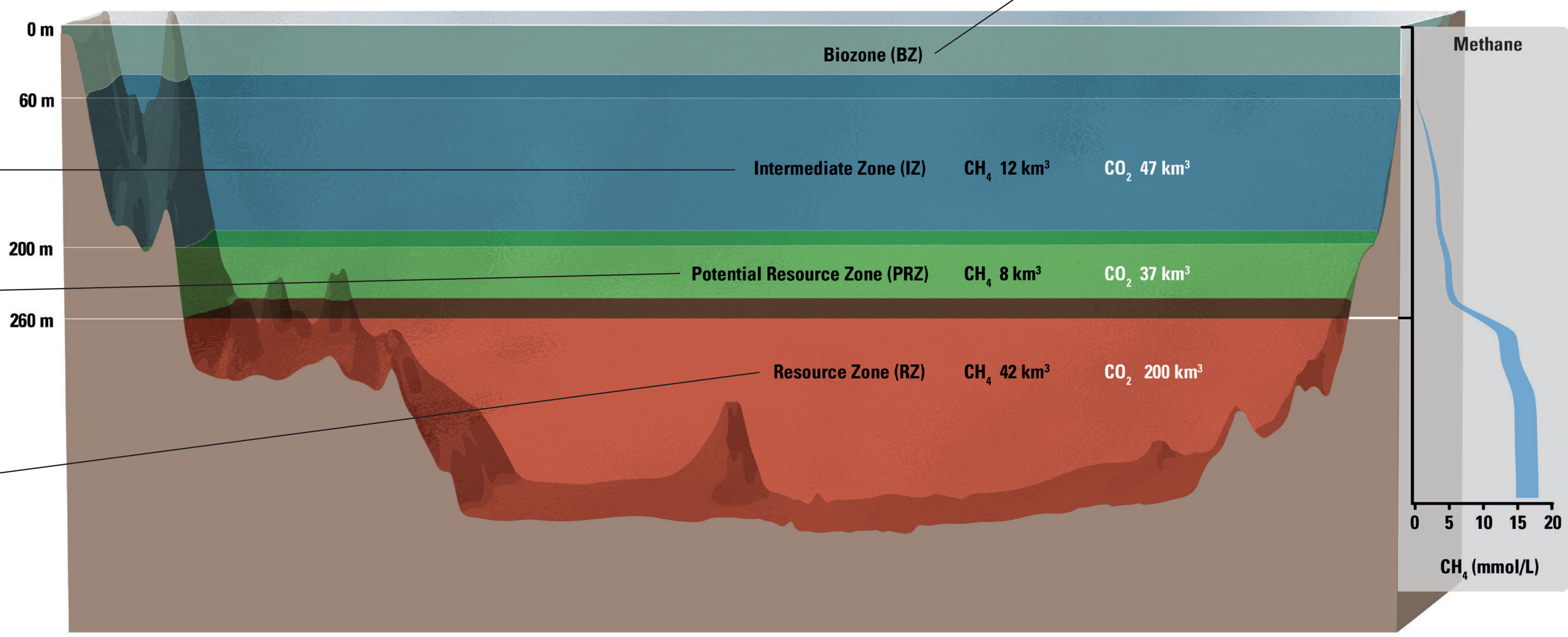
From the point of view of methane concentrations, the lake can be split into four different layers:

The surface water is also called **Biozone** in the context of methane extraction. Most of the methane that enters this zone from below is consumed by methane-oxidizing bacteria, and only a small amount evades to the atmosphere. Methane concentrations in this zone are similarly low as in many other lakes.

The **Intermediate Zone** contains 20% of the methane, but at concentrations that are too low for commercial methane extraction with currently available methods. Because the Intermediate Zone is flushed comparably fast by the upwelling water, methane concentrations in this zone will never accumulate to much higher concentrations.

The **Potential Resource Zone** contains about 15% of the methane in the lake. The methane concentration in this zone is about one third of that in the Resource Zone. It is difficult to commercially exploit methane at these concentrations. But this could change in the future, if concentrations should increase, or if more efficient extraction techniques are developed.

The **Resource Zone** contains two third of the methane (42 of 62 km³) and of the carbon dioxide (200 of 300 km³) stored in the lake. This is the zone from which current and planned extraction facilities withdraw the water for exploiting the methane.

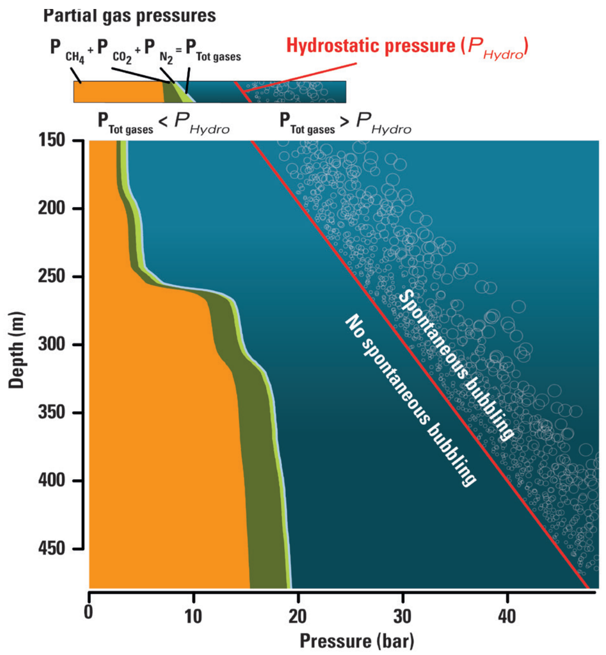


Where do the gases come from?

The methane in Lake Kivu stems from two sources. Above the main gradient, most of the methane is produced by methanogenic bacteria. These bacteria consume dead organic matter and convert it to methane and carbon dioxide. This is the same process that is also used commercially to produce biogas from manure. Besides that, a second source of methane contributes a similar amount to methane production and occurs only below the main gradient: either carbon dioxide is reduced with hydrogen of unknown origin, or the hydrothermal springs carry methane of geogenic origin into the deep water. Most of the carbon dioxide enters the lake with the hydrothermal groundwater.

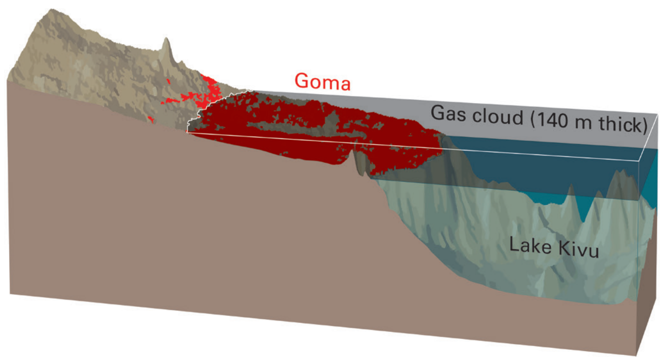
When do gases form bubbles?

The gases stored in Lake Kivu are dissolved under pressure in the water, like the carbon dioxide in a bottle of mineral water. In case of the mineral water, the pressure is maintained by the cap, and bubbles can form only when the cap is opened and the pressure reduced. In the case of Lake Kivu, the pressure at a certain depth is produced by the overlying water. This so-called hydrostatic pressure increases by approximately 1 bar per 10 m depth. Each dissolved gas has a certain tendency to leave the water and form bubbles, which is measured by the partial pressure of this gas. If the sum of the partial pressures of all dissolved gases exceeds the hydrostatic pressure, bubbles can form spontaneously. Due to its low solubility, methane contributes most to the total gas pressure, although its concentrations are only about a fifth of those of carbon dioxide. Currently, the total gas pressure at any depth in the lake reaches at most about half of the hydrostatic pressure at the same depth.



Risk of a gas eruption

Catastrophic gas eruptions from lakes are rare natural disasters that became well known in the 1980's because of two events at Lake Nyos and Lake Monoun in Cameroon. There are indications that partial mixing events and possibly gas eruptions may have repeatedly occurred at Lake Kivu in the past, but the deep water of the lake must have remained stable for at least several hundred years. At present, the probability for a gas eruption is very low, and it cannot occur spontaneously or result from an earthquake or a usual volcanic event. The gas pressure is far from the hydrostatic pressure at all depths, and large amounts of water would have to be moved far upward, for example from 300 to 150 m depth, to possibly trigger a gas eruption. It however remains unclear whether an unusually strong volcanic event at the lake floor could cause such an eruption. The total amount of gas in Lake Kivu corresponds to a gas cloud of about 140 m thickness above the lake. As the gas mixture is heavier than air, the gas cloud would fill the valley , cover densely populated areas including most of the city of Goma, and asphyxiate people. Such a gas eruption would therefore have catastrophic consequences. Removing methane from the lake decreases the gas pressures and thus reduces the risk of a gas eruption.



How much methane is produced in the lake?

The amount of methane produced every year in Lake Kivu is not very well known. Because such high gas concentrations in a lake are unique, there is not much experience in measuring them under these conditions. Therefore, the measurements of gas concentrations have some uncertainty, as indicated by the shaded ranges in the profiles of methane and carbon dioxide on page 5. Nevertheless, methane concentrations in the lake have remained approximately constant over decades of observations. This means that the production of methane is similar to the loss of methane by upward transport (upwelling) and subsequent oxidation in the Biozone. If so, the production in the resource zone is 0.2 to 0.3 km³ per year. Regular monitoring of the methane concentrations in the lake over the next decades is needed to better quantify this production in the future.

Methane exploitation

Procedure of methane exploitation

The following method is currently used for methane exploitation from Lake Kivu:

1 Water is withdrawn through a pipe from a certain depth range in the Resource Zone. The uplifted water starts to form bubbles at the depth where the hydrostatic pressure is lower than the total gas pressure in the pipe (see page 8). These bubbles lift the water in the pipe, and a continuous syphoning is maintained without pumping.

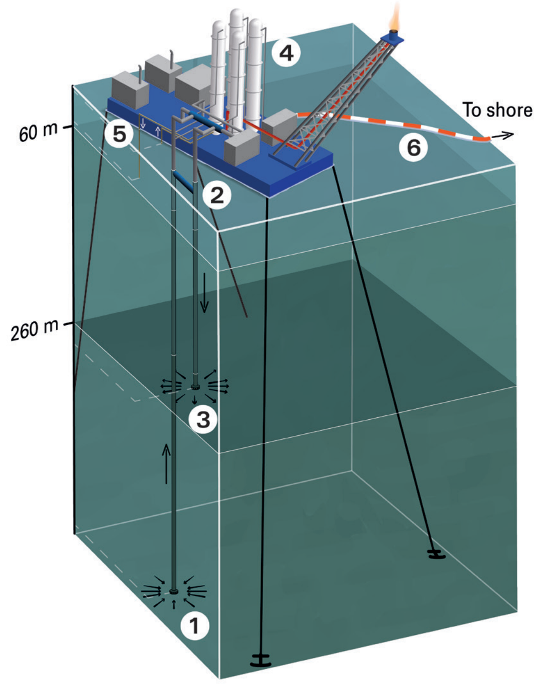
2 Close to the surface, the water and the gas phases are separated in a gas exchange chamber. Because carbon dioxide is more soluble in water than methane, a larger fraction of the carbon dioxide remains dissolved in the water. The raw gas leaving the separator still contains too much carbon dioxide to be used as a fuel. It also contains hydrogen sulphide, which is a poisonous and corrosive gas.

3 The partially degassed water is returned to the deep water in a pipe. It cannot be released to the surface layer, because it contains very high concentrations of nutrients and of oxygen-consuming substances.

4 The raw gas is transferred into washing towers where it is cleaned using lake water taken from the surface layer. This process removes most of the highly soluble carbon dioxide and hydrogen sulphide from the raw gas. The less soluble methane mostly remains in the gas phase.

5 The washing water is returned to the lake beneath the base of the surface layer.

6 The sweet gas leaving the washing towers is pumped through a pipeline to the shore for further processing.



Potential risks of the exploitation

From the lake perspective, there are three major potential risks of the gas exploitation:

Increased risk of a gas eruption. This could happen if an exploitation method brings gas-rich deep water closer to the surface or weakens the lake stratification to such an extent that gas-rich water could migrate towards the surface.

Increased nutrient flux to the surface layer. As described on page 7, a too high flux of nutrients to the surface layer would be detrimental for the lake ecology, potentially resulting in harmful algal blooms, with subsequent oxygen deficits and fish kills. To avoid this, the nutrient-rich degassed water must be returned to the deep part of the lake into the Potential Resource Zone or the Resource Zone.

Negative effects of washing water. The hydrogen sulphide in the washing water is toxic for fish and other animals. The washing water should therefore not be returned to the lake close to the surface, but rather below the Biozone. It can then spread horizontally, mix into the ambient water, and join the hydrogen sulphide that is naturally uplifted from the Intermediate Zone to the Biozone. The hydrogen sulphide is then oxidized to non-toxic sulphate at depths without fish and major biological activity. Still, the effects of the additional hydrogen sulphide need to be carefully monitored.

What to do with the degassed water?

Two main methods have been proposed for methane exploitation from Lake Kivu: the Gradient Drawdown Method and the Individual Zone Exploitation Method. The main difference between these two methods is the depth where the degassed water is returned into the lake. Both methods seem acceptable from a safety and environmental perspective. But they can't be simultaneously applied at large scale because the Individual Zone Exploitation Method relies on the gradient remaining at the same level.

Individual Zone Exploitation Method

In the Individual Zone Exploitation Method, the degassed water is re-injected at the top of the same zone from which it was extracted. The Resource Zone is split up into an Upper and a Lower Resource Zone, which are individually exploited. For this method to work properly, the density of the re-injected water needs to be adjusted very accurately such that it forms a new layer at the very top of that zone and does not mix with the original water from that zone. Otherwise, the resource would be diluted with the re-injected water, and gas extraction would become increasingly difficult and uneconomical with time.

Advantage: The overall layer structure of the lake and the properties of the different layers will remain similar to today. As a consequence, there is a smaller risk for unexpected changes.

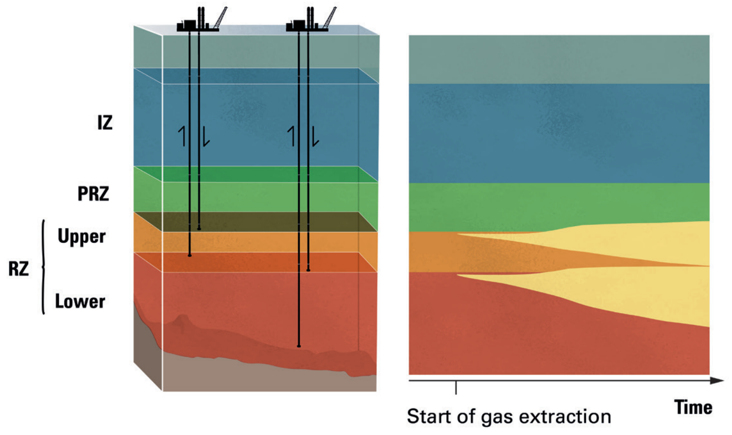
Disadvantage: The density adjustment of the re-injected water, which is absolutely essential for this method, is difficult to achieve, resulting in a high risk that the resource will be diluted and can only be partially used.

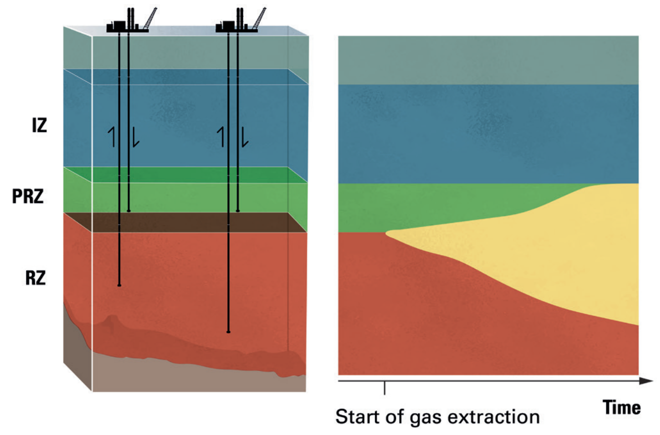
Gradient Drawdown Method

The Gradient Drawdown Method is the method applied by the current KivuWatt power plant. Water is extracted from the Resource Zone and reinjected to the Potential Resource Zone. This method draws down and weakens the main gradient. A new layer containing a mixture of re-injected water and Potential Resource Zone water will form in the lower part of the Potential Resource Zone.

Advantage: There is no risk of diluting the resource, and the methane from the resource zone can be completely exploited. In the long-term perspective, all methane produced between the reinjection depth (PRZ) and the lowest intake pipe can be withdrawn, and the loss of methane by upward transport towards the surface will be minimized.

Disadvantage: The overall layer structure of the lake will be changed. According to model projections, this should not have a negative impact on the safety or ecology of the lake. But the method implies larger changes in the structure of the lake than the Individual Zone Exploitation and therefore requires very careful monitoring of the changes and willingness to adapt the method if needed.

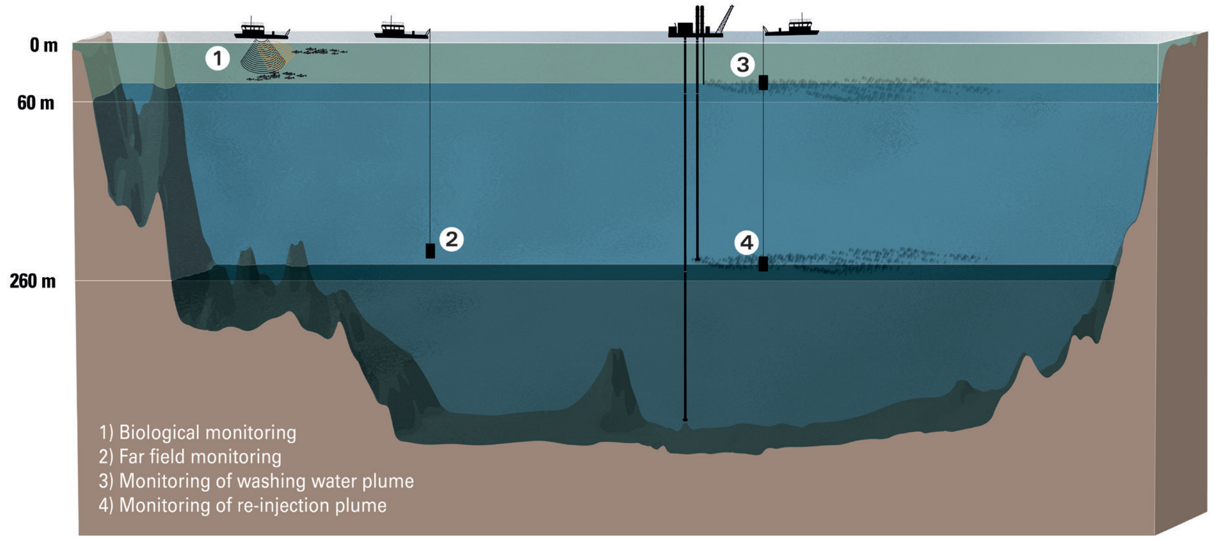




Monitoring Lake Kivu

Aims of monitoring Lake Kivu

Both natural processes and human activities, including the methane exploitation, lead to changes in Lake Kivu. Such changes could potentially increase the risk of a gas eruption, they could deteriorate the water quality and lake ecological integrity, or they could negatively affect the methane exploitation. The lake monitoring aims at detecting such changes as early as possible before they develop into larger problems. The lake management and methane exploitation strategy can then be adapted to either avert a negative development, or at least to reduce its negative impacts.



Lake Kivu Monitoring Programme

The monitoring of Lake Kivu is carried out by the Lake Kivu Monitoring Programme (LKMP) within the Rwanda Environment Management Authority (REMA) and by their partners. Their monitoring activities on the lake include:

- Routine measurements of vertical profiles of temperature and conductivity in the lake both close to and in far distance from the gas extraction facilities. These profiles can be measured with high accuracy using a CTD probe that automatically records pressure (to determine the sampling depth), temperature and conductivity while being lowered on a cable. Any changes in the stratification of the lake will result in changes in the temperature and conductivity profiles. These measurements are therefore most effective to early detect changes in the lake.
- Measurements of gas concentrations and total gas pressures in the lake. Because of the unique properties of Lake Kivu, in particular the high gas concentrations, no standard protocols are available for measuring the dissolved gas concentrations with high accuracy. Different methods have been tested in recent years, and routine measurements are planned for the future. After a few decades, such routine measurements will allow to better constrain the formation rate of methane in the lake.
- Biological monitoring, including assessments of fish stocks, is conducted every few years in order to check whether any changes in the lake ecology can be observed that could have been caused by the methane extraction activities.

Risks that can be assessed by the lake monitoring

Slow natural changes in stratification

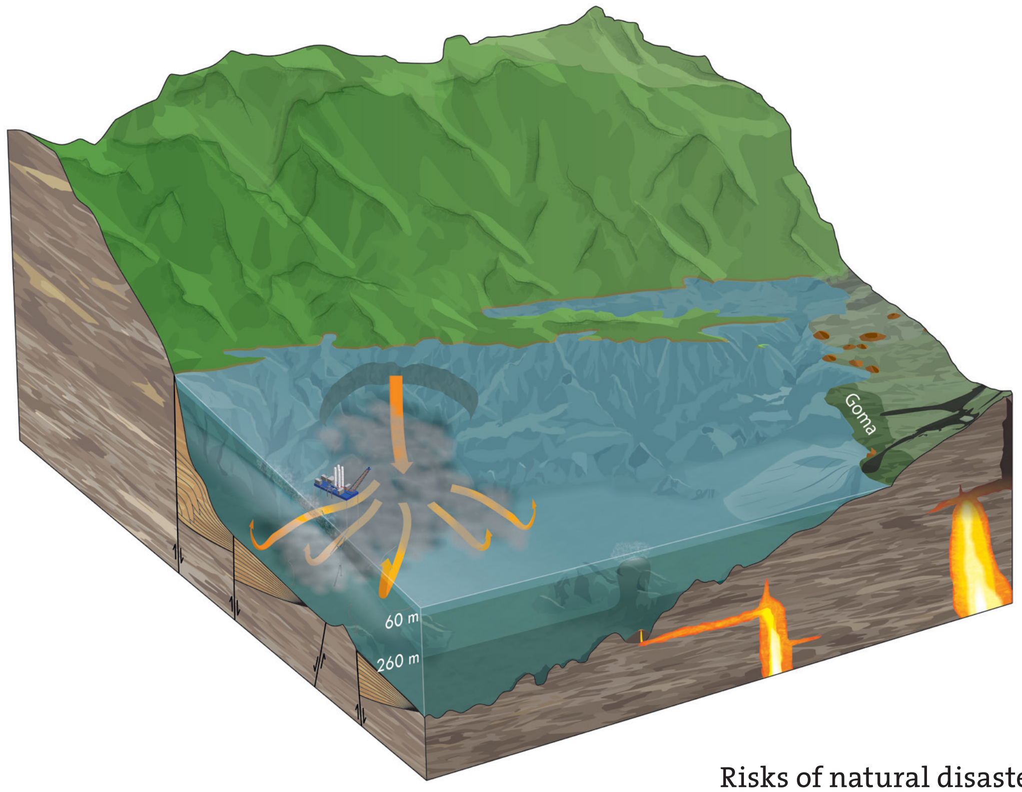
The stratification of Lake Kivu can change naturally, for example as a result of changes in the discharge or the properties of the groundwater springs. Because of the large volume of the lake and the high deep water residence times, such changes will occur very slowly and gradually. But after several decades, they could for example result in increased total gas pressures or have negative impacts on the gas exploitation. Such changes can be easily detected by regular CTD measurements. For example, measurements in the past decades have shown a recent slow warming of the deep water. Until now, the observed warming rate is small and therefore not a problem, but it needs to be carefully monitored and assessed, in case it should accelerate in the future.

Risk of ecological impacts of the washing water

The washing water released from the gas extraction facilities contains toxic hydrogen sulphide, which could potentially have negative impacts on the life in the Biozone. This can be assessed by chemical and biological monitoring in the lake both close to and far away from the extraction facilities.

Changes in stratification caused by the methane exploitation

The methane exploitation redistributes water masses within the lake. It thus changes the vertical stratification of the lake. Numerical models have been used to project these changes. The monitoring observations are compared to these simulations to test whether the impacts of exploitation are as expected. If unexpected changes are observed, their potential to develop into a problematic situation needs to be assessed. In such a case, an adaptation of the regulations for gas exploitation may be required. Changes induced by the exploitation happen slowly on time scales of decades and can therefore be well observed with the CTD monitoring. There is also a possibility of accidental impacts, for example if a water extraction or re-injection pipe should be leaking or break. This can also be observed with temperature and conductivity profiles measured close to the gas extraction facilities.



Risks of natural disasters

The large number of geologically recent volcanic structures in the lake (page 3) implies that volcanic events could occur within the lake also in the future. A volcanic eruption within the lake, if strong enough, could potentially trigger a gas release from the lake. Furthermore, an earthquake could result in slope failures within the lake. The resulting tsunami-like internal waves could damage gas extraction facilities. Such risks cannot be assessed by lake-internal monitoring. However, the Goma Volcanic Observatory in collaboration with international partners monitors the activity of the two active volcanoes, and the seismic activity (earthquakes) and ground deformation in the region.

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Purpose
Methane gas extraction from Lake Kivu aims at using the resource while at the same time increasing the safety of the lake without jeopardizing the lake's ecology. This document summarizes and visualizes the essential scientific knowledge about Lake Kivu. It presents general information about mixing processes, nutrient dynamics and the distribution and sources of dissolved gases in Lake Kivu. Additionally, it introduces the basic principles of methane extraction and the monitoring of the lake.

Illustrations
Guillaume Cailleau, Data-Partner.ch.

Data sources for illustrations, besides the literature in the reference list, and literature cited therein:

- Topography: NASA JPL (2013). NASA Shuttle Radar Topography Mission Global 1 arc second [Data set]. NASA EOSDIS Land Processes DAAC https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL1.003
- Lake bathymetry: Lahmeyer and Osae (1998) Bathymetric survey of Lake Kivu. Final report. Republic of Rwanda, Ministry of Public Work, Directory of Energy and Hydrocarbons, Kigali
- Administrative boundaries, Goma city map: OpenStreetMap
- Eruption history of Nyiragongo and Nyamuragira: Smithsonian Institution Global Volcanism Program

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