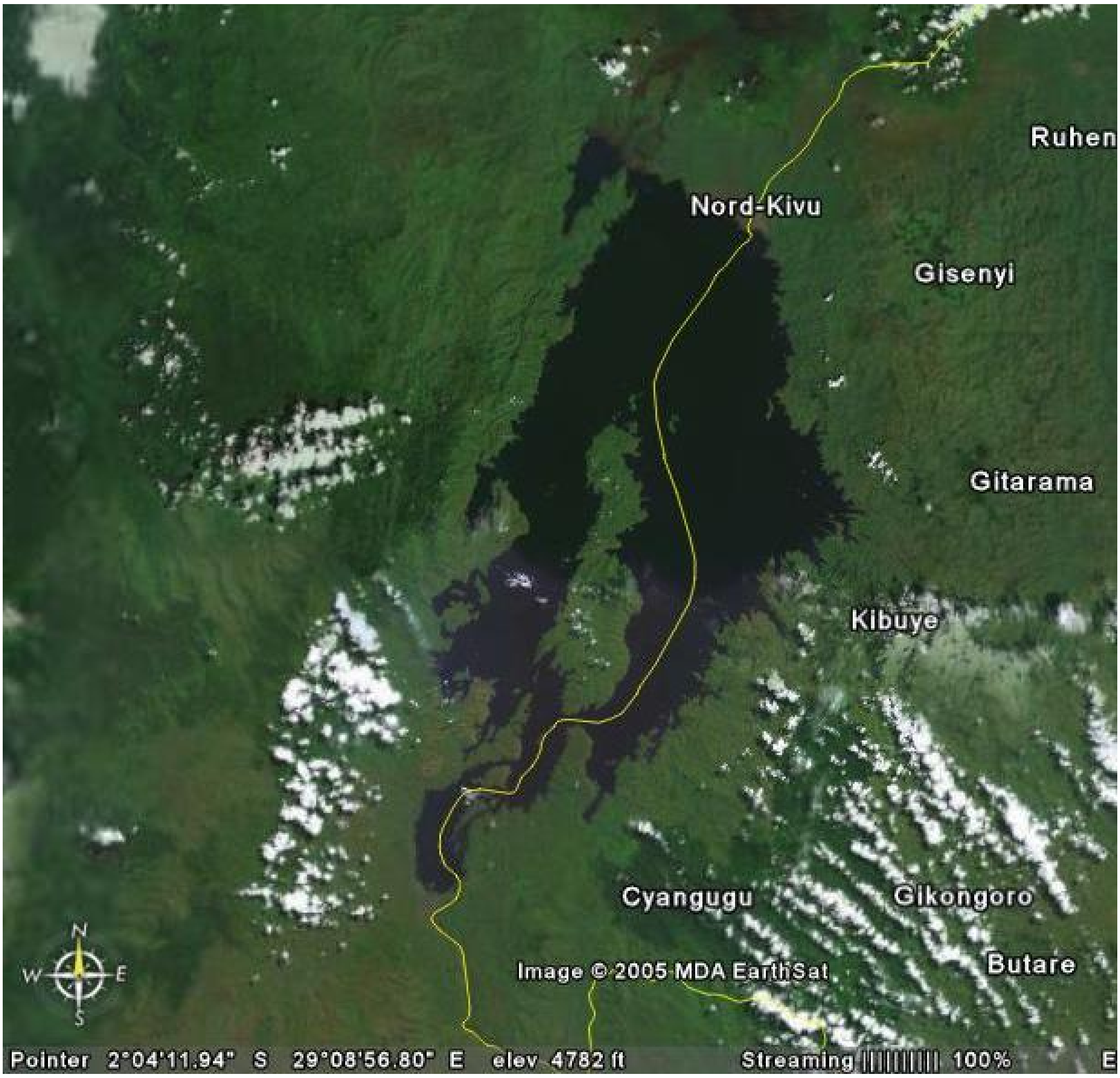
Lake Kivu Gas Extraction

Report on Lake Stability

July 2006



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0 Reader's guide

The present report is prepared by an Expert Committee with a charge as described in Section 2. Sections 4 through 9 report on the work carried out and outline the opinions and recommendations by the Expert Committee.

To aid the reader an extended Section 3 summarizes the conclusions and recommendations with a minimum of scientific explanations.

Section 1 is the very brief version of the report in the form of an Executive Summary.

1 Executive Summary

In Lake Kivu on the border between the Republic of Rwanda and the Democratic Republic of Congo some 300 km^3 of dissolved carbon dioxide and 55-60 km^3 of methane gas is accumulated and trapped at significant depth in the lake. The lake is 485 m deep with a surface area of 2400 km^2 at an altitude of 1462 m.

A natural concern is that Lake Kivu could erupt, as occurred in Cameroon at Lake Nyos in 1986 and at Lake Monoun in 1984. These two gas eruptions from the lakes themselves suffocated more than 1700 people. For these lakes the remedial measures consist of venting the remaining gas to the atmosphere in order to eliminate the eruption risk. In all three lakes gases are continuously accumulating, and they will erupt eventually if nothing is done.

For Lake Kivu the gas content is still below saturation, and the risk of an eruption is not imminent. However, if nothing is done the accumulating gas will cause a catastrophic eruption in all likelihood within the time span of 100-200 years. An eruption may take place with the current level of gas accumulation, but this requires a very strong earthquake, a very significant lava inflow or a volcanic eruption at the lake bottom. The probability of these triggering events is low, but the consequences of a major eruption are very dire as hundreds of thousands to millions of people living around Lake Kivu and the northern part of Lake Tanganyika could be affected.

To reduce or eliminate the risk of eruption the gas in the lake could be vented to the atmosphere. However, a large part of the methane gas in Lake Kivu is extractable and may be used to fuel power plants to supply electricity at a very competitive price rather than being vented and lost to the atmosphere.

The first phase in the harvesting of methane gas consists of a project developed by the "Kibuye Stage 1 Power Limited", KP1. This is a public-private partnership between the Government of Rwanda (GoR) and Dane Associates Limited. The project consists initially of a Pilot Plant placed one kilometre off shore from Gisenyi and a 35 MW power plant at Kibuye powered by gas extracted nine kilometres offshore.

The project is being reviewed by an Independent Engineer on behalf of the lenders, and as part of this assignment the Independent Engineer has assembled an Expert Committee to produce an opinion on the impact of the project on lake stability and the risk of an uncontrolled gas release.

The Expert Committee has critically assessed the available information on the gas reserves in the lake, the conditions of the lake facilitating the accumulation of gas, the risks associated with the gas in the lake, the environmental observations pertaining to the lake ecology and environment, and the requirements for the gas extraction project with regard to maintaining lake stability.

The unanimous results and recommendations of the Expert Committee work may be summarized as follows:

1. Lake Kivu is a stratified lake with several gradient layers (density variation of the water with depth) which serve as “flexible lids” ensuring both a resistance to mixing (which could cause a gas release), and a barrier which allows for the accumulation of methane gas (and carbon dioxide) in the lake. Notably there are two gradient layers at about 80 and 260 m depth, respectively, where the upper layer protects the overlying biozone and the lower layer confines and protects the major part of the gas deposit.
2. Measurements in the lake from 1975 to 2004 indicate that the amount of methane gas has increased by 10-15 %, and that saturation and accompanying eruption may be reached in 100 to 200 years without human intervention.
3. Due to the inherent dangers of the large gas deposit in Lake Kivu, living around the lake means accepting a higher risk than living elsewhere in the region. Extraction of gas from the lake must occur to reduce the risks and avoid a major disaster with loss of lives in the hundreds of thousands to millions around the lake.
4. If the extraction projects are properly regulated and monitored, they will decrease this risk for the population. In the course of the methane extraction it is possible that errors or accidents would increase the risk temporarily, which is why continuous monitoring and regulation is mandatory.
5. The Expert Committee recommends an action plan based on monitoring programmes at three levels: (i) the Pilot Plant at Gisenyi, (ii) The main KP1 Production facilities, and (iii) a baseline study of Lake Kivu at large. The programmes are detailed in the report and involve the formation of:
   - An international "Monitoring Group" for evaluation of monitoring results in relation to lake stability and technical conditions related to the gas extraction concessions.
   - A local scientific institute for continuous (yearly) monitoring of the lake. Internationally recognized scientists will assist with the establishment of the institute and with maintenance of the continuous monitoring, in cooperation with the Monitoring Group.
   - Tendering for the baseline study carried out by an internationally recognised group of scientists.

The clearconclusion by the Expert Committee is that from the point of view of risks, the environment, and economics, the only viable action is to produce the methane gas in Lake Kivu and use it for power production, observing that

- **three or more KP1-sized plants are needed to gradually reduced the risk of catastrophic gas outburst from the lake**
- **future plants (after KP1) should be located over the deepest part of the lake**
- **gas concessions should be based on volumes of gas extracted rather than on defined areas of the lake**
- **fisheries may well be enhanced by discharging some degassed water into the biozone; testing this possibility should start during the pilot plant operations**

To do nothing is clearly unacceptable because of the risks and the wasted economic benefits to the population., To vent the lake instead of producing the gas is worse from all points of view in that this

- **excludes the power production benefits, where renewable methane is replacing combustion of fossil fuels**
- **adds methane rather than carbon dioxide to the atmosphere which is significantly less desirable for global warming reasons**
- **adversely impacts the biozone.**

2 Charge of Expert Committee

The present report was prepared by an independent Expert Committee. This Section introduces the parties involved in the gas extraction project, the charge of the Expert Committee, the purpose of the report, and the schedule of the Expert Committee.

For the project of gas extraction from Lake Kivu to fuel a new power plant, the firm COWI has been appointed as Independent Engineer. The role of Independent Engineer includes reporting independently to project lenders, including *inter-alía*, Emerging Africa Infrastructure Fund, FMO of Netherlands, the Finnish Fund for Industrial Cooperation Ltd., the International Finance Corporation, PTA Bank of Nairobi, and the World Bank.

As is specified in the detailed terms-of-reference for the Independent Engineer, the Independent Engineer has assembled an *"expert-committee" to produce an independent report on whether the lake stability is likely to be enhanced or to deteriorate as a result of the project. The expert committee also will consider the needs for monitoring of the lake and provide recommendations as appropriate. In providing recommendations, the committee will seek to provide practical, workable approaches to any recommended monitoring. Although the committee's focus will be on human health and safety issues, it should also consider recommendations on monitoring or other relevant issues derived from the Environmental Impact Assessments (EIA) to the extent that the committee's recommendations may complement or dovetail with those in the EIA.*"

"In case the committee members are not unanimous in their findings, dissenting opinions are acceptable. In case additional testing or experimentation is required, this should be part of the committee's opinion. The expert committee's report is not part of the IE's report nor is the IE responsible for its recommendation or outcome."

Before establishing the Expert Committee, a pre-meeting was held with Mr. Avi Muginstein from the Project Developer Dane Associates, Mr. Thomas Bonn, a representative of Electrowatt-Ekono, the firm that prepared the EIA, Dr. Klaus Tietze, author of the year 2000 review of Lake Kivu, and three senior staff members of COWI, Mogens Winkler, team leader of the Independent Engineer, Professor Jørgen S. Steenfelt, coastal and lake hydrologist, and Dr. Finn Hirslund, senior process engineer. The Expert Committee recognizes the very valuable background information provided by Dr. Tietze for the preparation of the present report.

The Expert Committee was accepted by the lenders and assembled in Washington late February 2006. The committee members are:

- Professor Sally MacIntyre, University of California, Santa Barbara, USA
- Professor George Kling, University of Michigan, USA
- Dr. Finn Hirslund, COWI A/S, Kgs. Lyngby, Denmark and
- Professor Jørgen S. Steenfelt (Chairman), COWI A/S, Kgs. Lyngby, Denmark.

The Expert Committee subsequently met in Santa Barbara in late March 2006 to coordinate and report on the opinions reached by the committee.

Among all the typical risks to be considered for a project of this nature, one risk stands out as exceptional, namely the natural risk caused by gas accumulation in Lake Kivu and its uncontrolled release. This risk is the main subject for the present report.

The project to be reviewed by the Independent Engineer consists of the development, construction and operation of a gas production and processing plant with an installed capacity of 234,000 Nm^3 per day of methane extracted from Lake Kivu; and a 35 MW gas-fired power plant. A pilot plant with approximately $1/10^{th}$ of this capacity is expected to be established 1 km off the shore from Gisenyi in order to verify the gas extraction concept later in 2006. After this, it is the intention that a number of similar production plants will follow. Smaller quantities of methane have been produced for some 40 years for use at the Bralirwa Heineken brewery (1 MW power plant) in Gisenyi using an extraction process developed by Union Chimique Belge.

The Expert Committee has gathered as much information as available on the gas reserves in the lake and produced an opinion on the proven and probable reserves and the rate of replenishment. The Expert Committee has also commented on the likelihood and impact of localized depletion through deepwater extraction.

3 Summary and Recommendations

In Lake Kivu on the border between the Republic of Rwanda and the Democratic Republic of Congo some 300 km^3 of dissolved carbon dioxide and 55-60 km^3 of methane gas is accumulated and trapped at significant depth in the lake.

A natural concern is that Lake Kivu could erupt, as occurred in Cameroon at Lake Nyos in 1986 and at Lake Monoun in 1984. These two gas eruptions from lakes suffocated more than 1700 people. Although there are no historical records of similar gas eruptions at Lake Kivu, there is evidence from sediment cores for large disturbances in the lake that could be related to gas releases in the past (thousands of years ago). In addition, it is now understood that these are recurring events, and that gas releases could occur at any of the lakes in the future.

Figure 1 African continent with location of "killer lakes" in Cameroon and Rwanda

The accumulation of gas is due first to a source of gas coming into the bottom of the lakes, and second to a strong stratification (layering by density) of the lake waters, and third to the depth of the lake. Only 3 such lakes are known in the world, and the rarity is because even though there are many sources of carbon dioxide and methane gas worldwide, the probability that these gas sources would discharge directly into the bottom of a very deep, strongly stratified lake is very low.

Because these gas-charged lakes are substantial natural hazards, any project involving removal of the gas or disturbance of the stratification must be carefully examined. In Cameroon, pipes have been added to both lakes to remove the gas in a controlled manner, and changes in lake stability have been monitored. In Lake Kivu, a proposed project of large-scale gas extraction will use the methane as fuel in power plants to generate electricity. The project is expected to lower Lake Kivu deep-water gas pressure and help avoid a potential humanitarian disaster.

Several studies on Lake Kivu and its stability have been performed and generally conclude that at the present time the lake is relatively stable and that the project would have minimal effects on its stability. However, measurements included in the studies indicate a growing concentration of methane that - if nothing is done - will result in a catastrophic eruption some time in the foreseeable future, perhaps within 100 to 200 years.

3.1 Background

Lake Kivu consists of a large main basin and four smaller, "separate" basins with a total surface area of ~2400 km^2. The lake surface is maintained at level 1462-1463 m above sea level, controlled by the dam for the Mururu power plant near Bukavu at the southern end of the lake. The maximum water depth is 485 m and the water volume is about 550 km^3, and the discharge rate through Bukavu is ~3.2 km^3/year. Seasonal mixing reaches to a depth of some 60 m, and gas accumulation begins below about 70 m.

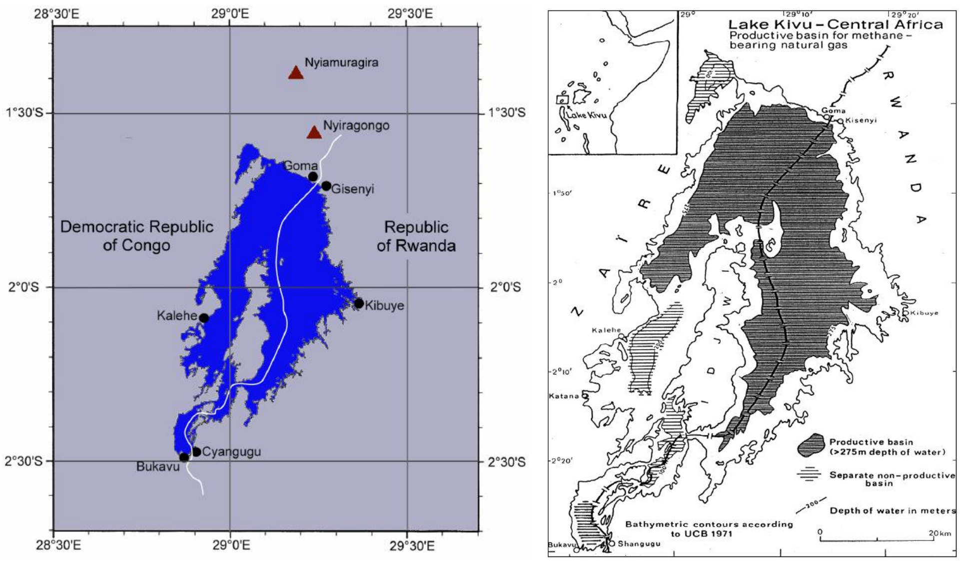

Figure 2 Lake Kivu on the border between Rwanda and Congo and the division in main basin and four smaller "separate" basins

The existence of dissolved gas in the deep waters was first established by researchers in 1935 and has subsequently been investigated in a series of scientific expeditions to the present time. The gas is kept dissolved at the lake bottom by the weight of water above it, and mixing toward the surface is prevented by strong *density gradients* which act like flexible 'lids' or *stability layers* at certain depths in the lake.

Large amounts of data regarding the lake water variables in general and the gas content and water layering in particular have been collected and analyzed by the various researchers. However, due to the inevitable differences in measuring tools, measuring techniques, position of measuring points and profiles, and evolution in accuracy and precision of electronic equipment, the data from these studies are not directly commensurable.

Notwithstanding these difficulties, the data do show a number of irrefutable trends, and can be used to establish various baseline quantities and characteristics. This includes a plausible explanation for the current stable state of the lake, inferences regarding extraction of methane gas for commercial use, and scenarios for the stability of the lake with and without future gas extraction.

3.2 Potential risks

The potential risk of a large, uncontrolled gas release from the lake depends on (1) the gas pressures at depth, (2) the stability of lake stratification, and (3) the probability of triggers (internal or external) such as submarine landslides or volcanic eruptions that would weaken or destroy the stratification now keeping the gas safely in place.

Various measurements indicate that the methane and carbon dioxide pressure (concentration) has increased in Kivu over the past 29 years. Such increases are expected in these gas-charged lakes, and for Lake Kivu they result in the prediction of devastating gas eruptions within the time frame of a century or two (depending on the future rate of increase) if nothing is done to reduce the gas concentrations.

The apparent increase in gas concentration over a relatively short time span (29 years) must either signify a change in "environment" (for instance increased production due to changes in lake conditions or the rift system (sources of the methane and carbon dioxide), or signify that eruption is a recurrent event which must now be controlled in view of the consequences. For this last hypothesis it is interesting that there are two indications of such earlier eruptions about 1500 to 2000 years ago and 5000 years ago, respectively. Thus recent changes in the gas content are consistent with a natural cycle of volcanic events and geochemical changes in the lake. At present the important questions are which mechanisms control the accumulation and release of gas, what are the expected different sizes of eruption, and what may be the consequences thereof.

For the discussions in this report, the authors have found it useful to split the potential eruptions from Lake Kivu - into three size-based categories:

- The *moderate, local eruption* of the order of magnitude of 100 to 10 000 cubic metres of gas released, potentially influencing only persons on the lake or nearest shore. The nature of this moderate type of eruption is that some external force causes an eruption to start, but the stability forces in the lake bring the localized eruption under control and stop it from progressing.

- The *large eruption* of the order of magnitude of 1 cubic kilometre of gas released, potentially influencing all inhabitants in the valley of Lake Kivu in the downwind direction.

- The *catastrophic eruption*, emptying much of the over 300 cubic kilometres of gas from the lake. A trigger such as a large lava inflow into the lake causes the eruption to start, and it then self-progresses until the waters in the lake have mixed substantially and much of the dissolved gases have escaped. Such an eruption has the potential for killing the entire population in the Kivu region as well as a significant fraction of the inhabitants around northern Lake Tanganyika.

For comparison, the gas disaster at Lake Nyos in 1986 released from 0.2 to 1 cubic kilometre of gas, which puts it in the above category of a *large eruption*. The Nyos gas release had consequences in terms of loss of human life up to 26 km away from the lake. Note that Lake Kivu is 1600 times larger than Lake Nyos and contains 300 times more gas, and thus the potential for loss of human life is much greater.

Evaluating the specific risks of such eruptions at present (in 2006) is difficult, but overall our analysis indicates that with the present concentration of methane and carbon dioxide the *catastrophic eruption* can only be caused by extraordinary volcanic activity, either discharging very large amounts of lava into the lake (much more than came from the eruption of Mt. Nyiragongo in 2002) or having a volcanic eruption directly into the bottom of the lake. In general the risk of such volcanic activity acting as a trigger is very low, and the occurrence of these events is rare and difficult to predict. Because such volcanic eruptions are also impossible to prevent, the only course of action at present is to remove most of the dissolved gases from the lake in order to prevent the described consequences should a large volcanic event occur.

The intermediate category of large eruptions has the potential for killing many thousands of people around the lake. The probability of such an event is still remote (today, but not in the future), and the potential triggers include:

- Volcanic activity at a larger scale with larger amounts of lava flowing into the lake than was registered at the last eruptions in January 2002.

- Accumulation of methane in the lake is allowed to continue and it reaches closer to the level of saturation. This situation may be then combined with any of a number of probable events (such as underwater waves at the lower stability layer) that would trigger an eruption.

- A combination of the above two causes; for example, there could be a 'normal size' quantity of lava flowing into the lake after the lake has been allowed to come closer to the gas saturation point.

- Failure of the dam at Bukavu (which in itself is improbable) occurring after gases are allowed to accumulate close to the point of saturation.

The third category of *moderate, local eruption* can be triggered by natural causes as well as by accidents caused by the gas extraction project.

Note that it is difficult to predict exactly what size of initial disturbance or trigger will lead to what eventual size of gas release because there are gradients of force and energy involved for several different triggers. For example, a "volcanic eruption" may be massive beneath the lake, or it may be expressed as geothermal activity and localized plumes of water coming from the sediments. A large earthquake could produce a huge underwater tsunami (at the main stability layer), but a mild earthquake may only produce some relatively small internal waves in the lake. In the first case of these examples the triggers would lead to a catastrophic eruption, but in the second case the triggers may only result in a modest eruption. Examples of relatively low-energy triggers are:

- A Tsunami or internal wave caused by a mild earthquake.

- Spontaneous eruption of gas from a localized patch of sediment at the bottom of the lake.

- Geothermal activity and water plumes emanating from the bottom of the lake.

- Accidentally dropping an anchor or other heavy objects into the bottom sediment which could produce a localized gas release.

- Accidental rupture of the production pipe below the production platform, at a depth where there is two-phase flow (gas bubbles plus water) and where the surrounding water is gas-rich. In this case, the platform is likely to sink as well.

As mentioned at the beginning of this section, the evaluation of risk depends on the concentration of gases, the stability of the lake, and the energy input from a triggering event. Of these factors, the one under most control is the amount of gas and how close to saturation the gas pressures are at depth. The risk and or the consequences will increase with increasing saturation of the gases trapped in the lake, and the risk of the catastrophic eruption will also increase to certainty when the partial pressures of the dissolved gases reach saturation. In plain terms, when enough methane has accumulated, the catastrophic eruption will occur. And that may happen spontaneously some 100-200 years from now, depending on the future rate of gas accumulation and whether any action is taken to reduce the gas content.

3.3 Gas Reserves and Method of Extraction

Location of methane extraction

Substantial quantities of methane are being produced and accumulated in the lake every year. So, the longer it takes to extract or use all of the methane, the more will be available for extraction altogether. Part of the objective of this report is to produce an opinion on the long-term concentrations of dissolved methane.

One important lesson from degassing Lake Monoun in Cameroon is that the lake behaves much like a bath tub that is being emptied by siphoning out the water from a point near the bottom. All water above the suction point will eventually be drained away, whereas gas that is contained in the lake below the inlet depth of the pipe cannot be “reached” by the pipe and will remain in the 'tub'. During the process of emptying, the stability layers will sink in an undisturbed manner, whereby the density gradients will remain pretty much undisturbed until they reach the level of suction at the pipe inlet. Therefore, in order to extract the full amount of gas possible in an efficient manner the inlet pipe must be placed near the very bottom of the lake. In the following scenarios it is assumed that the pipe inlet is placed near the bottom of the lake.

Venting must follow after extraction

Whenever the economically extractable quantities of gas have been all removed from the lake, a number of platforms must be placed above the deepest point of the lake with a pipe long enough almost to touch the bottom. Then this pipe should be used to vent the last parts of the gas from the bottom of the lake.

It is suggested, that any production platform located in the deepest parts of the lake (i.e. not KP1) should be made in such a way that at the end of its production life, it may be converted into a venting system functioning by auto-siphoning like in the lakes Nyos and Monoun, but in such a way that water degassed after venting still will be returned to the lake below the biozone.

This venting system must function for many years and must be monitored, and that will cost money. The most appropriate solution would seem to be for the concessionaires (present and future) to pay money into a fund that shall then be used for that purpose much later. We recommend that this concept and the amount of money to be paid should be studied further and that it be made part of future concession requirements for the platforms to follow after KP1.

Extraction is lake-wide

Another conclusion from the 'bath tub' behaviour is that the withdrawal of gas from depth is effectively “lake-wide”, and not “localized” or contained within a given area or zone around the extraction platform. Concessions for extracting gas may well be specified for a given surface area of the lake, but in reality the gas is removed from the entire lake in the depth layer of the inlet pipe. Therefore all concessions should be thought of in terms of the amount of gas removed (or power generated) rather than in terms of the surface area of the lake or of a concession 'area'.

Constraints on extraction method

When extracting gas from the lake, any developer must comply with the following constraints in order preserve lake stability and thus the gas reserves:

- Any production scheme must be made in such as way as to respect and maintain the upper density gradient (pycnocline, from -60 to -80 metres) as well as the lower density gradient (-260 to -270 metres).
- Degassed water can only be re-injected into the lake where the density of the surrounding water exactly matches that of the re-injected water. Otherwise, gravity and buoyancy flows would disrupt or destroy the density gradients. Because of the salt content of the degassed water, this must be re-injected between the upper and the lower density gradient.
- Both extraction and re-injection can only be allowed in the horizontal direction – that is, the pipe inlet and the re-injection point must be from a very narrow layer in the lake (1 to 2 m thick) instead of spread vertically across several or tens of meters. This constraint must be imposed on any developer.

The need to verify that these constraints are complied with is one of the main reasons for the local monitoring around the extraction platform that must be carried out by (and imposed on) any developer. The present concessionaire, Dane Associates, is aware of this responsibility.

KP1 project

The present gas extraction project is based on the 40-year old idea from the Bralirwa Brewery of using a bubbling pipe for extracting the water from the lake as well as on suspending this pipe from a barge as in the lakes Nyos and Monoun. But the key gas processing concept was developed by Dane Associates Limited. The timetable of development of gas extraction from Lake Kivu is foreseen as follows:

1 A pilot plant will be installed and tested in the course of 2006. If feasible, this test facility will later be converted into a production platform, feeding a small-scale power plant in Gisenyi.

2 Pending a positive outcome of the Pilot Plant testing (in terms of extraction, production, and re-injection principles together with environmental impacts and impacts on lake stability) the first production platform is expected to be designed and installed imminently at Kibuye.

3 After this, it is the plan to continue installing new gas extraction plants offshore and the associated power generation facilities onshore as the demand for power develops.

The extraction technology developed by Dane Associates has the following consequences:

- By far the largest part of the hydrogen sulphide is returned to the deeper parts of the lake, whereas a significant fraction of the carbon dioxide together with some of the methane is vented to the atmosphere.

- Not all of the methane extracted ends up in the methane gas produced. 84 % of the methane extracted ends up in the produced gas, 15 % is vented to the atmosphere and 1 % is re-injected and returned to the upper part of the lake (below the biozone).

Kibuye is not the right location for future extraction plants

The site foreseen for the KP1 project (and the Dane concession "area") is at moderate depth off the coast at Kibuye. At that location it is only possible to extract from a depth of -320 metres. As can be seen above, this location only allows extraction of approximately half of the gas reserves in the lake.

Obviously, this extraction of only 50 % of the gas is not sufficient. First of all, any gas volume left at the bottom of the lake would eventually have its methane content rising to dangerous levels. And second, it would be unacceptable not to use as much as possible of gas for methane production due to the adverse greenhouse effect of methane released to the atmosphere.

Extraction scenarios

Therefore, in order to extract the full amount of gas possible in an efficient and safe manner the inlet pipe must be placed near the very bottom of the lake. In practical terms this means that this production must take place close to the northern shore of the lake where the water depth is greatest, and that the electrical grid at that location must be upgraded to take all power produced other than that from KP1. In this way it is also of lesser importance whether the extraction takes place in Rwanda or in P.R. Congo, since it is a technically simple matter to expand the power grid into Goma and possibly further so that the entire northern region of the lake would also benefit from the cheaper power based on gas from the lake.

Under the assumption of a deep extraction point for the rest of the platforms, the extractable gas reserves at present have been estimated at 36-42 km^3 (STP) of methane whereas the in-situ reserves amount to 50-55 km^3. The difference between the two amounts is due to inefficiencies in the extraction process and to gas that has accumulated higher in the lake where the gas pressure is insufficient to drive the extraction pipes.

Based on the assumption that the future extraction platforms (KP1 to KP6) will be put in service in the years 2007, 2012, 2020, 2030, 2040, and 2050 respectively, the forecast development of the total gas reserves is shown in Figure 3 as function of time and extraction strategy. It must be emphasized that the underlying data are uncertain and thus, so are the forecasts.

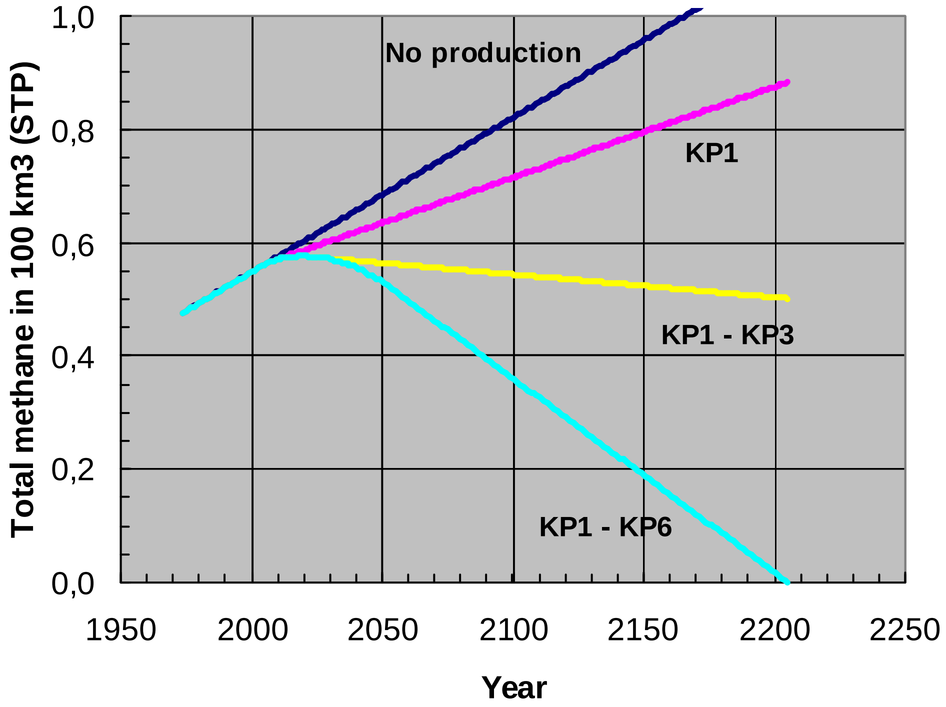

Figure 3 - Calculated development of methane reserves in Lake Kivu as a function of the number of extraction projects (based on assumptions in Table 5 and Table 4).

If the bottom of the lake (below 320 m) were well mixed, then the above figure would also represent the changes in total gas pressure (relative gas saturation at -320 m, dimensionless) that determines the stability of the lake and the ultimate danger of an uncontrolled gas release. It so happens that the vertical scale in the above figure is correct for in-situ gas reserves expressed in 100 km^3 of methane as well as for relative total gas pressure (dimensionless number). The relative total saturation of both methane and carbon dioxide is shown because the pressure of both gases together drive the extraction process as well as the risks in the lake.

From the above curves it can be seen that establishing one KP1 station is insufficient to counteract the natural accumulation of methane and thus to avert the resulting dangers. The calculations show that around 3 stations would be required to arrive at a slow decrease in methane concentration and thus to a slow decrease of the associated risks. Operation of the six stations (which is the maximum under the present Dane Concession) would result in emptying of the methane gas reserves over a period of possibly 200 years. Since the basic data at present are less accurate than desired, so is also the resulting number of stations and the amount of time required to empty the reserve. However, the above curves still illustrate rather well the orders of magnitude involved and that there is a turning point from overall gas accumulation in the lake to overall gas reduction. Depending on conditions in the lake, the amount of methane generated naturally in the extraction period shown above could be on the order of 20-40 km^3 (STP) of methane; however, only the future monitoring programme can confirm such a number. This obviously not only depends on the actual rate of future gas accumulation, it also depends very much on the actual number of gas extraction platforms installed. A decision on the best strategy and number of extraction platforms can only be decided after decades of monitoring. This could allow a optimization of total extractable reserves while maintaining the eruption risks at or below the present level.

The overall and most important observation is that the gas extraction project goes hand in hand with necessary mitigation measures required to minimize the risks of a natural gas eruption from the lake.

A scenario with a moderate production rate that might last “forever” (corresponding to a horizontal line in the above figure) has been considered, but it is not possible for the KP1 extraction plant. However, because this scenario would be attractive for the future extraction plants that draw from deeper waters, the feasibility of this scenario should be evaluated anew when more data have been obtained from the monitoring programme.

Re-injection

It is not obvious that the intended re-injection point at -90 metres for the degassed water is sufficiently deep to avoid influencing the upper stability layer. The potential concern is that the re-injected water will “create a hole” locally in the stability layer, and increase the amount of mixing and weaken the layer. It is considered probable that the pilot plant at Gisenyi is of such small capacity that the impacts on the upper stability layer would be negligible, and even if there was some disturbance it would remain local and be of no concern. In the future, however, the main production platforms (including KP1) must maintain this upper stability layer. This situation must be carefully monitored and the results reported by the Developer for the pilot platform at Gisenyi. Based on the results, it may be necessary to re-inject water at the deeper point of ~100 to -120 m, well below the stability layer, for the future production platforms including KP1.

Nutrients and fish yield

As is described more fully in Section 3.4 below, the re-injection water will be nutrient rich and could impact the biozone. If testing of a controlled inflow of nutrients to the biozone should prove positive to fish production without creating *eutrophication* (noxious algal blooms), it would be possible to introduce this feature for all future production platforms and for a minimal extra cost. If such an extra benefit can be obtained from the gas production projects, it would enhance the acceptance of the projects by the local communities. It is therefore recommended that such testing be carried out during the pilot project at Gisenyi.

Risks

It is important to ensure that the risks from the lake will not increase above the present level. As soon as possible, extraction of gas from the lake should start and it should be brought to such a level that it at least outweighs the annual gas production plus inflow in the lake. The knowledge of these variables (production of carbon dioxide and of methane) and inflow (of carbon dioxide) is at present uncertain, wherefore a monitoring programme should be started as soon as possible.

Most of the conclusions in this report regarding stability in the lake are based on the present state of affairs - namely that the layer below -320 metres apparently used to be and would remain fairly well mixed so as to present a nearly uniform concentration of dissolved gases. There are indications, however, that the situation in the lake is actually dynamic and that (at least for many years to come) nothing may be taken for granted. If, for instance, a new stability layer were to develop further around -400 metres and if the extraction platforms are put into operation more slowly than anticipated above, then the risk of eruption from these deeper layers might increase to dangerous levels.

Monitoring is required

Taken together, the potential changes in lake stability, gas accumulation, and impacts on the biozone are the main reasons why a lake-wide monitoring programme must continue at least until dangerous levels of methane have been removed from the whole lake. Even after having emptied the lake of methane, monitoring should be repeated with intervals of ~50-100 years in order to monitor new increases in gas concentrations and the build up of gas. In fact it is possible that some centuries from now a new gas extraction scheme might recommence.

3.4 Environmental impact

Atmospheric emissions

If left untouched, the recurring eruptions of gases accumulating in Lake Kivu would eventually release all gases from the bottom of the lake into the atmosphere. It is against this fact of nature's behaviour that the gas extraction project needs to be evaluated. Even if the gases were simply vented to reduce the pressure and thus the risk of the recurring eruptions, averaged over time, the resulting emissions to the atmosphere would be the same.

Simple venting to the atmosphere as is done in the two lakes in Cameroon would have a significant impact on the upper layers of the lake (the “biozone”). Note that here the “*biozone*” is defined as the top part of the lake that contains oxygen and organisms that depend on it such as fish and snails.

Evaluated against this base case, any extraction project represents a significant improvement in terms of emissions to the atmosphere because around 84 % of the methane is converted to carbon dioxide in the power generating turbines before being emitted to the atmosphere. Since the greenhouse effect of methane is 20-25 times that of carbon dioxide, the advantage is very substantial.

Obviously, the power generation will result in emissions of nitrogen oxides, but that would be the case with fossil fuels as well, and the emission limits will be kept below the World Bank emission standards. Also, the extracted gas holds minute quantities of hydrogen sulphide. The resulting emission of sulphur dioxide is to be counted in grams per hour and this emission is completely inoffensive, especially when comparing with the tens of thousands of tons per day being emitted by the neighbouring volcano Nyiragongo.

Impact on the lake

Stratified lakes like Lake Kivu are unusual in that nutrients are transported from the biozone to the bottom of the lake and remain there. So, whereas excess inflows of nutrients often lead to nutrient enrichment (*eutrophication*) in normal lakes, the problem is rather much the opposite in strongly stratified lakes: they are relatively deficient in nutrients and biological production (and therefore fish production) is constrained by this deficiency. In addition is the effect of global warming in the neighbouring African lakes, which is believed to increase stratification and thus increase this nutrient deficiency.

Therefore, any moderate increase in transport of nutrients into the biozone could only be an improvement, and this is exactly the anticipated result of the extraction projects. The degassed water that is high in nutrient content is discharged below the upper stability layer, thereby moving nutrients from deep in the lake to a shallower layer, which will increase the slow diffusion of nutrients upward through this stability layer. The impact of such moderately increased nutrient fluxes into the biozone would be to increase biological productivity, which may also be of benefit to the fisheries in the lake. This situation should be distinguished from the *eutrophication* that would result if large amounts of bottom water were released directly within the biozone at the lake surface. In such a case, the potential environmental impacts would warrant further study.

It has therefore been considered that a direct discharge of controlled quantities of degassed water into the biozone might be beneficiary to fish production in the lake - without causing eutrophication or growth of noxious blue-green algae. In order to verify this assumption, a biological test programme is recommended at the same time as the pilot plant testing. Should the assumption prove true, it would require only minimal modifications to the production platform to obtain this important windfall benefit from the gas extraction project.

In the lake, the zones below the biozone will be most strongly influenced by the gas extraction. The water below the biozone is anoxic and thus contains no fish or other organisms requiring oxygen, and the extraction will not change the oxygen status of the lower lake.

Finally, it is likely that the platforms will serve as “artificial reefs” for various organisms such as mosses, snails, sponges, and aquatic plants and insects – these organisms may become a nuisance for plant operations, and thus will need to be removed or held in check.

3.5 Monitoring programme

3.5.1 Rationale and components

The monitoring programme comprises four main activities: **(1)** monitoring at the Pilot Plant at Gisenyi, **(2)** monitoring at the production facility KP1 at Kibuye (and subsequent facilities), **(3)** a baseline study of Lake Kivu at large and **(4)** frequent monitoring of lake water variables all over the lake.

The key activity is monitoring changes in the physical, chemical, and biological conditions of Lake Kivu. This monitoring will allow the lake stability to be quantified, and will allow determination of the impact from the gas extraction projects on lake stability and thus on the risk of an uncontrolled gas release. The monitoring will also record and help minimize any harmful changes to the lake ecology. At the same time these monitoring data will provide a tool for intervention, optimisation, and regulation of the gas extraction project. A fourth aspect of the program, which is not actually monitoring but is part of the action plan (see Section 8), includes testing the impacts of recharged water in the biozone on primary production and fish yield. This fourth activity will require a combination of chemical and biological measurements and should be carried out as part of the testing of the pilot plant. The details of the required and recommended monitoring programmes are described in Section 9 below, and include specifications and requirements for monitoring instrumentation in Table 6.

The basic rationale for the monitoring programme is the current lack of information on critical lake characteristics and processes. This knowledge base must be improved in order to determine the impacts and risks of gas extraction to the lake and to those living around the lake, to forecast future gas reserves, to guide the day-to-day production operations, and to develop a decision tool for the stakeholders of the project. For these reasons a monitoring programme of sufficient detail and accuracy is of the utmost importance.

The success and safety of any gas extraction project in the lake will depend on maintaining the integrity of the two main stability layers in the lake. These layers contain a steep gradient of density that acts to resist mixing and transport across the layer. The upper layer at about -80 metres serves to protect the surface biozone from nutrient-rich, anoxic and potentially poisonous bottom waters, and the lower layer at about -260 metres confines most of the gas and prevents its diffusion upwards and out of the economically important gas reserve. This lower stability layer also serves as the main resistance in the lake to an uncontrolled and catastrophic gas release. Thus all gas extraction operations must be monitored to prevent the weakening or destruction of these stability layers.

Given the important role of these two stability layers, and the potential impacts on their function from the gas extraction, it is critical to first characterize these layers with highly accurate measurements, and then to monitor the layers over time. The physical monitoring will be done mainly by CTD profiles (Conductivity and Temperature with Depth) and a chain of sensors placed in the water column. The chemical monitoring of nutrients and gas pressures will be done by the water sampling and *in situ* instrumentation installed. Finally, the impacts of changes in chemistry on the biozone will be monitored by measures of lake ecology, including the biomass and production of algae and tests on whether controlled nutrient additions from the pipe would be potentially beneficial to the lake fishery.

The Developer must record a number of production variables onboard the gas extraction platforms, and must also continuously monitor for all subsequent platforms that there is no significant vertical disturbance in the lake as a consequence of the extraction and discharge activity.

Further to this continuous monitoring, baseline studies must be performed before any real production starts in the lake. This could be after the pilot tests, but before using the pilot installation at Gisenyi for continuous production, or before the KP1 platform (whichever comes first).

The justification for this baseline study is that very little is known about the true concentrations and amounts of gas throughout the lake, about the density structure and stratification in the lake, and about the lake productivity and ecology. In order to make any firm conclusions about the impacts of gas extraction and the risks of an uncontrolled gas release that could kill thousands near the lake, the current or “baseline” conditions must be established as a point of reference. Once this baseline is established the continuous monitoring at the platforms will detect any dangerous changes in the lake, or any changes that will impact the reserve of gas that can be exploited from the lake.

3.6 Oversight and Responsibilities for the Monitoring Programme

The monitoring programme must be overseen by a “Monitoring Group”as outlined in Section 8.2. To be effective and to ensure the overall quality and integrity of the monitoring for the benefit of Lake Kivu at large, it is important that the Monitoring Group is project independent; it should preferably be anchored with some International Environmental Body. The WB/Emerging Africa could be instrumental in the initial setting up.

The Monitoring Group must coordinate the measurements and monitoring with the appropriate government institutions, and all data collected need to be distributed to the Monitoring Group, initially on a weekly basis. The Monitoring Group must also develop a set of standard operating conditions such that if routinely monitored variables fall outside of these conditions the extraction is shut down for safety. These conditions will be followed by the Developer on site. All of the monitoring and measurement are specified, contracted and supervised (on behalf of the GoR/Lenders) by the Monitoring Group.

Whereas the Developer must be responsible for all the Pilot Plant measurements and monitoring, and for the routine measurements made for each subsequent producing platform, the responsibilities for funding and completing the monitoring are not fully defined. The baseline survey must be carried out before the full KP1 extraction begins, and responsibility for funding the survey should begin with the World Bank groups in conjunction with the GoR. The same applies for the funding of the yearly monitoring by the local scientific institute.

The baseline survey may be conducted by any qualified international group, but they should follow the general and universal requirements described for the monitoring programme in this report. The yearly monitoring will be done by researchers at a new local scientific institute with additional support from the operators of KP1 and other plants as well as from the Monitoring Group. It is the recommendation that the international group of scientists carrying out the first baseline survey should use the (new) staff at the local scientific institute as assistants and in this way train them for their task of carrying out the annual monitoring. Furthermore, it is recommended that the necessary calibrated instruments are transferred to the new institute after the baseline study.

4 Density, Stratification and Stability

4.1 Background for gas accumulation in lakes

The large methane gas deposit in Lake Kivu is unique on a world scale, and so is the associated risk of gas eruptions. This risk is only known from two other lakes in volcanic regions, the lakes Nyos and Monoun in Cameroon. These extraordinary properties are the result of the complex interaction of quite a large number of natural phenomena and physical and chemical principles. It requires fulfilling all of the following conditions for a lake to present an eruption risk:

- The lake must be deep (more than ~100 metres) so that the gas pressure at the bottom can reach high levels.
- The bottom part of the lake must have an inflow of gas, either dissolved in saline or thermal ground water or as free gas in bubble form, or it must produce large quantities of gas *in situ*.
- The lake must be strongly stratified so that the gas inputs to the bottom can accumulate. If the lake water mixed from top to bottom each year the gas would be released harmlessly to the atmosphere and never build up to dangerous levels.

The combination of these three conditions is what makes Kivu, Nyos, and Monoun so special. Methane from biological activities is present in all three lakes, but in very different concentrations. This difference is mainly caused by the difference in the accumulation rate of carbon dioxide and thereby in the frequency of the eruptions and the time available for accumulation of methane by biological processes.

Mixing mechanisms in the lake determine the magnitude of mass transport, which determines whether and under what circumstances gases may accumulate in the lake, or may be released. The following sections provide a detailed description of relevant processes and their interactions.

It is important to remember that if lighter water is on top of denser water, there will be no movement, whereas in the opposite case, gravity will make the two bodies of water change places which will result in mixing. In other words, with an ever increasing water density from the top to the bottom of the lake (over and above the effect of compressing the water), there will be no gravity-induced spontaneous mixing; the body of water is stable. And the steeper the density gradient (the more the density is increasing per metre of depth) the more the body of water resists gravity-induced turbulent mixing. This resistance is generally termed “lake stability”.

4.2 Factors that influence water density

Four main factors determine the density of water:

1 Temperature.

As already described, warmer, less dense water floats on top of colder, denser water. The normal situation is for temperature to decrease with depth, from top to bottom, which means that the lake density structure (layering) will be stable and will require inputs of energy (such as from wind) to mix. If on the other hand temperature increases from top to bottom, or from a layer higher in the lake to a layer below, the water column will be unstable and the warm water will rise, the cold water will sink, and mixing will occur spontaneously. The only way that warmer water can be found to persist beneath colder water is if some other factor is contributing more strongly to density than is temperature, such as the presence of dissolved salts.

2 Concentration of dissolved salts.

When dissolved in water, inorganic salts will increase the density of the water. This is why sea water is more dense than freshwater even at the same temperature, and it also explains how the temperature of Lake Kivu can rise as you move down in the lake (normally an unstable condition) – the warmer water is less dense and should rise, but the dissolved salts more than compensate and make the lower water more dense and thus stable, as is shown in Figure 5.

3 Concentration of dissolved gases.

Dissolved carbon dioxide and hydrogen sulphide both increase the density of water. Dissolved methane, however, has the opposite effect such that the more methane dissolved in the water the lower is the water density. Gases introduced into water in the gas phase (bubbles, not dissolved) always decrease the density of the water, and in fact provide a very strong mixing force as can be seen in any fish aquarium with a bubbler.

4 Pressure and depth.

As any swimmer or scuba diver knows, the deeper you move in the lake, the greater is the weight of water above you and the higher is the pressure in the water. Since water is a (slightly) compressible fluid, its density will increase with pressure and thus with the depth in the lake. This is why even in a well-mixed layer of water, with no gradient of salts or temperature, the change of density with depth (such as shown in Figure 6) retains a small, positive value.

In terms of stability however, this mechanism is neutral; it neither enhances nor decreases the tendency of the water to move in vertical directions, because any body of water moving up or down will see the same changes in density due to pressure.

Because of the geothermal heat gradient, an upwards average heat flux will provide heat to the bottom of a lake and thus enhance the mechanism of temperature-induced turbulent mixing. This tendency is most pronounced in areas with high volcanic activity. But Lake Kivu (and many other lakes) has an inflow of saline ground water into the bottom of the lake as well as the fresh water falling on the lake and flowing into the top part of the lake from rainfall. The freshening of the upper layer and incoming solutes at depths leads to a pronounced increase in salinity (or electrical conductivity as shown in Figure 5) with increasing depth. Therefore, there is a divergence between the increase in temperature and salinity with depth; the former enhances turbulent mixing and the latter attenuates turbulent mixing.

4.3 Normal Mixing and Transport Mechanisms

Due to heating by the sun, deep water bodies become thermally stratified with warm, less dense water near the surface and cool, denser water near the bottom. This stable state can be disrupted due to winds and to passage of cold fronts in summer, and due to the extensive cooling during autumn and winter in the temperate zone and Arctic in autumn and winter. In contrast, in large tropical lakes, thermal stratification is the normal situation. With respect to the African Great Lakes, those greater than 100 m deep are *meromictic*, meaning they do not mix fully to the bottom on a yearly basis. Lake Victoria, which is 80 m deep, provides the basis for the depth scale as it mixes to the bottom during the monsoon. Because solutes and gases which influence the ecosystem function of lakes (and their economic importance) are found below the depth of seasonal mixing, it is important to understand the different mechanisms of mixing that occur in a lake.

4.3.1 Movements and Transport on Molecular Scale

The random, “Brownian” movements of molecules make them bump into each other and move back and forth. When a faster moving molecule bumps into a slower moving molecule, momentum is transferred from one to the other. And since temperature is nothing but the intensity of momentum in the molecular movements, these collisions of molecules is what dissipates (transfers) heat in solids as well as in liquids. If there is no turbulent movement in the liquid (water), this mechanism is the only one available to spread heat.

But not only do the molecules such as dissolved salts bump into each other, they also slowly shift relative positions from regions of high concentration toward regions of low concentration. This form of transport is what is known as (molecular) diffusion. The speed with which molecules of salt or gas diffuse is typically a hundred times slower than that of heat. Transport by diffusion is by far the slowest of all mixing mechanisms. It is so slow, that it generally is not called mixing.

It is also the only transport mechanism that is not influenced by gravity and water density as opposed to all the other mixing mechanisms that are described below. By the stochastic nature of these movements, the influence driving the rate of diffusion is the difference in concentration between two locations; a larger difference, or "gradient", results in faster diffusion.

4.3.2 Temperature Induced Turbulent Mixing

Warmer water below cooler will create turbulence because the warm water is lighter than cold water. Under the influence of gravity, the warm water will rise toward the surface and the cold water will sink toward the bottom. This rise and fall of water masses produces turbulence and results in mixing. Therefore, the more the temperature rises with depth the bigger is the driving force and the more efficient is the resulting mixing of the water.

In most places of the world with significant variations between summer and winter temperature it is therefore normal that during fall and early winter when the surface waters cool down, they sink to the bottom of a lake, thereby causing a complete mixing of the lake waters at least once a year.

In the case of Lake Kivu annual temperature variations are moderate, and only the upper 50-60 m layer of the lake is strongly affected. Below that, the density gradient caused by the build-up of salts in lower waters creates a "*stability layer*" or *pycnocline* that is resistant to mixing. This stability layer is what separates the biozone from the rest of the water body. The rationale for this behaviour is further discussed below. However, Lake Kivu is also heated from the bottom, so the temperature induced turbulent mixing can be important. This mixing will be discussed again under the heading double diffusive convection.

4.3.3 Effects of external forces

Down to a certain depth, turbulence is caused by waves and currents generated by wind and eddies (circular motions) caused by surface cooling. In the case of Lake Kivu, this mechanism is predominant in the top ~ 60 - 70 metres of the lake. Just as autumn cooling can induce deep mixing in temperate and arctic lakes, tropical lakes often have a season with enhanced mixing due to wind and cooling. For the African Great Lakes, this large-scale mixing occurs during the monsoon season with its strong southerly winds and generally dry conditions, but is generally limited to the upper part of the lakes (e.g., ~100 m in Lake Tanganyika). The upper layer that is mixed by wind and cooling is called the upper mixed layer, and in many lakes it is the layer that contains oxygen and thus supports higher life such as insects and fish (the "biozone").

4.3.4 Effects of internal waves

All stable fluids can support internal waves. In the case of lakes, these waves are typically induced by wind forcing but can also be caused by a disturbance such as an earthquake. They are found below the upper mixed layer. They can either be standing waves which basically make the pycnocline rise and fall across the entire lake basin, or they can be progressive waves with a much smaller length scale and which propagate across the lake and reflect on the far shores. Internal waves are the major mechanism inducing currents, shear, and mixing below the upper mixed layer.

4.4 Lake Kivu

As shown in the schematic diagram, Figure 4, saline and fresh water reaches Lake Kivu in large quantities. Freshwater inputs enter the surface with an estimated discharge rate through the Ruzizi River of 3.2 km^3/year. Groundwaters with higher salt concentrations enter at depth. The difference in density of saline and fresh water is instrumental in maintaining the multilayered lake.

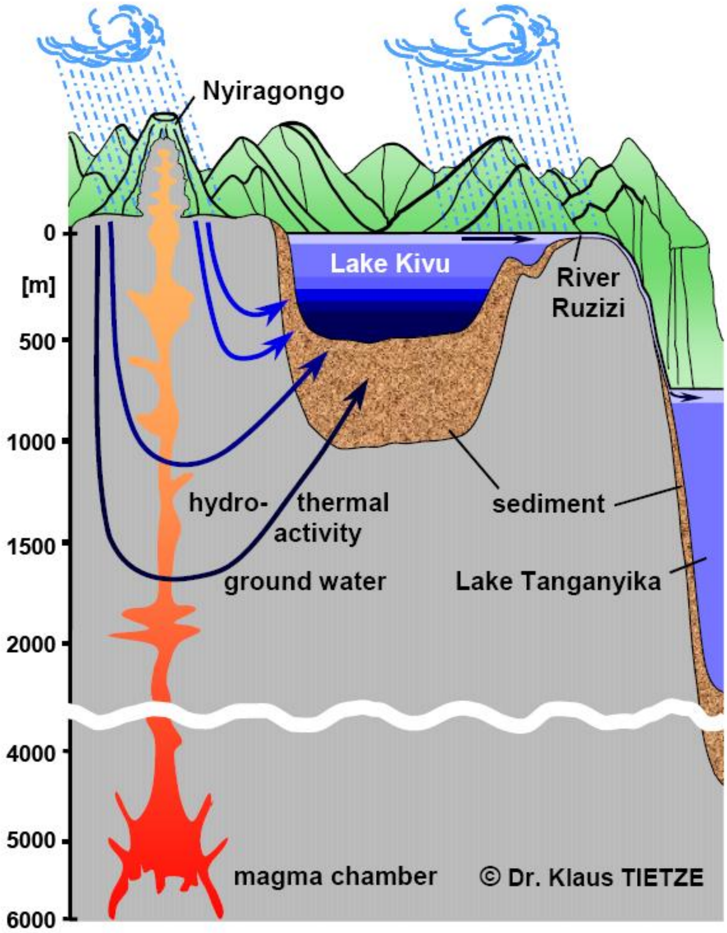

Figure 4 *Schematic cross section through Lake Kivu and Lake Tanganyika showing the mode of influx and infiltration of fresh and saline water into Lake Kivu (after Tietze, 2005).*

The nearby active volcanoes provide magmatic carbon dioxide to the lake, and it is possible that high temperatures associated with volcanic activity form methane by *thermocatalytic* processes. However, most of the methane in the lake is produced by two main biological processes. The processes are (1) decomposition of organic matter (carbon) in the water column or accumulating as sediment at the bottom of the lake, which involves bacterial fermentation of acetate in the lake or sediments, and (2) the bacterial conversion of carbon dioxide and hydrogen into methane. The relative importance of these two pathways of methane formation is difficult to determine; one recent study (Schmid et al. 2004) suggests that nutrient input from growing populations around the lake have stimulated the production of organic carbon by algae, and that this carbon supply to bacteria might account for the estimated higher methane production over the past 29 years.

The main point here is that these inputs of gas (carbon dioxide and methane) to the lake also play a role in the density and stability of the water column. Carbon dioxide added to water increases the density of the water, just as salts increase water density, but methane added to water reduces the water density. Thus adding methane to the lake is similar to the effects of warming, both of which cause the water to become less dense. Therefore, concentrations of gas in the water must be measured in order to accurately predict and understand the layering structure in the lake, and how that structure may change as commercial methane extraction proceeds.

4.4.1 Lake Kivu density structure

What makes the lakes Kivu, Nyos, and Monoun so special is that they also see an influx of carbon dioxide that has two significant effects:

- It contributes to the concentration of dissolved components that increase the density of the water, and thus stabilizes the water column for even more carbon dioxide or for methane to accumulate without being mixed to the surface and released to the atmosphere.

- It dissolves and accumulates at the bottom of the lake under ever increasing partial pressure until such time that the partial pressure has reached the hydrostatic pressure of the above water. At such time, bubbles form and start rising rapidly and destroy the density gradient and thus lake stability – if the area or volume of bubbles is large enough, a disastrous spontaneous gas eruption occurs.

Based on the basic understanding of lake mixing given in the above part of Section 4, it is now time to show the most important gradients in Lake Kivu as recorded by Tietze in 1974/75, shown in Figure 5.

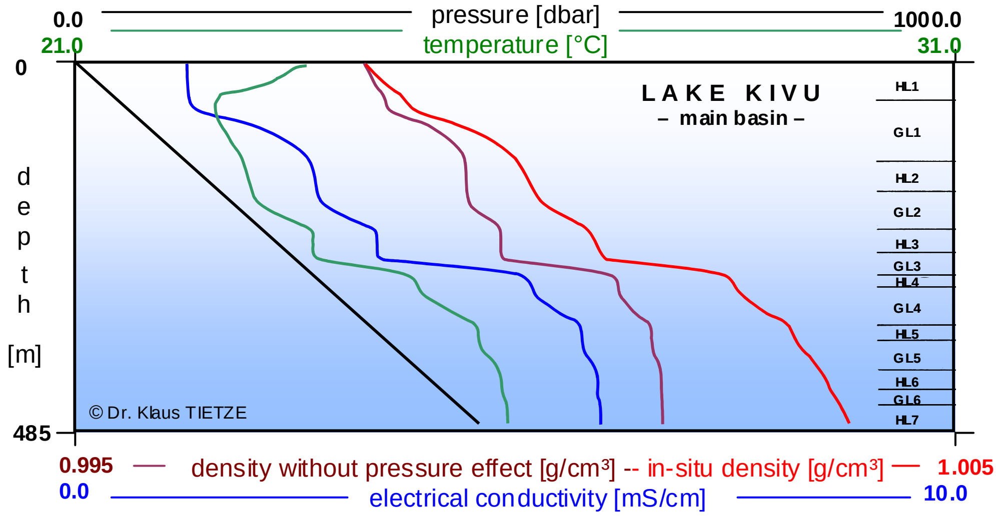

Figure 5 *Development in key water variables with depth (after Tietze, 1978, 2000, 2005).*

One of the important findings of the first measurements by Tietze was the similarity of the vertical gradients all over the lake; that is, there is very little horizontal heterogeneity in the lake. It therefore makes good sense to look at the average vertical gradients measured in many different locations over the entire lake.

The gradients in Figure 5 are average values of 23 profiles obtained at different locations in the lake. The straight, tilting line shows the increase in pressure with depth, whereas the other lines show some very marked changes in temperature, conductivity (salinity), and density (the latter being caused by changes in salinity, temperature, and gases with depth). As explained above, it is the density gradient from one depth to another that is responsible for resistance to turbulent mixing, and this is why steep changes in the other variables can be observed as well. The marked change in density blocks the upward movement of temperature-induced turbulent mixing in the lower depths, or wind-induced turbulent mixing at depths below 80 m. However, it is important to note that this density gradient is not strong enough to resist high-energy forces such as landslides, falling rocks or other objects, rising bubbles, or vertical water jets or displacements resulting from volcanic or earthquake activity.

A clearer picture of the stability layers, and of the layers in between where temperature induced turbulent mixing takes place, is seen by plotting the relative density gradient $(d\rho/dz)/\rho$ versus depth z as shown in Figure 6.

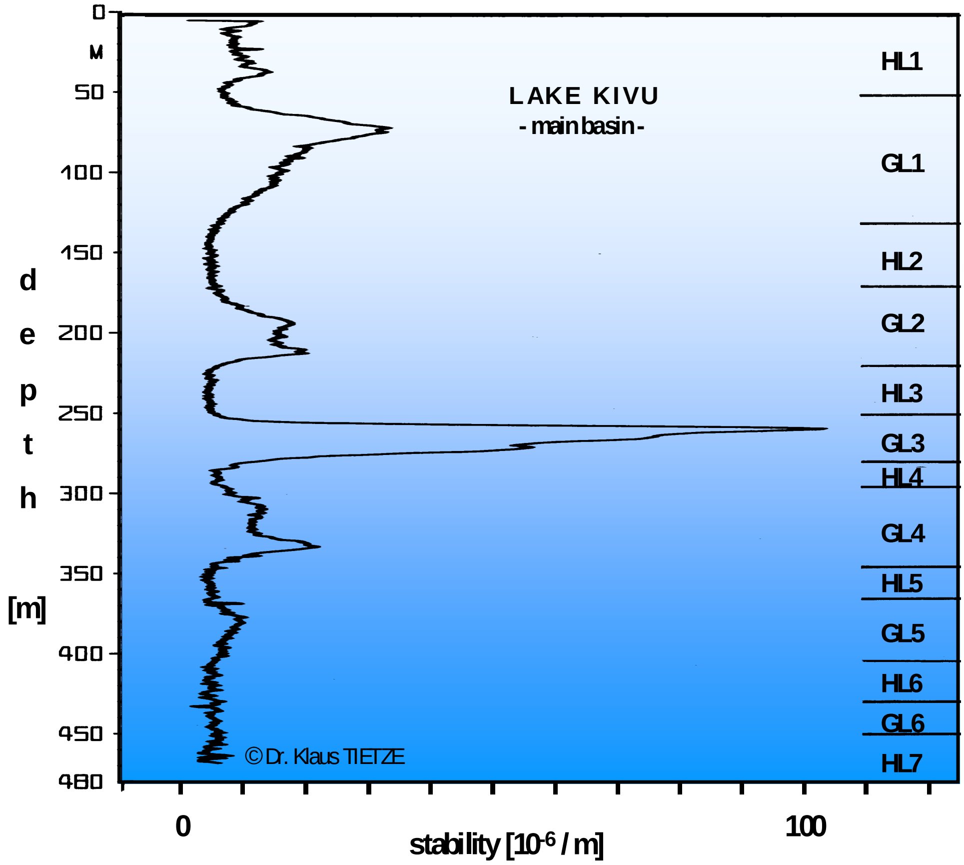

Figure 6 *Relative density gradient* ($d\rho/dz)/\rho$ *versus depth. The bigger the gradient, the bigger is the resistance to turbulent mixing (after Tietze, 1978).*

The abbreviations used in the above figure are: GL for Gradient Layer (or stability layer with very low mass transfer rates), and HL for near Homogenous Layer which, due to mechanisms described below, may have slightly higher mass transfer rates. The most important stability layer is found at a depth of approximately 260 metres. It is caused by influx of the most saline and gassy ground water from the bottom of the lake meeting the shallower water with lower concentrations of salt or gas.

Another secondary, but still important zone of stability stretches from ~ 60 to 80 metres. Its depth is most likely set by the degree of cooling and mixing during the monsoon period. There, the lower density water in the surface layer meets the higher density of the saline layers below and rates of mixing are reduced. It is this secondary stability layer that is responsible for keeping the waters in the biozone of Lake Kivu well-separated from the anoxic body of water below.

It is these stability layers that make accumulation of gas in the lower parts of the lake possible, because the layers act as flexible “lids”. Without these layers, the amount of gas stored in the lake would be much lower, and so would the risk and size of disastrous eruptions!

4.4.2 Details of mixing and stratification

Internal Waves:
Internal waves are a common feature along density interfaces such as those in Figure 5. The amplitude of the internal waves, the overall deflection of the pycnocline, and the anticipated mixing can be calculated using dimensionless indices. The two most valuable for lakes are the *Wedderburn* and *Lake numbers*. These are a measure of the stability of the lake relative to the wind forcing and further take into account the aspect ratio of the lake. The larger the Wedderburn and Lake Numbers, the harder it is for waves to influence the *pycnocline* and the lower the mixing.

The Wedderburn number is calculated as $W = g/\rho\ \Delta\rho\ h^2 /((0.001U)^2 {*} L)$ where g is gravity, ρ is density, h is the depth to the pycnocline, $\Delta\rho$ is the density difference over the pycnocline, U is wind speed and L is length of the lake. For lakes with multiple pycnoclines such as Lake Kivu, h is the depth to each pycnocline. It is easy to see, using an equation such as this, why deep tropical lakes with deep pycnoclines would inherently be stable over long time scales. However, h is smaller for the upper pycnocline, and if W drops to critical values, internal waves and mixing can result in the upper pycnocline. Calculations of Wedderburn and Lake numbers for Lake Kivu are presented in Section 5.2.4.

Double diffusive convection:

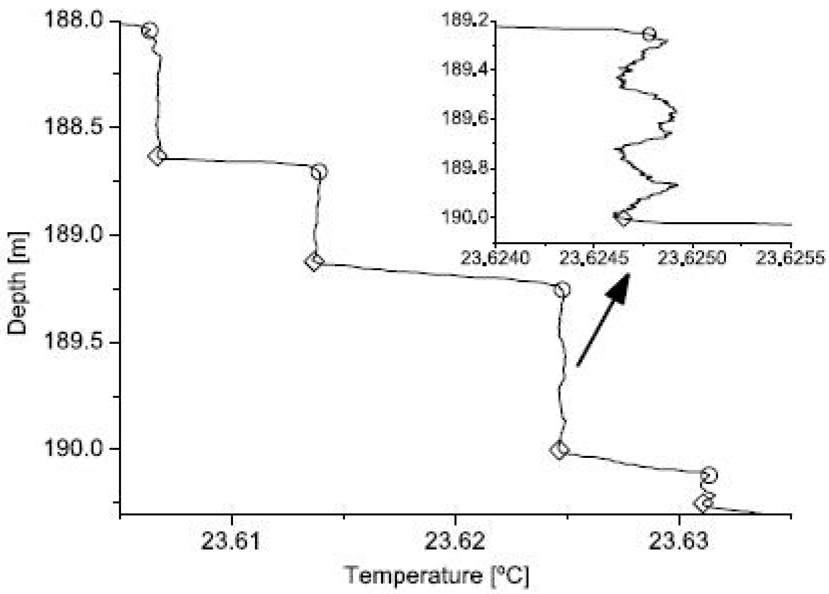

Figure 7 Example of double diffusive layering in Lake Kivu (after Schmid et al. 2005)

One result of the diverging forces on density is the phenomenon of double-diffusive convection which was first well-documented in Lake Kivu by Newman (1976) and has lately been recorded by Schmid et al. (2004) and Lorke et al. (2004). Figure 7 illustrates the resulting steps in the temperature profiles.

Double diffusive convection occurs due to the different rates of molecular diffusion of heat and salt. In fact, heat diffuses 100 times faster than salt. If cool, fresh water overlies warm, salty water, the heat will diffuse upward much faster than the salt will diffuse upward, resulting in instability. A series of instabilities creates the step structures as in Figure 7. Mass transfer coefficients due to this process may be 10 times faster than the molecular diffusion of heat and 1000 times faster than the molecular diffusion of salts in Lake Kivu (Lorke et al. 2004). Studies in other lakes with similar temperature and salt stratification indicate that mixing rates may be even higher when double diffusive convection occurs (Spigel and Priscu 1998). Hence, double diffusive convection can lead to faster vertical transports than would be predicted for similar density gradients without geothermal heating.

Horizontal mixing
Double diffusive convection also induces horizontal flows and hence circulation cells at depth (Turner 1973; Spigel and Priscu, 1998). Thus, rather than the process occurring at localized regions, it occurs over a larger horizontal scale and material at the boundaries can be transported into the interior of a fluid. In addition, as the density discontinuity between steps breaks down, the overall scale of the circulation cells becomes larger. Hence, as also hypothesized by Lorke et al. (2004), the larger scale regions with weak density gradient (e.g., 260 to 300 m, 200 to 250 m) may in fact have resulted from these larger scale circulation patterns.

Bottom slope plays an important role in generating and maintaining transport within the circulation cells (Turner 1973). Differences in slope lead to differences in rates of geothermal heating within adjacent depth strata and can act to maintain the formation of density instabilities and continuous circulation between the boundary and interior. Thus, despite the overall density stratification within Lake Kivu, the water column below the biozone can be considered not as a static environment but as a dynamic one with transports occurring both in the vertical and horizontal directions.

Intrusions can be formed due to double diffusive processes when horizontal gradients occur in temperature and salinity even when compensated by pressure. Thus, withdrawal of water at one depth may create such conditions and lead to enhanced mixing rates. The impact of the potential increased mixing on the stability layer at 320 m must be monitored carefully.

Internal wave motions can also induce horizontal motion. However, transport only occurs if the waves are non-linear. As will be seen later, wind induced internal wave transports are only likely in the upper pycnocline. Internal waves induced by a disturbance such as an earthquake could cause increased vertical mixing and lateral transports. In addition, intrusions induced by horizontal heterogeneity often need a triggering event (Schmitt 1994) and internal wave activity has been proposed as such a mechanism.

4.5 Gas Production and Gas Accumulation

Our understanding of gas production, transport, and accumulation in the lake has been developed using results from measurements of gas concentrations, isotopes, and other chemical variables in the lake (e.g., Tietze, 1978; Schmid et. al. 2004). The current view is as follows:

- Most of the carbon dioxide originates from volcanic activity below the bottom of the lake sediments. It passes through the sediments and is released into the bottom layers of water in the lake.

- A smaller part of the carbon dioxide and most or all of the methane is formed by biological degradation of organic matter, mainly near the bottom of the lake. The same processes generate some hydrogen sulphide. As mentioned above, there are two major biological pathways of methane production that are used by bacteria. Although each of these pathways leaves different isotopic signatures in the methane, it is difficult to partition which pathway is most important because these isotopic signatures overlap.

- Even though carbon dioxide is probably entering the lake with the saline water, and it must be produced in the lake from biological activity, recent measurements have not been detailed enough to estimate the rates of accumulation. Overall, the carbon dioxide concentrations in the lake seem to be relatively stable over time.

- In the surface waters, the growth of organisms such as algae removes nutrients (nitrogen and phosphorus) from the biozone. As these organisms die and sink they transport the nutrients into the deeper parts of the lake where they accumulate. These dead organisms also serve as feed for the biological degradation producing methane and some carbon dioxide.

- In the upper part of the lake the degradation of organic matter by bacteria uses the oxygen available. Below the biozone, where oxygen disappears, other compounds such as nitrate and sulphate are used by bacteria to degrade the organic matter, and in the process produce carbon dioxide, methane, and hydrogen sulphide. Some of the hydrogen sulphide precipitates with iron and is removed from the lake, and some diffuses upward where it is oxidized back to sulphate.

- The main loss of the carbon gases is turbulent mixing and diffusion which transports the gases toward the surface of the lake. In the mixing zones (HL in Figure 6 above) mass transport is fast and in the gradient layers, mass transport is much slower. Schmid et al. (2004) have analyzed the microstructure (as shown in Figure 7) and found that - mainly due to the stability layer around 260 metres - the mass transport rate of methane from the bottom to the surface of the lake is less than 0.1 % of all methane generated. This means that almost all of the methane generated at the bottom of the lake is accumulated below the main stability layer, and so is the carbon dioxide.

In summary, carbon dioxide is mainly input from outside the lake and methane is mainly generated within the lake. The generation of methane may have increased in the last 29 years, and the loss of methane through upward diffusive and turbulent transport appears to have decreased. This is a very important conclusion since it has bearing not only on the potential for production of methane from the lake, but it also sends dire warnings about the future risk of a gas eruption from the lake if nothing is done to lower the gas content.

4.6 Measurements of gas concentrations

Because the accumulation rate of gases is critical for estimating the hazard potential of the lake as well as the power production potential, much interest is focused on the interpretation of actual measurements of gas concentrations and on the inferences based on measurements by different tools and at different locations. In 1974/75 Tietze (1978) was the first researcher to measure these variables at many locations and also quite accurately. In 2003, Schmid et al. (2004) repeated some measurements, but with less than desirable accuracy for the carbon dioxide and a different method than Tietze used for the methane. For the methane, however, the accuracy was claimed to be quite good, and the results of the two measurements of the methane profile in the lake are therefore compared in the Figure 8.

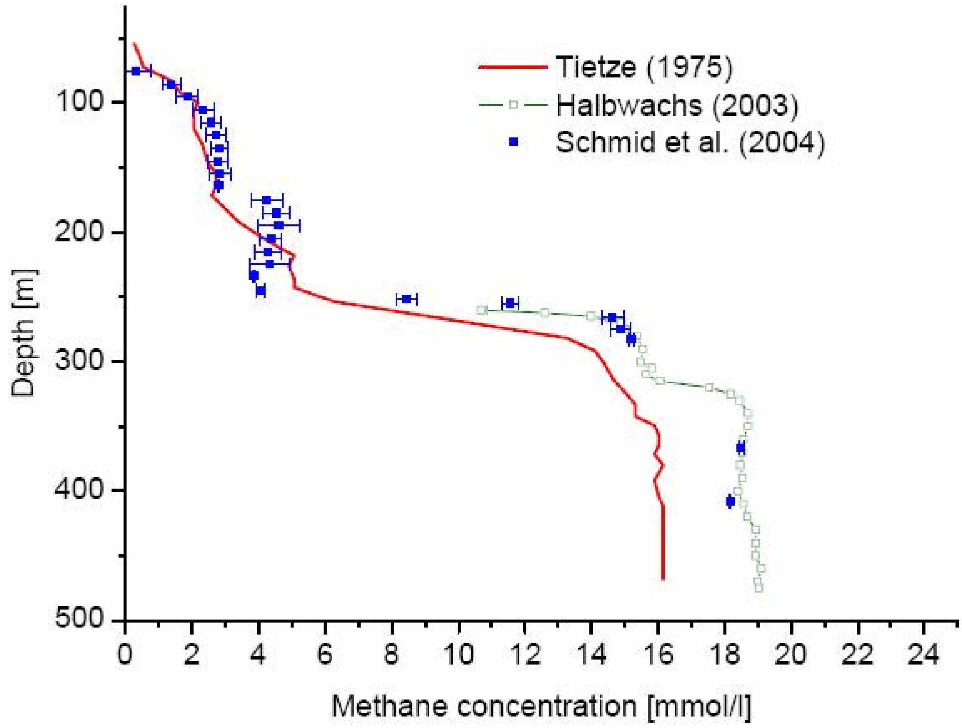

Figure 8 Development in methane concentration profile with time (after Schmid et al. 2004).

Tietze (1978) has reported that his measurements in 1974/75 were accurate to between 2 and 5 %. Based on this information, there is no doubt that the concentration of methane has increased in the lower levels of the lake over that period of 29 years from ~ 16 to ~ 18.5 mmol/l at a depth of 340 metres. But these changes over time retain some uncertainty. As explained below, this uncertainty may be directly translated into an uncertainty on the prediction of time before the lake will become unstable due to gas concentrations approaching saturation levels. It is therefore obvious that these measurements will have to be repeated to produce data that are precise, accurate, and comparable with previous measurements.

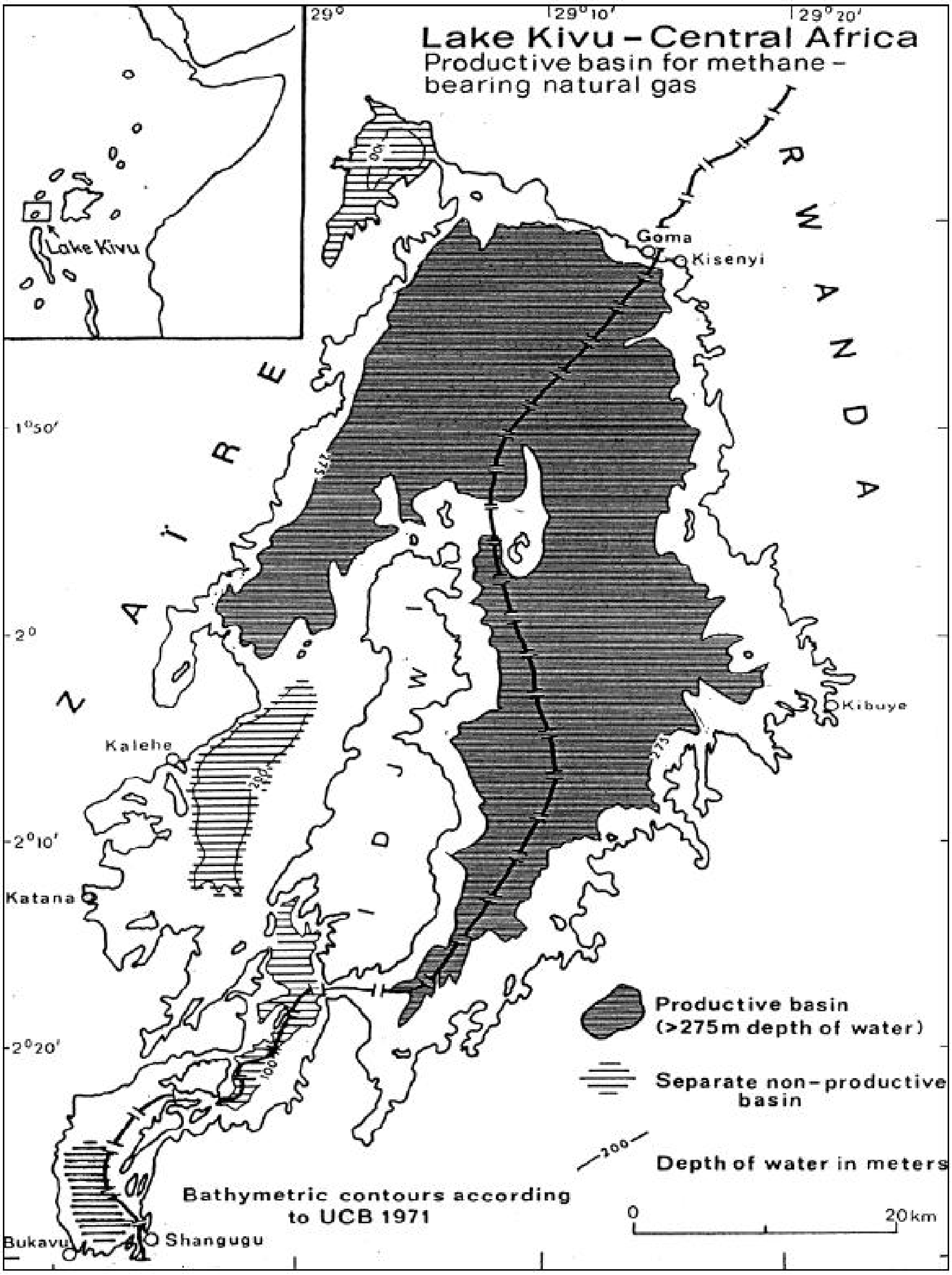

Figure 9 *Illustration showing deep waters with majority of dissolved methane (after Boigk 1973, Tietze 2005). The map shows the main basin and the non-productive separate basins.*

The lack of data above a depth of some 250 m by Halbwachs (Figure 8) is due to the method applied, where gas was allowed to flow freely through the measuring tube from the depth considered. At shallower depth the self-promoting flow could not be achieved.

As it can be seen above, methane is mainly found in the deeper waters of the lake. The map, Figure 9, shows in which parts of the lake the main quantities are found.

5 Risks

In this section the risks for and consequences of different types of eruptions from the lake are discussed and evaluated.

5.1 Nature of Risks

Although there is some uncertainty attached to the measurements from 1974/75 and 2003/2004, it appears that methane and carbon dioxide are accumulating as shown in Figure 10 and Figure 11, and there is a high probability that these increases are occurring at an accelerating rate. Note that different horizontal scales are applied in the two graphs.

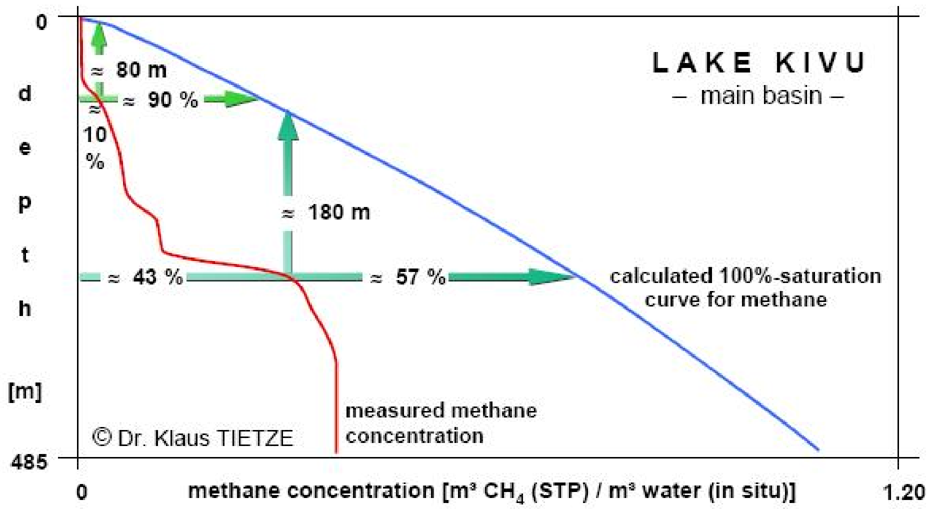

Figure 10 Measured methane concentration from 1974/75 and perceived saturation risk (after Tietze 2005).

Ideally, the solubility of methane is directly proportional to the pressure. In reality, this solubility is also influenced by temperature and salinity that both increase with depth. This is why the saturation curve in Figure 10 is not a straight line. However, note that it is not possible to directly compare the curves in Figure 10 and Figure 11 because the conversion from gas concentration (Figure 10) to gas pressure (Figure 11) is complicated. The main point of these two figures is to illustrate that gas saturation is reached (which triggers bubble formation and a gas release) either when water is moved upward to the point of saturation (vertical arrows in the figures), or gas pressures build up to the point of saturation with respect to the hydrostatic pressure (weight of the overlying water) as shown by the horizontal arrows in the figures.

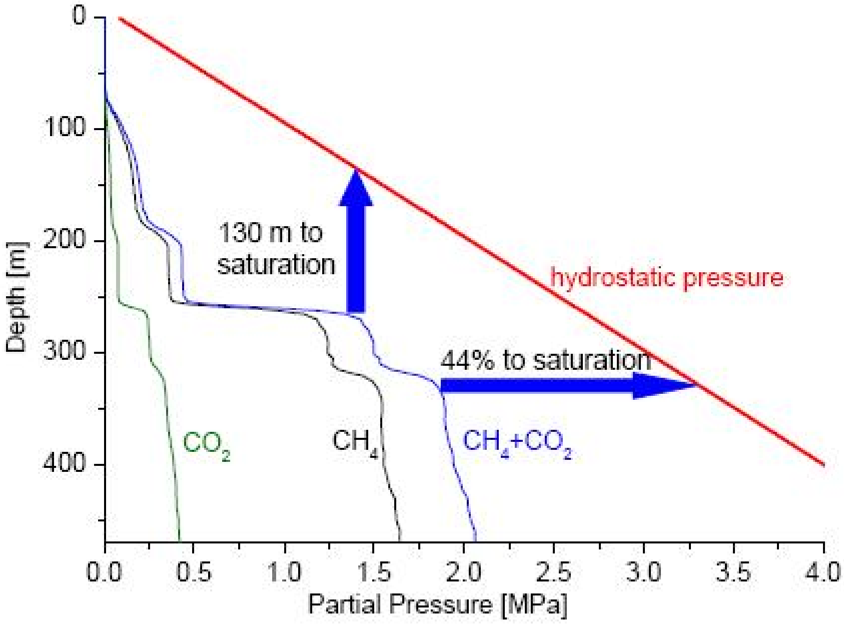

Figure 11 *Estimated gas pressures based on 2003/2004 measurements and perceived saturation risks (after Schmid et al. 2004).*

It is the total partial pressure of the dissolved gases that determines how close the lake is to saturation and a gas burst. If the partial pressure at any depth is compared with the hydrostatic pressure of the water, one gets a rather clear understanding of what is involved:

- In the vertical direction, the distance in metres between the saturation curves (the red and the blue curve in both Figure 10 and Figure 11) shows the magnitude of physical disturbance required to trigger a spontaneous eruption.

  As described in Section 5.6, there are several mechanisms that could achieve such large displacements of water, including earthquakes and volcanic activity.

- In the horizontal direction, the distance in pressure between the current concentration and the gas saturation curve shows the amount of gas increase required to trigger a spontaneous eruption.

There are indications of earlier eruptions from Lake Kivu, which show that gas eruptions are recurring events.

- Layers in the sediments dating to 1500-2000 years ago and ~5000 years ago are filled with terrestrial organic matter and certain species of diatoms (algae) that indicate great disturbance and mixing of the water column, probably associated with increased volcanic activity (Haberyan and Hecky, 1987). Each of these paleo-indicators is consistent with the hypothesis of a previous uncontrolled release of enough gas to force anoxic water to the surface and affect the algae, and to create surface waves large enough to strip the land near shore of terrestrial material and wash it back into the lake.

The present estimated rate of accumulation of methane and carbon dioxide in the lake, given the rate of accumulation of methane from 1975 to 2004, would indicate that saturation will be achieved within a span of approximately 100-200 years (see also Table 4 in Section 6.5).

5.2 Monitoring the lake stability and hazard risk

There are several methods that provide a measure of strength of stability in stratified lakes with gas accumulation, and each one has its advantages and disadvantages; three such methods are shown in Figure 12 and a fourth in Figure 13.

5.2.1 Density Gradient

The first illustrates the resistance to mixing across a local *density gradient* or *pycnocline* [$(d\rho/dz)/\rho$ versus depth], used by Tietze in Figure 6. This measure is appropriate for determining where resistance to mixing will be slowest in the water column, and as seen in Figure 8 and below (green dotted line) this occurs at around 260 m depth in the lake (differences between Figure 12 and Figure 6 are due to the coarse depth layers plotted in Figure 12, but the overall picture is the same).

5.2.2 Saturation Distance

The second measure is the *saturation distance* (plotted in red in Figure 12), which shows the distance that water must move vertically until the total gas pressure is saturated and would form bubbles (illustrated for one depth in Figure 11). The saturation distance is useful for determining the depths in the lake that are closest to gas saturation, and thus are most likely to be the initiation sites of an uncontrolled gas burst. Note that while the gradient measure indicates a “strong stability” around 260 m, the saturation distance is low at this depth and indicates greater danger.

5.2.3 E* stability

The third measure is the *E* stability* (plotted in blue in Figure 12), which takes into account the gradient stability and the actual gas pressures at each depth; it is a *relative* measure used to help understand the various processes involved in such complex systems when gas pressures are large. When the saturation of gas is reached the formation of bubbles destroys nearby water column stability regardless of the density structure due to temperature and dissolved salts. Because of this unusual behaviour, a modified local stability variable, E* =

$[d\rho/dz/\rho] \times [(P_{AMB}/P_{GAS})-1] \times (1/P_{GAS})$, was derived (Kling et al. 1994, 2005) to include the effects of dissolved gas and estimate a relative measure of the local resistance to mixing between two vertically adjacent, horizontally homogenous water layers. The first term defines the local, gradient stability. Inclusion of the second and third terms where P_{AMB} is the hydrostatic pressure and P_{GAS} is the total *in situ* gas pressure, is required to account for the non-linear effects of dissolved gas on lake water density, and to distinguish between conditions where gas saturation may be reached in a layer of low absolute gas pressure (e.g., near the lake surface). E* thus combines the effects of density stratification and percent of gas saturation into a single variable. As P_{GAS} approaches P_{AMB} the stability E* goes to zero. Negative values indicate instability and can be caused by more dense water overlying less dense water, or to over-saturation of gas pressures (P_{GAS}>P_{AMB}). Both causes result in overturning of the local water column, by gravity currents in the first case and by rising bubbles in the second case, and either case can initiate an eruption of gas.

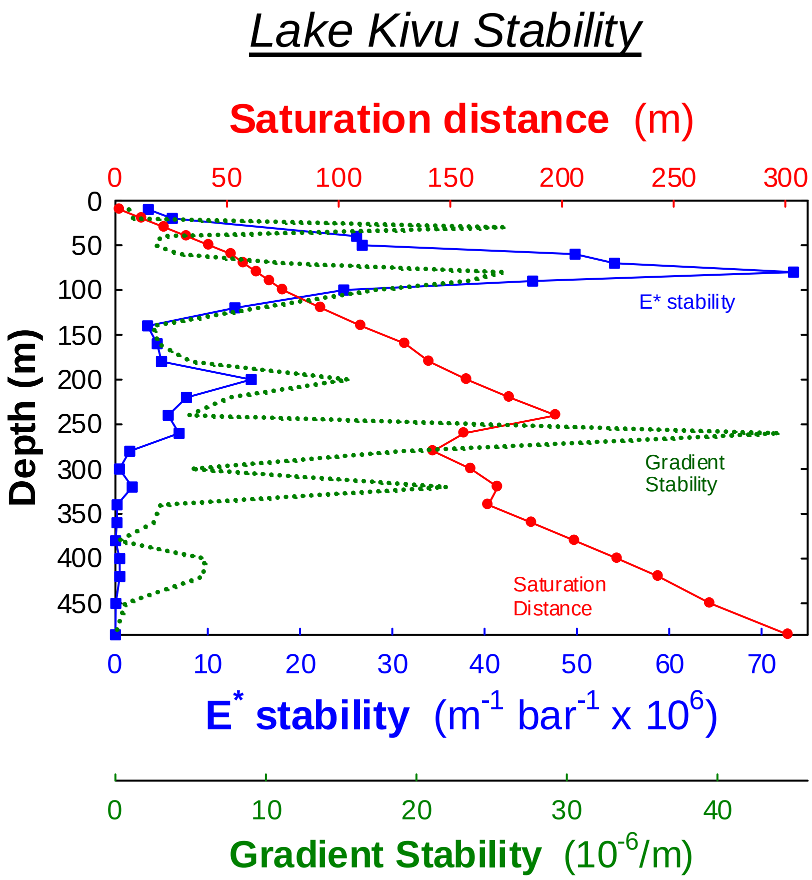

Figure 12 *Various measures of "lake stability" shown for Lake Kivu;calculated using data from Tietze (1978), Tuttle et al. (1990), Schmid et al. (2004), and data from Dane Associates. Gas pressures include the sum of carbon dioxide, methane, and nitrogen, the major gases contributing to the total in-situ pressure.*

Notice that in cases where the saturation distance is low (upper 100 m), which would by itself signal a dangerous situation, the E* stability is high because the *in situ* gas pressures are too low to be dangerous. In addition, in cases such as near 260 m when the gradient stability is high, the E* stability is low and properly indicates that this is a potentially dangerous region because of the high gas contents. The value remains low (but greater than zero) in the bottom 100 m of the lake in part due to the high gas pressures and low gradient stability.

5.2.4 Buoyancy Frequency

A final and related method to evaluate lake stability is called the *buoyancy frequency*, $N = (g/\rho\ d\rho/dz)^{1/2}$. It has the units radians s^{-1} or cycles per hour (cph). It is similar to the gradient stability of Tietze but includes gravity. In general, when N < 5 cph, we say the water column is weakly stratified. For 5 < N < 22, we say it is moderately stratified, and for N > 22, we say it is strongly stratified. When Lake Victoria is stably stratified during the dry season, maximum values of N are ~ 15 cph. Maximum values of N in temperate *dimictic* lakes reach 60 cph during the summer. Figure 13, which illustrates the buoyancy frequency in Lake Kivu using the data from Schmid et al. (2004), indicates that the density step at 260 m is strongly stable whereas the other steps are within the lake are only moderately stable.

Figure 13 also illustrates the stability computed as in Fig. 6. Interestingly, the magnitude of the stability at 260 m has doubled relative to Tietze's earlier observations whereas the stability of the other interfaces has remained the same.

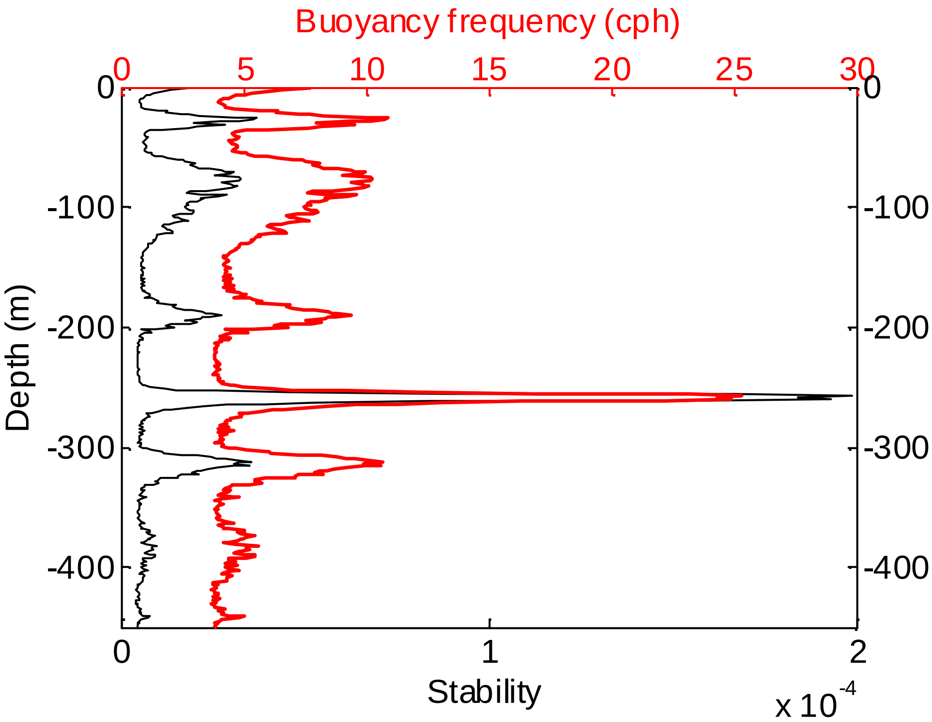

Figure 13 *Buoyancy frequencies in cph and stability in m^{-1} in Lake Kivu based on a profile taken in February 2002. Density calculation includes temperature, salinity, carbon dioxide and methane concentrations, and hydrostatic pressure.* (data courtesy of M. Schmid).

The difference between past and present calculations may be due to the resolution of the profilers and further demonstrates the need to obtain highly accurate new data. From the data (courtesy of M. Scmid) one might conclude that the gradients have sharpened and that the new gradient layers are more distinctive.

5.2.5 The Wedderburn number

None of the measures above characterize the dynamic stability of a lake, that is, how it would respond when forced by wind. The Wedderburn (W) and Lake numbers (L_N) are dimensionless indices which are used to do so. $W = g/\rho\ \Delta\rho\ h^2/(u_*)^2 * L)$. The buoyancy forces which indicate the resistance of a lake to wind mixing are given by $g/\rho\ \Delta\rho$. The inertial force from wind that would tilt the *thermocline* and induce internal waves and concomitant shear is included in u_*, the water friction velocity, which is equal to 0.001*U (where U is the wind speed). The index is further developed by inclusion of the aspect ratio of the lake, h/L, where h is mixed layer depth and L is the length of the lake. For deep mixed layers, a lake has significant resistance to shear induced mixing from internal waves. Long lakes are more likely to experience high shear and to mix, when, as in Lake Kivu, the wind direction is predominantly along the long axis of the lake.

For Lake Kivu, there are two density steps of interest. The first is the density step near 80 m below which the water from depth would be re-injected. The second is at 260 m, as this is the largest density gradient in the lake and provides the greatest stability to wind induced mixing. The Lake number is similar to the Wedderburn number but addresses the stability of the lake as a whole. Based on numerous laboratory and field experiments, we know that for $W > 15$, the thermocline of a lake will not tilt as a result of wind forcing. For $1 < W < 15$, partial tilting may occur, for $W \sim 1$ the thermocline upwells at the downwind end, and for $W<<1$, a lake will fully mix. Recent studies indicate that nonlinear waves that travel along the thermocline as surges with following solitary waves with high shear and a high probability of breaking occur for $1 < W < 3.3$. The interpretation of the Lake number is similar.

Lake Kivu experiences the strongest winds during the monsoon in the north-south direction. This is similar to Lake Victoria and Lake Tanganyika, where wind speeds exceeding 10 m s^{-1} are common and winds sometimes exceed 20 m s^{-1}. The available wind records for Lake Kivu also show that the strongest winds occur during the monsoon season and also come from the south. The existing data do indicate that wind infrequently exceed 10 ms^{-1}, but the averaging period for data is not included which makes comparison with other sites impossible . Examination of the thermal structure in Fig. 7 shows a temperature minimum at 80 m. The temperature minimum is likely indicative of the depth of mixing of the water column during the monsoon. At that time, as in other tropical African lakes, evaporation rates are likely to be their highest so the mixing occurs by the combination of evaporation and wind shear (MacIntyre et al. 2002). Since the data for Figure 5 were obtained in February, a time when thermal stratification is well established in Lake Tanganyika and Lake Victoria and these other lakes have deeper mixed layers during the monsoon, our interpretation hat mixing during the monsoon may go as deep as 80 m may be correct. The mixing depth during the monsoon is important due to current plans for depth of injecting bottom water. In addition, internal waves result from the wind forcing in Lake Tanganyika. The Wedderburn number in Lake Tanganyika drops to a value just above 1 during the monsoon and steep fronted internal waves form of the type likely to induce mixing. In Lake Tanganyika, these waves have crest to trough displacements of 50 m.

To address the stability of Lake Kivu dynamically, that is, as a function of wind forcing, we computed W and L_N for winds of 5, 10, 15, and 20 m s^{-1}. Based on the wind data currently available, the two higher wind speeds are worst case scenarios. However, if the available data has been averaged even over 3 hour periods, the latter two wind speeds may occur with some frequency.

For the upper pycnocline, values of W for these 4 wind speeds were 31, 8, 3.5, and 2 respectively. These values indicate the necessity for good wind data on the lake. For the two lower wind speeds, tilting of the pycnocline would be minimal. For the two higher wind speeds, which may occur during monsoon, the upper thermocline will tilt and internal waves will form. For the two highest wind speeds, the internal waves will be non-linear and mixing will be enhanced. The situation will be similar to that in Lake Tanganyika. For the two lowest Wedderburn numbers, eddy diffusivities, which are indicative of the intensity of turbulence, could be as high as 10^{-5} m^2/s at ca. 90 m depth and 10^{-4} m^2/s at ca. 50 m depth. These high values indicate that if nutrient concentrations are augmented in the upper thermocline by the recharged waters, mixing during the monsoon season may return them to the well lit zone where phytoplankton grow. Full assessment of the frequency of such events requires more extensive meteorological data than we presently have. An analysis of the likely nutrient transports and fluxes and their ecological significance is presented in Section 7.

Wedderburn numbers at the deeper pycnocline are 740, 185, 82, and 46 for the four representative wind speeds. These values indicate that the deep pycnocline is exceptionally stable to wind forcing! Lake numbers are 355, 89, 39, and 22, again indicating the lake is stable to typical winds of the region.

Results of this analysis indicate that internal waves may form at the upper thermocline but not at the lower interface due to wind forcing. An analysis of the theoretical modes possible within the lake indicates that a mode 2 internal wave may form at the upper interface. This wave will make the upper pycnocline alternately expand and compress as a result of wind forcing. Along the main axis of the lake, its computed period is 1.6 days. Consequently, as winds in this region have a diurnal periodicity (Piet Verburg, personal comm.) the wave field will be energized frequently. Due the likely non-linearity of the waves in the upper pycnocline, solutes upwelled at one end will likely be quickly traversed to the other end of the lake leading to the apparent one dimensionality discussed by Tietze. Nutrients injected at one location will thus quickly spread throughout the stratified zone below the biozone.

Thus we recommend that in future studies of Lake Kivu the data required to calculate each of these stability measures be collected and reported in order to consider the range of stability conditions that exist in the lake and may change over time.

5.2.6 Double Diffusive Convection

The magnitude of vertical mixing with double diffusive convection depends upon the density ratio (see Lorke et al. 2004 and references therein). This ratio requires knowledge of the expansion coefficients of temperature, salinity, CO2 and CH4 as well as the change in these constituents with depth. Due to the inferred double diffusive mixing above and below the main stability layer at 260 m (Lorke et al. 2004), and its drawdown and subsequent exposure to potentially different rates of geothermal heating which could lead to instabilities, it is imperative that this ratio be frequently calculated. In addition, rates of mixing should be computed based on microstructure profiling with a shear based profiler. A temperature-gradient profiler will not be able to quantify the turbulence in larger convection cells (Spigel and Priscu 1998).

Any change in the horizontal distribution of temperature, salinity or the dissolved gases will set the stage for an increase in intrusions formed by double diffusive convection (Schmitt 1994). These will increase both lateral and horizontal mixing rates. The extraction of water at depth will create horizontal heterogeneity of properties. The impacts of the heterogeneity can be evaluated following Joyce (1977) who developed an analysis which can be used to calculate the enhanced horizontal diffusivities.

5.3 Classification of eruptions

The nature of a lake eruption is difficult to anticipate and describe. However, for convenience one may classify a potential eruption in size-based categories:

1 A *moderate, local eruption* of the order of magnitude of 100 to 10 000 cubic metres of gas released, potentially influencing only persons on the lake or nearest shore. Once the disturbance is over, the rising plume of bubbling water is expected to stop due to the stabilizing effect of the surrounding density gradient – at least with the gas concentrations present in 2006.

2 A *large eruption* of the order of magnitude of 1 cubic kilometre of gas released, potentially influencing all inhabitants at the shore of Lake Kivu in the downwind direction and at a certain distance inland. In the case of local lava inflows triggering the event, the eruption is likely to be sustained for as long as the heat flow can generate the heated and rising water plume that would bring gas-rich water toward the surface. In this case, the eruption is expected to be limited by whatever plume the hot lava is capable of generating.

A very large gas cloud would probably result, with a potential for killing many thousands, possibly hundreds of thousands in the downwind direction. When the lava has cooled down sufficiently (that is, when the inflow of lava has stopped), the gas eruption would probably die out due to the stabilizing effect of the density gradient, again, at least with the gas concentrations present in 2006.

3 A *catastrophic eruption* would empty a large fraction of the over 300 cubic kilometres of gas from the lake. Such an eruption has the potential for killing the entire population in the region around Lake Kivu as well as a significant fraction of the inhabitants around northern Lake Tanganyika. In the case where gas pressures in the lake continue to rise and reach saturation, a catastrophic eruption will start spontaneously and it will not stop until a large fraction of the ~ 300 km^3 of gas in the lake has been released to the atmosphere. This is exactly what happened in Lake Nyos in 1986, except that the amount of gas dissolved in Lake Nyos was only around $1/300^{th}$ of the amounts in Lake Kivu.

As indicated above, the two first mechanisms depend on the gas pressure in the lake, and the nature of the events would behave very much in a non-linear fashion – especially for the second mechanism. At present, the probability of a lava inflow large enough to trigger a large gas eruption is relatively small, because it takes a lot of heat to force a water plume to rise the ~140 metres from a depth of ~275 metres where the gas would become oversaturated (see Figure 11 and Figure 12); minus the effect of rising partial pressure with temperature. For completeness, it should be noted that Schmid et. al. (2004) have underestimated the risk (Figure 11, personal communication), because they disregarded the increase in partial pressure with temperature.

If the gas pressure is allowed to build up in the lake, the probability of a gas release as well as the size of the possible eruption will rise exponentially. The currently small probability of a gas burst will develop into a complete certainty, and the currently limited consequences can only rise to the full catastrophic eruption.

In terms of the potential triggers of these events, the main danger from the extraction plants is a ruptured production pipe below a gas extraction platform. A fracture in the pipe above the bubble formation point, or “two-phase flow”, behaves in the same way as if the gas pressures had reached saturation. This implies that if a ruptured pipe is left undisturbed, gas venting will continue until in theory until a good part of the lake has been emptied of its gas content. However, in reality the venting happens at a much slower rate because it is limited by the transportation capacity of the pipe. And in the case of Lake Kivu, the transportation capacity of one such pipe running wild is not enough to reduce the gas concentration at the bottom of the lake, meaning that it will continue forever. The size of the cloud will be limited, but in adverse weather conditions (low or no wind) it would build up to a considerable size, and with moderate and changing winds the dangerous cloud could sweep past quite a large zone around the lake and onto the shore. In brief, casualties would be limited but a large population would have to be evacuated until the ruptured pipe was repaired.

However, if the rupture of the production pipe occurs just as the two-phase flow is reached, and still within a zone of relatively high surrounding gas pressure, then the venting of gas into the depths of the lake may also destabilize the water column and trigger a much larger gas release.

It is precisely to avoid these scenarios that an emergency valve will be installed at approximately 180 metres below the surface. Should a pipe rupture, this valve will close and thus prevent the above scenarios from happening. **Note that the valve must be placed below the two-phase zone in the pipe as calculated assuming lake surface pressure (<1 bar) rather than the higher pressure that may exist in the gas extraction chamber at the top of the pipe.**

5.4 Role of methane and carbon dioxide

The most important variable to measure in determining the role of gases in lake stability is the total gas pressure, because it is this total which determines when gas pressures reach saturation and trigger a gas release. Thus it is this variable that should be monitored in all future operations on the lake.

However, it is also necessary to understand what role the different gases play in generation of the total partial pressure. When one looks at concentrations (expressed in mmol/litre), the concentration of carbon dioxide is around 5 times that of methane at the bottom part of the lake, but when looking at the resulting partial pressure, Figure 11 shows just the inverse: methane contributes ~80 % of the partial pressure and carbon dioxide only ~20 %. This is due to the much higher solubility of carbon dioxide in water compared to methane.

As previously mentioned, it is not possible to directly compare Figure 10 with Figure 11, in part because both methane and carbon dioxide are not included in both figures. However, it is possible to compare the directly measured variable of methane concentration, because Schmid et al. (2004) have taken Tietze's 1974/75 data and compared them with the recent data. The effect of carbon dioxide concentration was ignored, probably because of the uncertainty in the measurements.

This comparison (Figure 8) shows that the methane concentration in the bottom waters is increasing and that the gas concentration below ~260 m is getting closer to saturation (which increases the risk of a catastrophic eruption in the future). At the same time the size of a disturbance (e.g., an internal wave) in the lake required to create an eruption is reduced. Notwithstanding the different types of measurement techniques, the difference in concentration shown in Figure 8 clearly illustrates a worrisome development in terms of lake stability.

It is therefore necessary to examine the data in more detail in order make extrapolations into the future. This has been done in Section 6.5, and the conclusion is that the catastrophic eruption would occur between 2160 and 2170 with the assumptions stated. Caution in using this prediction is necessary, because the calculation is based on a significant extrapolation of only two sets of uncertain data, and in a situation where it appears that the accumulation of gas is accelerating as the years pass and the population around the lake increases. The estimates of methane gas production might also accelerate based on the details of the production scheme (see Section 5.2). Taking the above into consideration, a probable forecast is that:

If nothing is done to remove the methane, we conclude that a catastrophic eruption will occur probably between year 2100 and year 2200.

5.4.1 Other Basins of Lake Kivu

Of the four "separate" basins in the lake, only the Kabuno basin presents a risk in terms of a gas burst. There is very little methane but a high concentration of carbon dioxide, and a very strong stability layer at shallow depth of 10-15 m. Tietze (2000) claims that the risk of eruption here is 100 times greater than for the main basin, and although the total gas content is much less than that of the main basin there is still sufficient gas to result in deaths on shore. It is unclear how this value of “100 times” was calculated, but given the data in Tietze (1978) we calculate that the gas concentrations are 6-8 times higher than in the main basin.

The other three basins are relatively shallow, and there is no significant methane or carbon dioxide trapped in the deeper strata.

5.5 Other Lakes, Nyos and Monoun

The risk of eruption in gas bearing lakes has been amply demonstrated by the incidents at Lake Monoun and Lake Nyos in Cameroon. These are smaller lakes than Kivu, and lie in “maar” basins that are formed by phreatic (steam) explosions occurring when magma meets groundwater close to the earth’s surface. These two lakes are deep and are fed with inflows of carbon dioxide that accumulate in the lake bottom. It is now well-established that these lakes have a natural cycle of gas building and then gas eruption, where a deadly cloud of asphyxiating carbon dioxide is released. In these lakes, especially in the larger Lake Nyos, there were no significant amounts of neither methane nor hydrogen sulphide, and carbon dioxide was the main culprit behind the previous eruptions and deaths. Some details of these lakes are presented below:

Table 1 Some properties of the lakes Nyos and Monoun

	Lake Nyos	Lake Monoun
Water volume, km^3	0.179	0.014
Depth, m	210	99
Last eruption	21 Aug 1986	15 Aug 1984
Degassing trials	1995	1992
Degassing started	Jan 2001	Feb 2003

The two lakes last erupted in 1984 (Monoun) and 1986 (Nyos), respectively. Whereas Lake Monoun, killed 'only' 37 persons, an event that passed almost unnoticed (Sigurdsson et al. 1987), the eruption in Lake Nyos created an asphyxiating cloud of carbon dioxide that spread and killed >1700 persons and more than 3000 cattle mainly in the valleys below the lake (Kling et al. 1987). Plants and property were left undamaged.

Figure 14 Lake Nyos in 1985 before and in 1986 after the catastrophic eruption (photos by G. Kling)

Based on surviving witnesses and the subsequent efforts of scientists, the following understanding of the eruption now prevails. The accumulation of dissolved gases had reached so close to the point of saturation that any minor natural disturbance in the lake would suffice to trigger the eruption. The initial eruption was relatively small and quiescent, but then the accelerating mixing of the water column permitted the base of the eruption jet to dig into deeper and deeper layers which contained even greater concentrations of gas. The event culminated with a roaring gas-water jet breaking the surface that reached 80-100 metres into the air and created surface waves up to 25 metres high. The eruption jet may not have penetrated all the way to the bottom of the lake, and therefore the lake was not completely drained of its content of carbon dioxide.

This massive mixing of the water column brought bottom water that was extremely high in dissolved iron concentrations to the surface, where it contacted oxygen and formed the iron-hydroxide floc seen in the “after” picture in Figure 14. Below ~10 m the oxygen was absent, the hydroxide floc dissolved, and the lake water was clear all the way to the bottom. Based on the experience from the Bralirwa Heineken Brewery at Lake Kivu, it was proposed to extract the gases from the waters of the two lakes. After numerous scientific expeditions and evaluations, a single venting pipe was installed in Lake Nyos in 2001 and in Lake Monoun in 2003. The latter was installed just in time, because gas concentrations halfway down in the lake had reached 97 % saturation (Kling et al. 2005, and Figure 19).

Figure 15 shows the fountain from the venting pipe in Lake Nyos, and on the graphs in Figure 16 the principle of degassing is shown schematically.

Figure 15 Degassing Lake Nyos, Cameroon by self-sustaining soda fountain (~50 m high; photo by G. Kling)

The principle behind the gas pressure venting jet is as follows:

1 A pipe is installed vertically in the lake, suspended from a floating and anchored platform.

2 A pump is used to start extracting water upward through the pipe (Item 1 on the figure).

3 As the bottom water reaches the level in the pipe where the gas pressure exceeds the hydrostatic pressure, bubbles start forming and the buoyancy of the water is increased. This causes the gas-water mixture inside the pipe to rise rapidly, and results in a jet at the surface with a high velocity (> 100 km/h) from the top of the pipe (see item 2 on the Figure 16 and the jet in Figure 15).

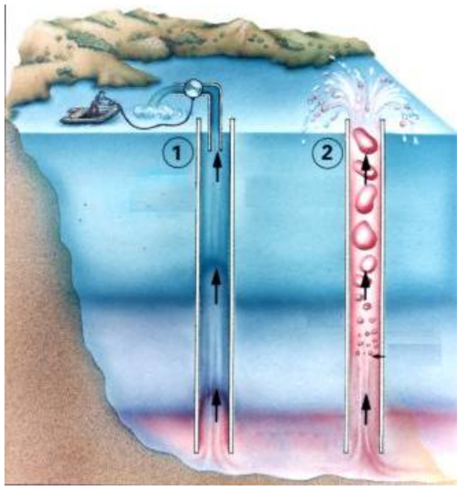

Figure 16 Principle of self-sustained soda siphon after priming by pumping (after http://perso.wanadoo.fr/mhalb/nyos/project/principle.htm)

5.6 Triggering events

In the process of evaluating the potential consequences of natural and man-made accidents and disasters it is important to understand the different mechanisms that can initiate or trigger an eruption.

Catastrophic eruptions

As described previously, currently the worst category of gas eruption can be caused only by extraordinary volcanic or earthquake activity, either discharging very large amounts of lava into the lake or having a volcanic eruption directly below the bottom of the lake. The risk of such a natural catastrophe is very small, but only removing most of the dissolved gases from the lake can prevent the described consequences if there is such a large triggering event.

In the case where gases are allowed to accumulate closer to the point of saturation, the lava inflow required to trigger a catastrophic eruption would become smaller and smaller, and the risk correspondingly higher and higher. If gas concentrations were close to saturation, even a moderate trigger such as a very large storm or small earth tremor could cause a catastrophic eruption.

Intermediate eruptions

The intermediate category of eruptions has the potential for killing many thousands of people around Lake Kivu. The probability of such an event is still remote (today, but not in the future), and the causes comprise events such as:

- Volcanic activity at a larger scale and with larger amounts of lava flowing into the lake than registered at the last eruptions in 2002, or fault movements caused by a major earthquake.
- The effect of an underwater Tsunami wave is more uncertain, but the important issue is creation of an underwater wave in the stability layer at -260 metres. Whenever the crest of such an underwater wave moves gas laden water vertically above the saturation line (blue line in Figure 10 and red line in Figure 11) bubbles will form and rise to the surface. Because of the

low difference in density across the gradient at -260 m (compared to the large difference in density between air and water that controls the height of surface waves), the amplitude of a Tsunami could be quite big. As this wave approaches the shore it could rise to dangerous heights, causing a blanket of bubbles forming from those parts of the lake that are swept by the primary wave. There may even be subsequent waves large enough to over-saturate the water locally and form bubbles, which would have the effect of rising rapidly and entraining deeper, gas-rich water toward the lake surface. This scenario could result in a local or even more widespread release of gas due to the areal extension of the gradient layer (at -260 m the extent of the lake is more than 1000 km^2).

It should be added that the expert committee has found no data on the magnitude of underwater waves, and therefore recommends that monitoring of underwater waves be made part of the monitoring programme for the lake. In addition, the committee recommends a laboratory study be undertaken to understand how underwater disturbances influence formation of internal waves.

Minor eruptions

The third and mildest category of eruption can be triggered by natural causes as well as by accidents caused by the project. The triggers for these events occur along a gradient such that a small input of volcanic heat or lava may cause a small gas burst, while a larger input would cause a more extensive gas eruption. The risk posed to the gradient layers by insertion of the production pipe per se, is considered negligible and will be monitored during the pilot plant operation. Examples of minor eruptions are:

- Spontaneous eruption from the sediment at the bottom of the lake. Such an eruption may be caused by a local super-saturation of gases in the sediments as gas concentrations build up over time, or there may be some disturbance of the sediment which moves deeper, gas-rich sediment upward and causes a super-saturation and bubble formation.

- Geothermal activity or water jets emanating from the bottom of the lake. There is good evidence that such activity and plumes exist, both in the temperature records at some sites and in the volcanic cones that are visible on the lake bottom. Figure 17 illustrates some of these cones, and it is unknown how large a volcanic or geothermal disturbance could erupt from these structures. Obviously in this case the danger for triggering a gas burst will scale with the size of the eruption from the sediment.

- Accidentally dropping an anchor or other large objects into the bottom sediment.

- Accidental rupture of the production pipe below the platform. In this case, the platform is likely to sink as well.

- Internal waves or mixing once the gas pressures have built up to the point where the saturation distance is relatively short (see Section 5.2).

Among the examples above, the risk and or the consequences will increase with increasing saturation of the gases trapped in the lake.

Increased rates of double diffusive convection due to horizontal heterogeneity of temperature and salinity from gas extraction could reduce the magnitude of the stability layers. Monitoring of the double diffusive process may largely contribute to the scientific understanding of the dynamics of the gradient layer development. This will enhance the possibility to address the lake stability issues.

5.6.1 Gas Accumulation in Sediment

It is currently unknown how much gas is stored in the sediments of the lake, or in pockets of gas beneath the sediments. Seismic surveys have not yet discovered such large reservoirs, which would register as impenetrable, high-density structures on the seismic trace. In Lake Nyos the surface sediments have been tested and found to contain similar concentrations of gas as found in the water just above the sediment-water interface. It may be that a similar situation exists in Lake Kivu, and this can be tested. The possible presence of larger concentrations or even of trapped pockets of liquid carbon dioxide in the bottom sediments depend on the inflow mechanism of carbon dioxide of volcanic origin in the lake: from below through the sediments or as flow of dissolved gas into the water body of the (lower parts of) the lake.

In any case, even if large pockets of gas were found in or beneath the lake sediments we know of no technology that could easily or safely remove them (drilling into such pockets is inherently dangerous). Thus it is the opinion of the authors that although this risk is currently undefined, there should be no cause to stop or delay the methane extraction project until more answers are found.

5.6.2 Volcanic Activity

In addition to the risk of lava input to the lake from nearby volcanoes, in Lake Kivu the bottom topography (see Figure 17) reveals that eruptions must have taken place in the past. As discussed above, this risk and the resulting gas bursts will scale with the size of the eruption from such vents or cones. The risk of a catastrophic gas eruption is directly related to the probability of a huge volcanic eruption. Such eruptions are difficult to predict and impossible to prevent, but at the present the probability of such a large event disrupting the lake is considered small.

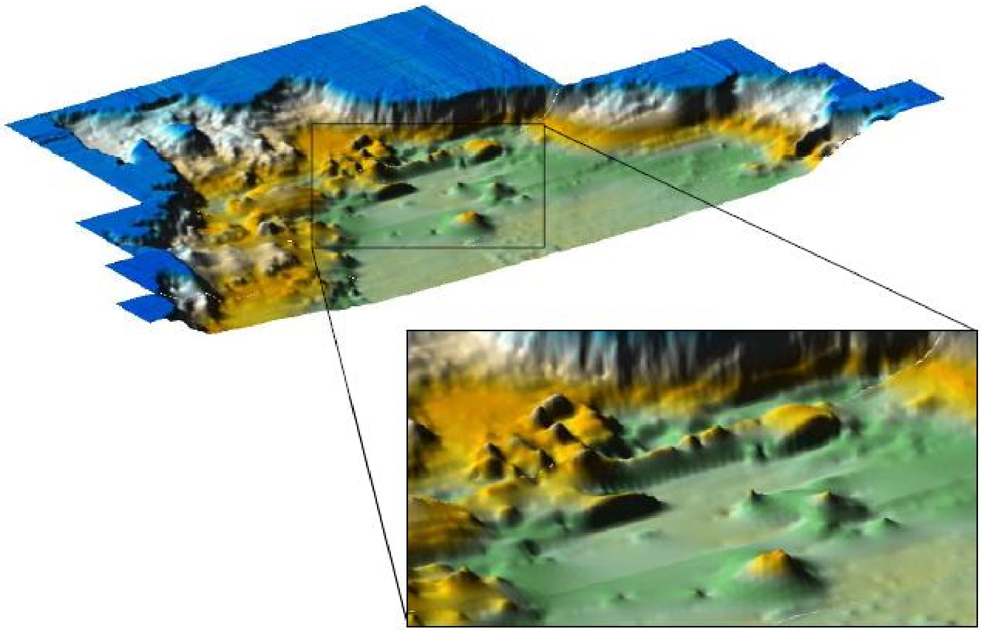

Figure 17 Bottom topography of the northern part of Lake Kivu showing numerous clearly visible volcanic cones (after Schmid et al. 2004).

5.6.3 Earthquakes

Lake Kivu is situated in the western branch of the East African Rift Zone. The zone is active as demonstrated by the recent earthquake events shown in Figure 18; also shown are the lava flows during the 2002 eruption of Mt. Nyiragongo. It can not be ruled out that the active fault zones may contribute to stepwise changes in the lake equilibrium, and that a major fault movement may trigger a catastrophic event in terms of gas eruption.

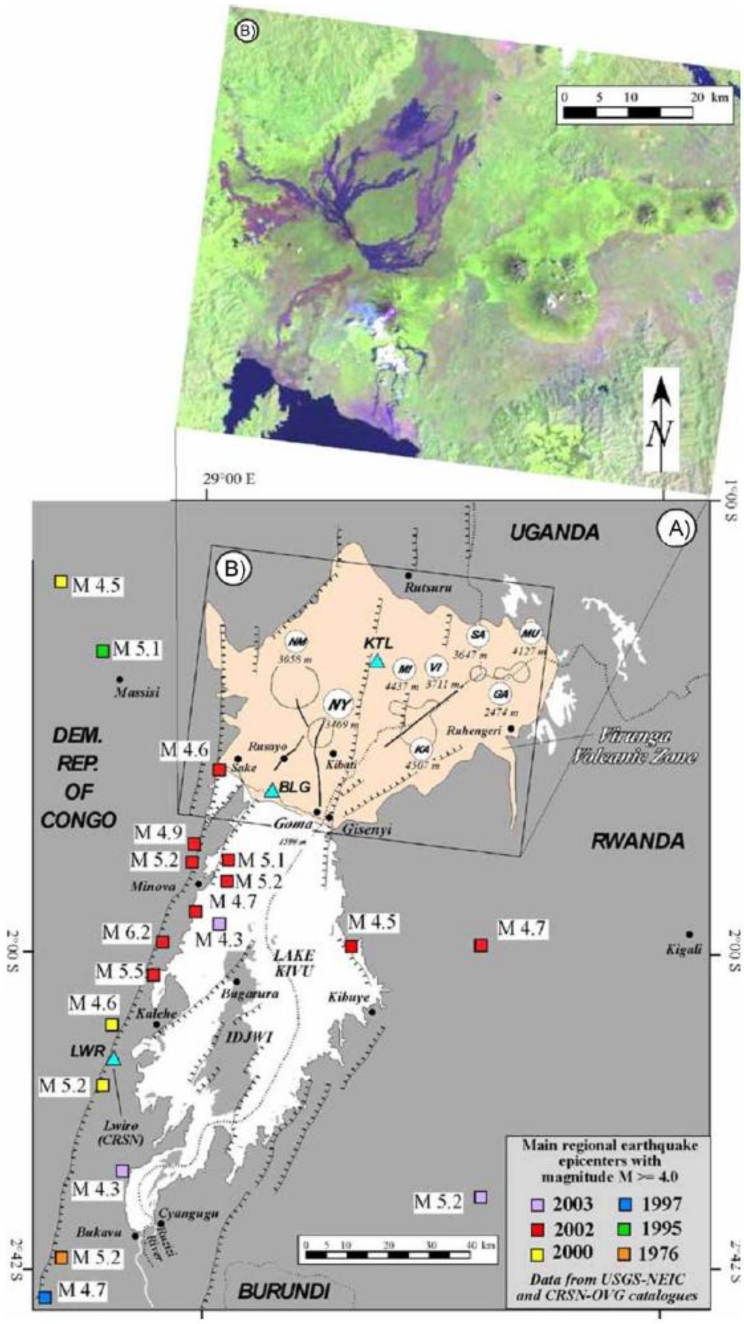

Figure 18 Map of Lake Kivu earthquakes (from Tietze, 2005).

5.7 Potential Consequences

For an immediate understanding of how a plume of carbon dioxide (and hydrogen sulphide) spreads in the landscape, it helps enormously if one has experienced how 'fog' spreads in a theatre. These clouds are a mixture of carbon dioxide and air, and because the cloud is denser than air it sinks and flows along the floor and down into any crevice. It is the fact that these theatre clouds are cold that makes some water condense and it is this water vapour in the cloud that makes it visible (carbon dioxide is colourless and invisible).

From the experience in the theatre one may also directly observe that only mixing with surrounding air can rapidly disperse the cloud. Drafts in the theatre and wind outside in nature are such dispersing mechanisms. On a still day, the cloud will silently spread to all lowlands because carbon dioxide is heavier than air. Only a strong wind has the capability to disperse the cloud and reduce the danger. For example, at Lake Nyos the gas cloud flowed down from the lake through the river valleys below, where it killed people up to 26 km away from the lake, and the last person died the morning after the gas release when concentrations were still lethal even after at least 12 hours had passed.

In the case of a gas eruption from a lake the main differences from a theatre are:

- The cloud is invisible, although the cooling effect of decompression of carbon dioxide is strong enough to condense water vapour from the atmosphere.

- The cloud is immensely much bigger, even in the case of the mildest accident.

- The cloud is not only asphyxiating because of the high concentrations of carbon dioxide, it is also toxic because of the hydrogen sulphide in the cloud
  Carbon dioxide in concentrations above ~15 % can be lethal (that is, even after a 7 fold dilution from the gas released from the lake), and hydrogen sulphide requires a dilution on the order of between 1:10 and 1:50 to survive the toxic effects. This makes the consequences of a potential eruption even more severe in the case of Lake Kivu.

Although methane is flammable, the methane in a gas cloud from Lake Kivu is diluted by carbon dioxide and thus is neither flammable nor explosive. For the consequences of a disastrous eruption, it is actually unfortunate that the cloud is not flammable. If it were, the first fire would ignite the cloud, after which it would spread upwards and not along the ground so that the killing zone would be much more limited.

In still weather, the mechanism by which the cloud will spread is gravity and diffusion. After the initial eruption, the cloud starts out being relatively thick and relatively concentrated around the point of eruption, but given time it will under the influence of gravity become thinner as the cloud spreads out horizontally. Without wind, there is little tendency for the cloud to be diluted. So, as long as the undiluted cloud is thicker than ~1 metre it poses a direct threat to all humans and animals, where it could affect people sleeping on or near the floor.

In the case of an eruption occurring in still weather the entire lake and its lowland surroundings is a dangerous place to be. The bigger the eruption, the larger will be the affected area, and in the case of a catastrophic eruption the potential exists to affect the northern area around Lake Tanganyika as well.

Any sizeable cloud will spread along the valleys - as was also seen at Lake Nyos in 1986. The only chance in this case is for the inhabitants to run uphill to the highest mound or peak nearby. If the eruption happens at night there is no chance to alert the population unless a widespread warning system would be established.

In the case of a wind blowing steadily in one direction, the affected area will change to a downwind zone, the extension of which depends on both the size of the eruption and on the wind speed. The stronger the wind, the quicker the cloud is dispersed to below deadly concentrations. If a warning system is established, this influence of the wind must be taken into consideration.

In terms of warning systems necessary for the gas extraction project, gas sensors must be installed at the platforms and at the power plant on shore where the staff will be instructed in the safety precautions and be taught to respond appropriately to alarm systems. Such carbon dioxide alarms have been used for many years around the world in volcanic regions, and at Lakes Nyos and Monoun, and are robust and reasonably priced. A general alarm system for carbon dioxide for the population at large is more difficult to establish due to the tremendous area of shoreline that must be covered and the costs. In addition, such a regional warning system would need to be coupled with or integrated into a warning system for earthquakes and lava flows (trigger mechanisms and dangers on their own right), and the instructions to seek high ground may be contradictory to the escape routes for lava flows. The Expert Committee recommends that this issue of a regional warning system is solved in cooperation with the disaster prevention programme rooted at the Goma Volcano Observatory (which is part of various development, outreach, and aid programmes funded by several donors such as the World Bank and others).

At a minimum, workers at the power plant can be taught to run for the nearest and highest peak. Similar instructions can be given to the general population along with instructions on how to determine if the lake "has changed" its colour, or there are many dead fish in the lake, or other such indications of a gas release. By such a combination of instructions and a warning system, it may be possible to save a significant fraction of the lives of those living in the dangerous zones. Making this situation worse is the fact that the densest populations are found in the flatland cities at the lake shore, which makes the escape possibilities less clear and simple.

Obviously, the above stipulation of saving lives by people responding adequately to an eruption assumes that proper instructions have been given. An instruction programme would seem to be appropriate, but there is a fine balance to strike between instruction and not creating panic; one of the main difficulties is that the layperson usually does not understand probabilities. An accident scenario with an acceptably low probability in the public domain is soon turned into an imminent event.

5.8 Conclusion for Lake Kivu

There are only three lakes in the world that fulfil all three conditions necessary for accumulating gases and thus causing a risk of eruptions: Nyos and Monoun in Cameroon, and Kivu in Rwanda/Congo.

When one compares the risks in Lake Kivu with that of the two other lakes, the following conclusion may be reached:

The main difference between Lake Kivu and lakes Nyos and Monoun lies in the inflow rate and the resulting concentration of carbon dioxide caused by the size of the lake. In the case of the Cameroon lakes, this inflow rate from volcanic activity below the lakes is relatively large in relation to the quantity of water in the lake, whereas in Lake Kivu this inflow appears to be relatively small to moderate when compared with the size of the lake.

The result is an important difference in that eruptions from the Cameroon lakes are naturally relatively frequent and “purge” the lake before methane can also accumulate. In Lake Kivu, however, the relatively slow accumulation of carbon dioxide allows time for biologic methane production at the bottom of the lake to become the main culprit in the risk of a gas eruption from natural causes. Since this mechanism leads to a much slower build-up of dangerous concentrations, the time between eruptions is also considerably longer and probably on the order of many centuries.

There is a clear danger lying ahead, and something needs to be done. From all points of view (environmentally, economically, and risk monitoring) it is better to carry out the methane extraction project than to just vent the gases from the lake to the atmosphere. To do nothing would be completely unacceptable.

Thus, the main conclusions for Lake Kivu are:

- **Severe volcanic activity may trigger a large catastrophic eruption, discharging most of the gases from the lake. The probability of such an event is very low, and there is nothing that can be done to stop the volcanic events. As time goes by, if gases are removed from the lake then the probability as well as the potential consequences will be reduced somewhat, but they could still be disastrous until most of the gas is removed from the lake.**

- **The most probable of all releases would occur when the gases in the lake have accumulated to saturation 100 - 200 years from now. This would result in a disaster killing many thousands of people, and maybe hundreds of thousands or even millions. The first gas extraction platform will postpone such an event, but alone it will not remove the hazard completely. More needs to be done, and the monitoring programme related to the project will help in clarifying the actions needed. At the same time the gas removal project will alleviates the potential consequences of a low probability seismic or volcanic event triggering the same kind of disastrous gas release.**

- **The project will add to the risk of a minor eruption (see Sec. 5.6) that will impact people nearby (or downwind) on the lake and on the closest shore. Everything possible should be done during the project to minimize the probability of such events, but they can not be entirely eliminated.**

There is no doubt that the increased chance of a minor release due to project operations is offset by the reduction in the inevitable catastrophic gas release if nothing is done. Thus the extraction project is not only desirable, it is mandatory in order to attenuate the greatest risks of gas releases in the future.

In summary, living around Lake Kivu means accepting a higher risk than living elsewhere in the region. If the extraction projects are regulated and monitored well, they will decrease this risk for the population. In the course of the methane extraction it is possible that errors or accidents would increase the risk, which is why the continuous monitoring and regulation is mandatory.

6 Gas Reserves and Method of Extraction

Important quantities of methane are being produced and accumulated in the lake every year. So, the longer it takes to use all of the methane, the more will be available for extraction altogether. But the extractable quantity also depends on other variables. One concern is whether methane concentrations at the 320 metre deep extraction point will diminish, mainly because of lower than expected replenishment rates at the extraction point. Part of the objective of this report is to produce an opinion on the long-term concentrations and reserves of dissolved methane.

6.1 Experience from Lake Monoun

In the situation where extracted water from depth is returned to the surface, as occurs in Lakes Nyos and Monoun, it is possible to evaluate the changes in density gradients and gas content.

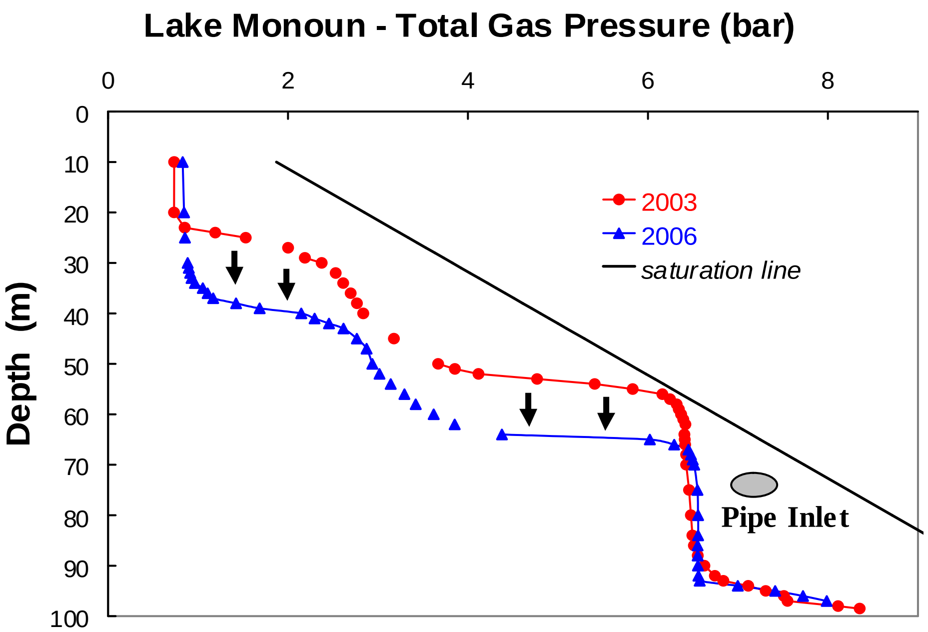

Figure 19 Illustration of changes in gas content and layering in Lake Monoun, Cameroon as water is removed from 73 m depth during controlled degassing. A similar effect of lowering the stratification layers while

maintaining their integrity is predicted for Lake Kivu (data from Kling et al. 2005 and Kling and W.C. Evans, unpublished.

As shown in Figure 19, the degassing at Lake Monoun has lowered the gas contents at critical depths (they were near saturation in 2003 at 55 m), while the layering and density gradients have remained in place. In fact, initially the water extraction will increase the density gradients and thus the stability at depth, because as water is removed from depth it is replaced by water from above which has a lower gas and salt content. The gas content below the extraction point stays roughly constant (or may even increase as is shown in Figure 19) because the gas removed is being drawn from water at and above the pipe inlet. This withdrawal feeds the pipe and a new, lower gas concentration water layer subsides from above. It should be noted also that as water with lower gas concentrations is fed to the pipe, the rate of extraction decreases because it is the gas pressure in the inlet water which drives the force of *exsolution* (formation of bubbles) that lifts water up the pipe without any external energy required.

The amount of gas extracted from the layers below the pipe inlet depends on the concentration gradient across the inlet and thus on the rate of diffusion from below into the pipe. It is quite possible that in order to fully exploit all the gas in Lake Kivu, the pipe inlet may need to be lowered over time or installed at a depth very near the bottom in the beginning.

The evolution of the gas reserve will depend on the balance between natural production and removal. The removal will be well quantified once the plant is in operation, but the gas production will still be uncertain. First there is the uncertainty in the *in situ* methane production in the lake, and second there is the uncertain inflow of salt-laden ground water into the bottom of the lake (the best estimate available from Tietze (1978) is 0.5 to 1 km^3 per year). Although this inflow of water is thought to contain mainly carbon dioxide, it may contain some methane and thus would tend to augment the quantity of gas and increase the size of the exploitable reserves with time. The KP1 plant will extract ~ 0.27 km^3 water per year, which at 320 m depth would contain about 63 million m^3 of methane.

One important lesson from the above Lake Monoun experience is that the lake behaves much like a bath tub that is being emptied by siphoning out the water from a point near the bottom. All water above the suction point will eventually pass through the pipe, whereas all water below the suction point is unreachable and will remain in the tub. During the process of emptying, the gradient layers will sink and the density gradient may sharpen until it reaches the level of suction.

Because the pipe removes a layer of water across the whole lake, which is then replaced by the layer of water above it that is less dense and has less gas, the gas pressure at the inlet pipe will decrease over time. As these lighter waters from above reach the level of extraction (bottom of the siphoning pipe) a new and very steep gradient will gradually develop. This new gradient will, therefore, in a very efficient manner retain any gas that is flowing into the lake or generated at the bottom, and the water below the gradient layer will eventually become saturated so that it would end up causing an eruption.

Even if the volume of gas at the very bottom of the lake triggering the eruption is relatively small, it would start from the very deep layers of the lake and therefore be much more violent in nature and would impact all the layers above it in the lake. In the case of Lake Kivu, even a small fraction of the total 300 km^3 (NPT) of gas would be absolutely devastating and such event must be prevented from happening.

The conclusion is that whenever the economically extractable quantities of gas have been extracted from the lake, a number of platforms must be placed above the deepest point of the lake with a pipe long enough to almost reach the bottom. Then this pipe should be used to vent the remaining gas from the bottom of the lake.

This venting system must function for many years and must be monitored, and that will cost money. The most appropriate solution would seem to be for the concessionaires to pay money into a fund that shall then be used for that purpose much later. We recommend that this concept and the amount of money to be paid should be studied further, and that it be made part of future concession requirements for the platforms to follow after KP1.

Another conclusion from the 'bath tub' behaviour is that withdrawal of gas from depth is effectively "lake-wide", and not "localized" or contained within a given area or zone around the extraction platform. Because there is little or no resistance to water movement horizontally in the lake, and there is great resistance to water movement vertically in the lake, water withdrawn from a specific depth will essentially "drain" that depth all across the lake. In other words, **concessions for extracting gas may well be specified for a given surface area of the lake, but in reality the gas is removed from the entire lake in the depth layer of the inlet pipe. Therefore all concessions should be thought of in terms of the amount of gas removed (or power generated) rather than in terms of the surface area of the lake**.

6.2 Present Gas Extraction Concept

The present gas extraction project as presented by the Developer is based on extracting a quantity of water from the lake through a pipe at 320 metres below the surface in which the bubbles forming provide the driving force for the extraction. The pipe is suspended below a platform; on the platform extracted gas and water are separated and this primary degassed water is returned to the lake at depth.

The gas is then treated further by rinsing with water taken from the surface of the lake. Also this washing water is returned to the lake. In the present configuration, both primary degassed water and the washing water are returned to the lake at a depth of ~ 90 metres below the surface.

The details of this extraction plant and the operating safety as well as the environmental impact onshore are discussed in a separate report prepared by the Independent Engineer. Only the safety and environmental issues related to the water being extracted from and returned to the lake are within the scope of the EC and treated in the present report.

The development is foreseen as follows:

1 A pilot plant will be installed and tested in the course of 2006. If feasible, this test facility will later be converted into a production platform, feeding a small-scale power plant in Gisenyi.

2 Pending a positive outcome of the Pilot Plant testing (in terms of extraction, production, and re-injection principles together with environmental impacts and impacts on lake stability), the first production platform is expected to be designed and installed imminently at Kibuye.

3 After this, it is the plan to continue installing new gas extraction plants offshore and the associated power generation facilities onshore as the demand for power develops.

The key design data for the two platforms are shown in Table 2 and the forecast of primary production variables from the test facility (in t/h) are summarized in Table 3.

Table 2 Key data for two foreseen platforms (note that yearly production corresponds to 73.6 % of pro rata hourly production).

	Gisenyi	Kibuye 1
Water extracted, m^3/h	3650	31152
Methane extracted, m^3/h	1144	9761
Methane extracted, $Mm^3/year$	7,37	62,9
Power produced, MW	4.1	34.9

Table 3 Overall predicted mass balances estimated for the test facility in Gisenyi (in t/h).

	Methane	Carbon dioxide	Nitrogen	Hydrogen sulphide
In extracted water	0.825	11.691	0.164	2.562
In primary degassed water	0.098	9.087	0.011	2.552
In primary produced gas	0.727	2.604	0.153	0.010

For the main gaseous constituents, the overall mass balance for the test facility is expected to be approximately as shown in Figure 20 (flow rates are in kg/h).

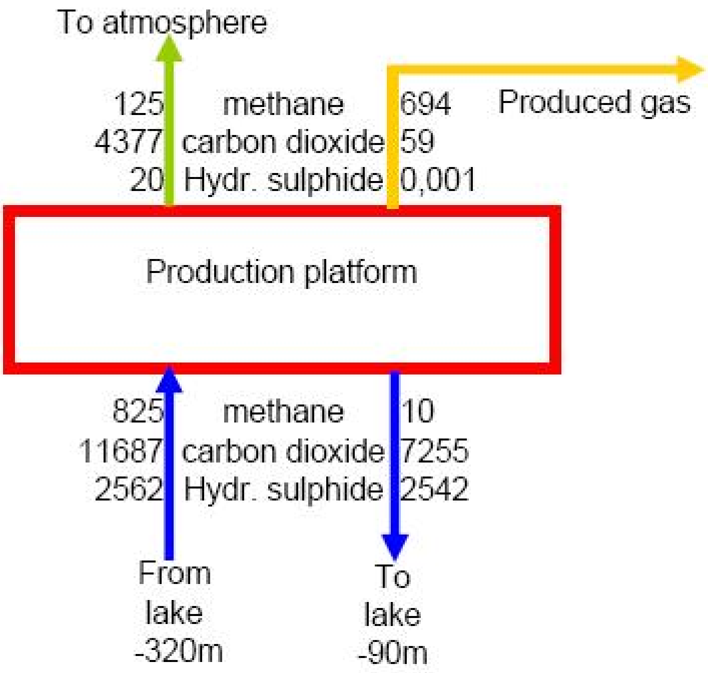

Figure 20 Calculated, approximate mass balance for the test facility (in kg/h).

As it can be seen, by far the largest part of the hydrogen sulphide is returned to the deeper parts of the lake, whereas a significant fraction of the carbon dioxide together with some of the methane is vented to the atmosphere. The molar ratio (carbon dioxide/methane) is 1.97 in the combined gas and vent streams.

The most important observation from the above mass balance is, however, that not all of the methane extracted ends up in the methane gas produced. About 84 % of the methane extracted ends up in the produced gas, 15 % is vented to the atmosphere, and 1 % is returned to the upper part of the lake (below the biozone).

6.3 Water re-injection constraints

When returning the extracted water to the lake, the influence of gravity will ensure that it sinks or rises to a level that has the same density as the re-injected water. This tendency or force is stronger than any density gradient (pycnocline) which acts to prevent vertical mixing. So, re-injection at the wrong depth will invariably result in mixing of layers in the lake, and such mixing must be avoided across the two main pycnoclines in the lake for the following reasons:

- The re-injected water must have a density very similar to the density at the level of the lake where the water is re-injected. Otherwise the water would sink or rise to find its similar density level, and would thus produce mixing which would weaken the stability of stratification

- If the upper pycnocline around -60 to -80 metres is weakened or destroyed, the primary consequence will be mixing between the anoxic, nutrient rich waters below and the oxygenated water of the biozone that has very low concentrations of nutrients. The secondary consequence would be a very steep increase in biological growth followed by probable eutrophication of the lake.

- If the main pycnocline around -260 metres is weakened or destroyed, the primary result would be mixing of the gas rich waters below with the waters above. The direct result is a dramatic increase of gas transport from below the 'lid', whereby the extractable reserves will diminish as the gas diffuses upward and out of the lake. The secondary consequence is, however, more serious. There is a significant risk that the gas laden waters from below could rise to such levels that the gas pressure is over-saturated, bubbles form, and an eruption of the lake would start much sooner than otherwise foreseen.

Briefly, if the upper pycnocline is significantly weakened, the lake would become eutrophic. If the main pycnocline is significantly weakened, there is a high risk of a premature eruption of the lake.

The conclusion is that any production scheme must be made in such as way as to maintain the upper pycnocline (-60 to -80 metres) as well as the lower pycnocline (-260 to -270 metres).

- A third constraint stems from the fact that if water is extracted over a large layer (say several to tens of metres instead of 1 metre), or if water is re-injected vertically into the lake instead of horizontally along the stable density gradient, the resulting jets of water may penetrate and weaken or destroy the pycnoclines. For this reason no extraction or re-injection by any developer can be in any vertical direction. **Both extraction and re-injection can only be allowed in the horizontal direction, and this constraint must be imposed on any developer.** Dane Associates hold the KP1 concession, and they are aware of and respect this constraint. In addition, the horizontal heterogeneity in temperature, salinity and gas concentrations due to extraction may increase rates of double diffusive convection and reduce the magnitude of nearby pycnoclines.

The need to verify that these constraints are complied with is one of the main reasons for the local monitoring around the extraction platform that must be carried out by (and imposed on) any developer. The present concessionaire, Dane Associates, is aware of this responsibility.

6.4 Gas reserves at present

Based on the measurements of methane profiles in the lake and on newer bathymetric data by Lahmeyer (co) and OSAE (co) (1998), Tietze (2005) has calculated the total volume of gas dissolved in the waters of the lake as a function of depth. The result is shown in Figure 21. It is estimated that by 2004 a total amount of some 55 km^3 (STP) methane was present in the main basin of the lake (zone 1).

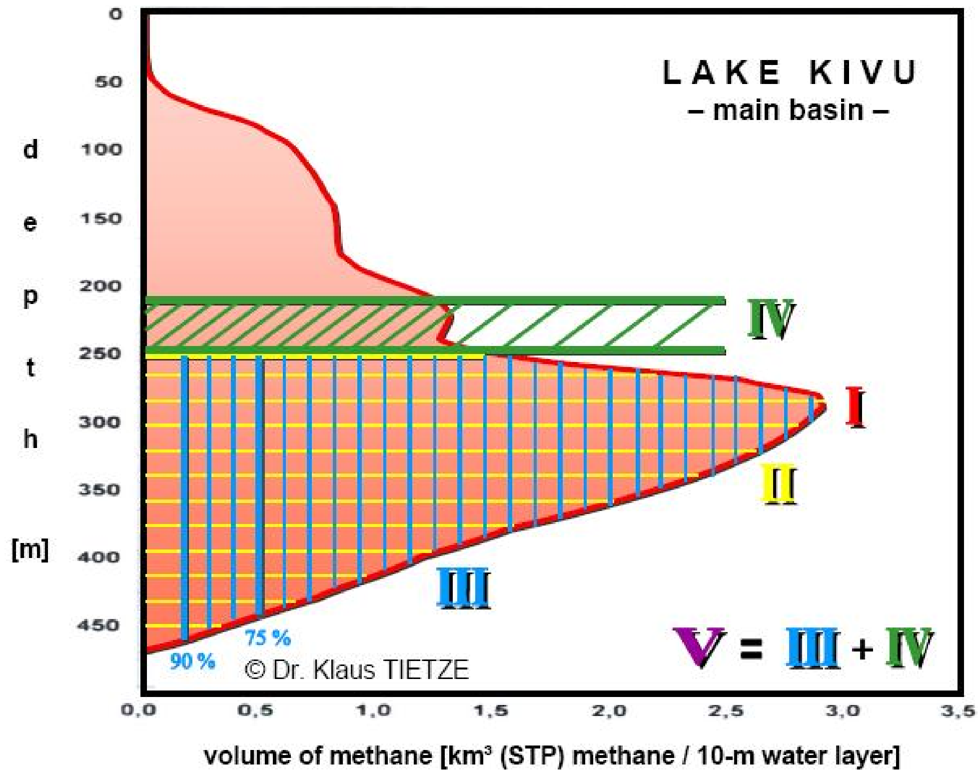

Figure 21 Illustration of the distribution of methane gas with depth (after Tietze 2005).

The majority of the gas (36 km^3) is found below the stability layer at around 260 metres in zone II, but it is also conceivable that the gas in zone IV (6 km^3) may be extracted. The 12 km^3 above zone IV are most probably not extractable.

As has been demonstrated in the section above, only the gas in the water above the extraction point of 320 metres is going to be removed (16 km^3 from zone II plus possibly ~5 km^3 from zone IV), whereas most of the 20 km^3 of gas below this point will remain in place. Although there will be some diffusion of gas from below the extraction depth upward to the pipe, it should be taken as a first approximation that the majority of gas below 320 m will be out of reach from the extraction pipe of the KP1 project. So, the depth placement of the inlet pipe will define the amount of methane that can be extracted. That is, gas that is contained in the lake below the inlet depth of the pipe cannot be "reached" by the pipe.

The site foreseen for the KP1 project (and the Dane Associates' concession area) is in waters with a maximum depth of -340 to -350 m off the coast at Kibuye. At that location it is only possible to extract at a depth of approximately -320 metres. As can be seen above, this location only allows extraction of approximately half of the gas reserves in the lake.

Obviously, this amount of extraction is not sufficient. First of all, any gas volume left at the bottom of the lake would eventually have its methane content rising to dangerous levels. And second, it would be unacceptable not to use as much as possible of the gas for methane production due to the adverse greenhouse effect of releasing methane to the atmosphere.

Therefore, in order to extract the full amount of gas possible in an efficient and safe manner the inlet pipe must be placed near the very bottom of the lake. In practical terms this means that extraction must take place close to the northern shore of the lake and that the electrical grid at that location must be upgraded to take all power produced other than that from KP1. In this way it is also of lesser importance whether the extraction takes place in Rwanda or in D.R. Congo, since it is a technically simple matter to expand the power grid into Goma and possibly further so that this northern region around the lake would also benefit from the cheaper power based on gas from the lake.

Under the assumption of a deep extraction point for the rest of the platforms, the extractable gas reserves at present have been estimated at 36-42 km^3 (STP) of methane, whereas the in-situ reserves amount to 50-55 km^3.

In the following scenarios it is assumed that the pipe inlet is placed near the northern shore and near the bottom of the lake.

6.5 Long term gas reserves

Based on the data published by Schmid et al. (2004, 2005) and simplifying assumptions summarized in Table 5, it is possible to make an approximate forecast of a possible time, when the lake would erupt all by itself in case extraction or other kind of venting would not be started (see Table 4).

Table 4 Concentrations in lake and simplified forecast of outburst.

	Methane	Carbon dioxide	Total
Partial pressure in 2004, MPa	1,55	0,35	1,9
Gas concentration in 2004, mmol/l	18,5	85	
Calculated coefficient, MPa/(mmol/l)	0,08378	0,00412	
Concentration increase from 1975 to 2004, %	17,5	10	
Concentration in 2004, mmol/l	19	85	
Concentration increase from 1975 to 2004, mmol/l	2,830	7,727	
Yearly change mmol/l/year	0,0976	0,2665	
Moles of carbon dioxide per mole of methane			2,7307
Calculated yearly pressure change, MPa/y	0,0082	0,0011	0,0093
Total pressure from gases in 2004, MPa			1,9
Total pressure in water at 340 metres, MPa			3,4
Difference, MPa			1,5
Corresponding to years			162
Calculated year of outburst			**2166**

Based on the known design variables and on assumed - start-up years of new platforms under the concession, it is also possible to evaluate the influence from the extraction strategies. The assumptions used are shown in Table 5.

Table 5 Basic project assumptions for evaluation of development in partial gas pressure with time. The different extraction plants are named 'Kibuye' even if all others than KP1 may turn out to be located elsewhere.

Assumption	Methane, km^3 (STP)
Amount of extractable gas in lake below 260 m, km^3(STP):	35
Amount of methane generated in lake below 260 m, km^3/y(STP):	
- calculated from assumptions in Table 4 and used in forecast	0.171
- maximum estimate by Schmid et al. (2004)	0.250
- minimum estimate by Schmid et al. (2004)	0.125
Amount selected for forecast	0.125
Gisenyi 'pilot plant' yearly extraction	0.00737
Kibuye Power Plant Project 1 yearly extraction	0.0629
Assumptions regarding operation start times:	Year
Gisenyi pilot plant in operation	2006
Kibuye Project 1	2007
Kibuye Project 2	2012
Kibuye Project 3	2020
Kibuye Project 4	2030
Kibuye Project 5	2040
Kibuye Project 6	2050

Based on the assumptions in Table 4 and Table 5 forecasts of the total gas reserves has been shown in Figure 22 as function of time and extraction strategy.

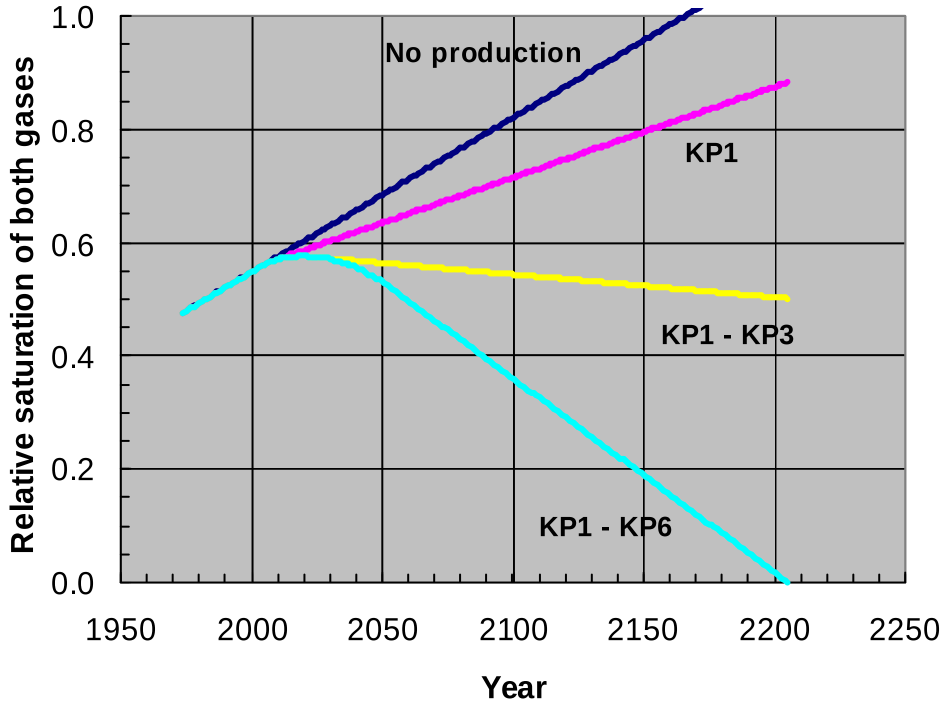

Figure 22 - Calculated development of in-situ methane reserves (km^3, STP) in Lake Kivu as a function of the number of extraction projects (based on assumptions in Table 5 andTable 4).

If the bottom of the lake (below -320 m) remains well mixed, then the above figure would also represent the development in total gas pressure (relative gas saturation at -320 m, dimensionless) that is decisive for the stability of the lake. It so happens that the vertical scale in the above figure is correct for in-situ gas reserves expressed in 100 km^3 of methane as well as for relative total gas pressure (dimensionless number). The relative total saturation of both methane and carbon dioxide is shown because the pressure of both gases together drive the extraction process as well as the risks in the lake.

With the current interpretation of the available data from Lake Kivu, the annual recharge rate is of the order of 0.12 to 0.25 km^3 (STP) methane. This may be compared with the amount extractable under the concession agreement with Dane totalling ~ 0.38 km^3 (STP)/year of methane for all six stations (KP1 to KP6).

From the above curves it can be seen, that establishing one KP1 station is not enough to counteract the natural accumulation of methane and thus to avert the resulting dangers. The calculations show that around 3 stations would be required to arrive at a slow decrease in methane concentration and thus to a slow decrease of the associated risks. Operation of the six stations that is the maximum fitting under the Dane Concession would result in emptying of the methane gas reserves over a period of possibly 200 years. Since the basic data at present are less accurate than desired, so is also the impact of number of stations, but the above curves still illustrates

rather well the orders of magnitude involved. The resulting accumulation of methane generated in the extraction period could be in the order of 20-40 km^3 (STP) of methane, but only the future monitoring programme can confirm such a number; and it obviously also depends very much on the actual number of gas extraction platforms installed and the position of their inlets.

The overall and most important observation is that the gas extraction project goes hand in hand with necessary mitigation measures required to minimize the risks of a natural eruption from the lake.

6.6 Alternative Gas Extraction Scheme?

A potential alternative extraction strategy that might optimize the gas production while minimizing the hazards has been evaluated. Theoretically, the outcome of this strategy would be to maintain the extraction at a controlled rate matching the methane production, and thus ensuring that the extraction of methane for power production could go on much longer than now foreseen.

If the production scheme were to be modified so that the rinsing water is kept separate from the primary degassed water, it might be possible to return the denser degassed water to approximately 275 metres which is just below the peak density gradient at 260-270 metres. In this scheme, the rinsing water would be returned to the biozone; since the rinsing water is drawn from the surface of the lake and therefore is not salt laden, this rinsing water would have very little impact on the biozone. The consequences of such a scheme are:

- The reduction in density from stripping off the methane together with 62 % of the carbon dioxide results in a density reduction of 0.43 kg/m^3. When extracting the water at a depth of 320 metres, it is this number that dictates that the point of discharge must be just below the strongest pycnocline at 260 metres. It is likely, therefore, that this pycnocline would be weakened and as a result more methane would be transported upwards and would eventually be oxidized in the zone between -80 and -150 metres of the lake. Such a loss of methane reduces the total extractable reserves.

- In addition, there is a non-negligible risk of “short-circuiting” between the point of suction and the point of re-injection. In other words, the re-injected water that is low in gas content may be pulled into the pipe inlet, in which case the siphoning would be stopped.

- Because of the weakening of the pycnocline by the re-injected water, it is possible that the bottom of the lake will split into two layers that do not mix. In this case nothing is gained from returning the water to below the main stability gradient, and the end result would be similar to the 'use it all' scenario.

Given this analysis, it must be concluded that a scenario with a moderate production forever is not possible for the KP1 extraction plant. Because

this strategy would be attractive for the future extraction plants at deeper waters, the feasibility of this scenario should be evaluated anew and using data from the monitoring programme on the effects of extraction by KP1 on the lake.

6.7 Improving fish yields?

In Lakes Nyos and Monoun in Cameroon the degassing pipes that remove carbon dioxide gas from the bottom waters also have affected the biozone. The effect has been to bring nutrient-rich water from depth and release it at the surface, where it has stimulated the primary production of algae and decreased the transparency of the water. It is unknown at present whether this increased production in the lakes has been translated into greater fish production, but the possibility exists.

For Lake Kivu, there is also the possibility that releasing some nutrient-rich bottom water at the surface will increase the primary production, and may in turn benefit the fishery of the lake. This potential is dependent on the balance between nutrients diffusing slowly upward from the re-injected water at -90 metres, versus the re-injection weakening or destroying the upper stability layer.

It is probable that the pilot plant at Gisenyi is of such small capacity that even if the re-injection weakened the upper stability layer or if a "hole" was created in the stability layer, the effect would be local and of little consequence to the lake. However, the future main production platforms (including KP1) are of greater capacity and should be prevented from weakening the upper stability layer.

The evaluations in Section 7.2 indicate that the upper parts of the lake are poor in nutrients and that more primary production of organic matter (growth of algae) from a controlled nutrient inflow into the biozone could actually increase the production of fish in the lake. This would be of benefit to the population around the lake, and should be possible without any negative effects such as eutrophication.

Therefore the following is proposed:

1 Allow the pilot platform to re-inject water at a depth of -90 metres.

2 Require the Developer to monitor carefully the influence on the -60 to -80 metre stability layer during pilot test operations at Gisenyi. If the results show no negative effects on lake stability, then allow this production platform to continue into a long-term production phase.

   The results from the pilot plant should be sufficient to determine whether water re-injection at -90 metres can be allowed from KP1, or whether re-injection must be at a greater depth (e.g., -100 to -120 metres) which would maintain the upper stability layer.

3 Encourage a group of scientists to use the degassed water samples from the platform experimentally evaluate whether certain quantities of degassed, nutrient-rich water would be of benefit to the biozone.

In case it should prove to be beneficiary, the Developer could be asked to design the processing system on the future production platforms (starting with KP1) so that an adjustable fraction of the extracted water is returned to the surface of the lake (e.g., between 10-20 metres). The remaining water should still be re-injected below the first stability layer as planned.

In case re-injection of some degassed water into the biozone should prove to be harmful or of no benefit, then all the extracted water on the production platform will continue to be re-injected below the upper stability layer.

If testing of a controlled inflow of nutrients should prove positive to fish production without creating eutrophication, it would be possible to introduce this feature for all future production platforms and for a minimal extra cost. If such an extra benefit can be obtained from the gas production project, it would enhance the acceptance of the projects by the local communities. It is therefore recommended that such testing be carried out during the pilot plant operation.

6.8 Conclusions regarding reserves and production method

It is important to ensure that the risks of an uncontrolled gas release from the lake will not increase above the present level. As soon as possible extraction of gas from the lake should start and it should be brought to such a level that it at least outweighs the annual production or inflow in the lake.

The knowledge of these variables (production of carbon dioxide and of methane) and inflow (of carbon dioxide) is at present uncertain, and hence a monitoring programme should be started as soon as possible.

The initial design of the production plant were based upon data taken by Tietze in the 1970s which indicated the gas concentrations were relatively uniform below 320 m. If the water column below that depth were continuously mixing, then extraction at 320 m with sufficient plants would deplete the lake of the high levels of dissolved gases. The development of a new stability layer around -320 metres in recent years (as can be seen from Figure 8) indicates that the situation in the lake is dynamic and that (at least for many years to come) nothing may be taken for granted. If, for instance, a new stability layer were to develop around -400 metres, and such a layer is evident in Figures 12 and 13, and if the extraction platforms are put into operation more slowly than anticipated, then the risk of eruption from these deeper layers could reach dangerous levels.

These risks are mainly why a lake-wide monitoring programme must continue at least until the whole lake has been depleted of the dangerous levels of methane. Even after having emptied the lake for methane, monitoring should be repeated with intervals of say 50-100 years in order to monitor new increases in gas concentrations. It is even possible that some centuries from now a new gas extraction scheme might recommence.

The combination of active lake dynamics and current data uncertainty imply that the six extraction plants mentioned in this report are probably the minimum number required to maintain an acceptably low level of risk in the lake. The recommended monitoring programmes are necessary prerequisites for determining changes in the lake and for making predictions of potential gas production.

When the profitable extraction of methane comes to an end many decades from now, gas production and inflow will still continue. The monitoring of the lake must therefore continue under some form, and so must the venting of excess gas from the lake. It is therefore suggested that any production platform located in the deepest parts of the lake (i.e., not KP1) should be constructed to eventually serve as a venting system functioning by autosiphoning like in lakes Nyos and Monoun, but in such a way that degassed water will still be returned below the biozone.

7 Environmental Observations

According to the scope for the Expert Committee: "*Although the committee's focus is on human health and safety issues, it has also been considered, which recommendations on monitoring or other relevant issues derived from the Environmental Impact Assessments (EIA) may complement or dovetail with those in the EIA.*"

7.1 Emissions to atmosphere

7.1.1 From Lake Kivu

At present, gases accumulate in Lake Kivu and if nothing is done these gases will be released to the atmosphere in sudden lake eruptions whereas smaller quantities are released by diffusion and mixing. So, in any case these natural gases end up in the atmosphere. Because of the future risk of a gas eruption something must be done, however, and there are two main options:

1 To simply vent the gas to the atmosphere as it is done at Lake Nyos and Lake Monoun. In this case, all methane and all carbon dioxide is vented to the atmosphere instead of the majority of the methane being burned first in an engine and subsequently being emitted as carbon dioxide that has a much smaller impact on global warming.

   In this case, also all the bottom water will be discharged at the surface and will thus have a very substantial impact on the biozone of the lake.

2 To extract and use most of the gas while converting the methane to carbon dioxide in the turbine driving the power generator. Because the greenhouse effect of methane is 20-25 times that of carbon dioxide, the overall environmental effect is very positive. A second benefit is that the renewable methane source is replacing combustion of fossil fuels to generate power.

   In this case, the salt-laden waters from the bottom of the lake will be discharged somewhere below the biozone and will therefore only marginally influence the biozone, as described below. This is also highly preferable to option 1 above.

3 To do nothing and wait for the lake to erupt all by itself, which is unacceptable because of the catastrophic loss of lives that would result. Doing nothing, if averaged over time, would also emit the same quantities of gases to the atmosphere as the less desirable option 1 above.

In all cases, the carbon dioxide and some hydrogen sulphide from the lake will be vented to the atmosphere. In this respect, there is no difference in the long run between the options.

On this basis the clear conclusion is that from the point of view of risks, the environment, and economics, it is far more preferable to produce the methane gas and use it for power production. To do nothing is clearly unacceptable because of the risk, and to vent the lake instead of producing the gas is worse from all points of view.

7.1.2 From Nyiragongo

After the most recent eruption in 2002 the Nyiragongo Volcano, just north of Lake Kivu, is the major environmental hazard in the area. With a renewal of the magmatic activity and its fast evolving dynamics the volcano presents a major direct risk to about half a million people in the area, and a possible major lava flow is one of the serious trigger mechanisms for an eruption in Lake Kivu.

Between November 2002 and November 2004 Nyiragongo Volcano released the same amount of sulphur gas as all other volcanoes in the world. According to the report from the United Nations Interagency Programme (BCPR-UNDP/ISDR/OCHA, Goma Volcano Observatory, 2005) the daily outputs of sulphur dioxide are ranging from 17,000 to 24,000 metric tonnes per day, with peaks up to 57,000 t.

As a consequence, acidic rains destroy crops and polluted rain water is a threat to the population. Due to the prevailing westerly winds in the atmosphere the plume is not directed towards Lake Kivu, but the polluted rain water (mainly sulphuric and hydrochloric acid) may have an effect on the ecology of the lake from runoff water.

The behaviour of the volcano is thus several orders of magnitude worse than any emissions from the lake.

The monitoring programme set up for Lake Kivu should liaise with the volcano monitoring programme based at the Goma Observatory. Finally, as described elsewhere in this report, lava may under certain conditions also trigger a major release of gases from the lake.

7.2 Ecological changes within the lake

Deep lakes in warm regions of the earth typically undergo at least one mixing cycle each year. For this reason, soluble nutrients in the lake would tend to become equally distributed at least once a year. The nutrients are used in biomass production in the biozone and such lakes can have periods with enhanced productivity. In deep lakes like Lake Kivu, dissolved nutrients are not redistributed throughout the lake during the mixing period. Instead, organisms, as they die, or other organic particles are continuously transported from the biozone to the lower parts of the lake, where they decompose and the regenerated nutrients remain at depth and accumulate over time. In Kivu, there is a very small littoral (near-shore zone) and then the bottom steepens rapidly. Hence, when particles settle, a large proportion does go to great depths. . During the monsoon period, in the deeper lakes, upwelling occurs that brings some of the nutrients back into surface waters. The depth of upwelling depends upon the strength of the wind and the magnitude of the upper stability layers. We do not know the depth of upwelling in Lake Kivu, but assume, based on current estimates from the much larger Lake Tanganyika, that it is to depths less than 100 m. Shallow upwelling, combined with steep morphometry of the lake basin, leads to levels of nutrients which are quite low in the biozone of Lake Kivu and production of organic matter and of fish is moderate. The main contributor to nutrients in the biozone of Lake Kivu is rivers and storm water with its content of agricultural and human waste, and these nutrients, once incorporated into organisms, are transported toward the lake bottom when they die.

For the evaluation of the impacts of gas extraction from the lake, it is therefore essential to consider the impacts of transport of nutrients from deep in the water column on the ecology of the upper layer. At present very little is known about the primary productivity in the lake and the fishery is relatively modest. Increased nutrient loading could be advantageous if it led to increases in the fishery, but disadvantageous if it led to eutrophication and a shift in the primary producers to *cyanobacteria* as has been observed in Lake Victoria (Hecky 1993). Cyanobacteria are often inedible by fish and numerous species are toxic. We do not anticipate this fate in Lake Kivu as the relative proportions of inorganic nitrogen to phosphorus is high and phosphorus limitation is most likely. Cyanobacteria are not favoured in this case.

The ecology of the lake is likely changing already due to global warming. Lorke et al.’s (2004) results indicate that the stratification of the upper mixed layer has been increasing. Similar to Lake Tanganyika, this increase could lead to a reduced flux of nutrients into the euphotic zone (biozone) during the monsoon where this transport is at it highest, and thus to a decrease in primary productivity (Verburg et al. 2003). The impact of global warming on the fishery of Lake Tanganyika is not known, but **predictions are that it would decrease fish yield. In the case of Lake Kivu, the introduction of nutrients at depths slightly below the mixed layer could, therefore, be beneficial if the increased supply counterbalanced the reduced fluxes associated with global warming. Thus, this impact of the gas extraction project might improve the local economy and increase the protein available for people in the region.**

It is actually plausible that a controlled transport of nutrients from the lower part of the lake up into the biozone might enhance the production of fish in the lake - without any negative effects from eutrophication. This should be tested by biological experiments in connection with the pilot

tests, and if the expectations should prove to be true, it would require only a very small and inexpensive modification to the extraction platforms to obtain this additional benefit from the gas extraction projects.

The impact of increased productivity on methane production at depth must also be addressed. Most of the methane produced is due to microbial activity. Some of this production is associated with the carbon dioxide from geological sources, and some is due to decomposition of organic matter produced in the upper layer which settles deep into the water column. If the productivity of the lake increases, the flux of decaying phytoplankton, zooplankton, and faecal material to greater depths will increase. Methane production in Lake Nyos has increased as the algal productivity was stimulated by the flux of nutrients into the surface waters. A similar phenomenon may occur in Lake Kivu if large amounts of nutrients diffuse into the surface waters. If several platforms and large amounts of bottom water are extracted for methane production, increased productivity is expected lake wide and methane increases will occur as explained in detail elsewhere in this report.

7.2.1 Observations helpful for assessing ecological change:

Primary production in Lake Kivu is estimated to be 325 g carbon m^{-2} yr^{-1}, which is ~ 1 g carbon m^{-2} d^{-1}. Little is known about the error associated with this value, nor about the productivity variation by season. Measured values from Lake Tanganyika are similar. Melack (1980) measured 0.5 g carbon m^{-2} d^{-1} and Hecky and Fee (1981), based on many more measurements, obtained an average value of 1 g carbon m^{-2} d^{-1}. In terms of seasonal differences in productivity, based on several reports and on the experience from working in Lake Victoria, it is anticipated that nutrients from deeper in the water column will be mixed toward the surface due to the combination of wind and evaporative cooling during the monsoon. This flux of nutrients would initially support the growth of diatoms. When seasonal stratification commenced again following the monsoon, the increased nutrient concentrations are likely to support *cyanobacteria* and other species.

7.2.2 Flux calculations:

Concentrations of nutrients at the depth of extraction are higher than in the upper water column. For instance, ammonia at 320 m is 3700 µmol and soluble reactive phosphorus (SRP) is 177.6 µmol. The introduction of water from depth at -90 m will impact the ecology if the nutrients are subsequently diffused or mixed into the euphotic zone. The flux of nutrients into the euphotic zone can be calculated using two different approaches.

In the entrainment model, all the nutrients that are concentrated at depth will be mixed into surface waters during the combined cooling and upwelling that accompanies the monsoon. To evaluate the effects of entrainment, the concentrations that would occur in the upper mixed layer are computed with and without extraction.

the second approach, uses a model based on turbulent diffusion. The flux of nutrients required to support productivity can be estimated as $F = K_z\, dC/dz$ where K_z is the coefficient of eddy diffusivity and dC/dz is the gradient in nutrient concentrations. The eddy diffusivities from the Wedderburn and Lake Numbers are then estimated (Romero et al. 1998; MacIntyre and Romero 2000; Yeates and Imberger 2004). For this approach, the increased concentrations in the strata from 80 to 90 m are calculated, then allow them to mix to 70 m and further allow them to mix to 50 m.

Entrainment model approach

Using the entrainment model, and mixing all the nutrients between 80 and 90 m into the euphotic zone which are there presently, the concentration in the upper 80 m would be 2.3 µmol SRP and 38 µmol ammonia. Using an estimated extraction rate of 31152 m^3/h at Kibuye (8.65 m^3/s), the increased nutrients in the depth strata between 80 and 90 m are then calculated. Mixing of the nutrients which are introduced into this zone leads to concentrations of 2.6 µmol SRP and 43.6 µmol ammonia respectively. A 13% increase in concentration occurs for one extraction plant assuming such deep mixing occurred. These nutrients would not be observed in the water column as they would be taken up by phytoplankton, however, increases in primary productivity may result.

Eddy diffusivity approach

Following the eddy diffusivity approach, after determining the increased nutrient concentrations between 80 and 90 m depth, the flux between 90 and 70 m and then the flux from 70 to 50 m are calculated. The bais is eddy diffusivities of $1\times10^{-6}\ m^2\ s^{-1}$ and $1\ \times10^{-5}\ m^2\ s^{-1}$, values which span the range for the Wedderburn numbers when winds are $10\ m\ s^{-1}$. The calculations show SRP will be the limiting nutrient (this partly depends on the reactions of P with anoxic and oxic water) and the flux of SRP would at most support a 2 % increase in production. While these increases are low; 6 extraction platforms would increase primary production by 12 %. At that point, the nutrient flux would begin to be important for the ecology of the lake.

The two methods of calculating nutrient flux suggest different outcomes of introducing the recharged water at 90 m depth. With the few existing measurements of primary production (see Schmid et al.(2004) for summary) and the low fish stocks at present, any increase in nutrient flux may be beneficial for the ecology of the lake. These results indicate that monitoring and modelling should incorporate changes to the primary productivity of the lake and the concomitant effects on methane production and fish yields. It is also possible that test releases of high-nutrient water directly to the lake surface by the extraction pipes, coupled with measurements of primary production, could be used to determine if deliberate, long-term enrichment of surface waters would be beneficial to the lake.

7.3 Conclusions on Environmental Observations

To summarize, there are several environmental aspects that must be monitored and might change with the gas extraction project.

1 The impact of released greenhouse gases (methane and carbon dioxide) from the lake will be small in the long term, and beneficial overall. The accumulated methane and carbon dioxide will be emitted to the atmosphere in any case over time as they diffuse out of the lake or are released quickly during a catastrophic event. Therefore the releases during gas extraction are simply operating at a different time scale to release the gases than are the natural processes. In addition, the benefit is that with the use of methane in the power plant a large fraction of the methane formed is burned and emitted to the atmosphere as carbon dioxide, and much less hydrogen sulphide is emitted as well. Because the greenhouse effect of methane is 20-25 times that of carbon dioxide, the overall environmental effect is very positive. A second benefit is that the renewable methane source is replacing combustion of fossil fuels to generate power. Obviously, the power generation will result in emissions of nitrogen oxides, but that would be the case with fossil fuels as well, and the emission limits will be kept below the World Bank emission standards.

2 In the lake, the zones below the surface biozone will be most strongly influenced by the gas extraction. The water below the biozone is anoxic and thus contains no fish or other organisms requiring oxygen, and the extraction will not change the oxygen status of the lower lake.

3 In the biozone there is the potential for impacts on water chemistry and especially nutrients. Because water from great depth (~320 m) and high salt and nutrient content will be re-injected after gas removal to a shallower depth (~90 m), nutrient concentrations will increase at the re-injection depth. The nutrients will then diffuse outward from that point, and upward into the biozone. The magnitude of this diffusion and mixing will depend on the depth to which the nutrients are injected, and on the disturbance to any density gradients (stability layer) in the upper part of the lake. This disturbance must be monitored in the Pilot Plant project; if the re-injection causes the stability layer to break down, any future platforms must re-inject water to a greater depth of ~100 to 120 m, well below the upper density gradient.

4 The impact of nutrient fluxes into the biozone would be to increase biological productivity, which may also be of benefit to the fisheries in the lake. Such increases in productivity were observed in Lakes Nyos and Monoun when nutrient rich bottom water was released at the lake surface by the degassing pipes. In Kivu the nutrients from the Pilot Plant will be released 90 m below the lake surface, where the density gradients and resistance to mixing should impede their movement to the surface waters. This situation should be distinguished from the strong nutrient enrichment (*eutrophication*) that would result if large quantities of bottom water were released directly within the biozone at the lake surface. In such a case, the potential environmental impacts would warrant further study.

5 It is also likely that bacteria living in the depths of the lake will be redistributed by the extraction and re-injection of water. However, it is difficult to distinguish different bacterial "species" that might be replaced or relo-

cated. Even if the bacterial communities were adequately characterized and did shift in composition due to the gas extraction, there are no bacteria listed as endangered or threatened species. The most likely result for lake ecology would be that the transported bacteria would be maladapted to their new environment, and the better adapted resident bacteria would out-compete them and dominate in numbers.

6 Finally, it is likely that small amounts of human wastes or withdrawn bottom water will leak into the lake around the platform. Strong mixing in the surface waters will rapidly dilute these "point sources" of nutrients, and no impacts will be noticed. **It is likely, however, that the platforms will serve as "artificial reefs" for various organisms such as mosses, snails, sponges, and aquatic plants and insects – these organisms may become a nuisance for plant operations, and thus will need to be removed or held in check.**

8 Required and Recommended Activities

An action plan necessary for the safe extraction of methane for power generation is proposed by the Expert Committee. These actions are by and large closely related to maintaining the stability of the lake and its resistance to a catastrophic, uncontrolled release of gas. The action plan is closely tied to the monitoring programmes recommended (see Section 9). In this section the main elements of the recommended action plan is outlined.

8.1 Pilot plant feasibility

A prior statement issued by the Expert Committee on the feasibility of the Pilot Project is restated below, and following that the specific elements of the recommended action plan for the gas extraction projects are explained.

In order to proceed with the gas extraction trials without delays the Expert Committee was asked by the lenders to provide an early statement regarding the impact of the Pilot Plant on the lake stability in order to provide the lenders to decide whether to proceed with the procurement of the Plant.

On 27th of February the Expert Committee issued the following statement (updated slightly for this report):

Based on the information available to us, the Expert Committee does not see any reason why the pilot plant at Gisenyi should cause any disastrous eruption of the lake.

We do, however, recommend that the following conditions for starting the tests with the pilot plant be conveyed to the Developer:

1 *Instruments and other necessary equipment or approaches shall be provided and a monitoring programme shall be initiated prior to any testing, and shall continue during the tests and all results shall be reported after completion of the tests. The details of this monitoring are described in Section 9.3.*

2 *There must exist a way of bringing the pipe to the surface for inspection and/or repair and testing of the subsurface valve. The developer must explain how this will be accomplished.*

3 *When the reports on testing results are available, an evaluation of the results must be performed by an independent body, and the possible consequences for the continued operation of the pilot plant for power production at Gisenyi shall be defined and reported to the lenders. Therefore, the design of the modifications will not be complete and procurement should not begin until these possible consequences have been taken into account by the Developer.*

4 *A HAZOP (HAZard and OPerability analysis) shall be made of the conversion of the pilot plant into a gas production facility, prior to completion of the detailed design of said facility.*

5 *The pilot plant as well as its later conversion into a gas production facility should be treated under the umbrella of the EIA for the KP1 project.*

Whereas the present report is sufficient to conclude that the pilot plant may safely be tested (but not put into continuous operation), the basis for a similar conclusion on continued operation is still insufficient. Also, the means of optimizing the future production and the necessary constraints for continued and long-term gas extraction can not yet be determined. The results of the monitoring programmes will serve to establish the basis for these conclusions.

8.2 Elements of the recommended action plan

The monitoring programmes proposed by the Expert Committee require guidance and coordination. In order to achieve oversight and a clear definition of responsibilities the Expert Committee suggests that the following elements of an action plan for safe extraction of gas from Lake Kivu are considered and implemented:

1 Set up a Monitoring Group that will evaluate the results of the monitoring programme, which is summarized in Section 3.5 and detailed in Section 9. This Group will use the monitoring results to evaluate changes in lake stability and lake ecology. This group should consist of at least one person from each of the following organizations:
– The relevant Rwandan ministry or ministries
– The relevant Congolese ministry or ministries
– The financing organisation(s)
– The independent engineer, who understands the production processes and their relationship and interaction with lake stability variables
– A university or research institution, having an expert in volcanic lake stability.
– A university or research institution, having an expert in limnology including lake physics and biogeochemistry.

The scope and responsibilities of this Monitoring Group would be lake-wide, i.e. on the Rwandan as well as on the Congolese side:
– To define and evaluate all platform monitoring results from the developer's operations

– To evaluate all lake monitoring results and the influence thereof on lake stability, lake ecology, and potential to increase fish yields
– To define, monitor, and update technical conditions for the extraction of gas under the KP1 concession and any other concessions in Lake Kivu
– To define the need for and scope of monitoring programmes and other scientific evaluations as might be required
– To serve as an advisory body reporting to the two governments and to the financing bodies.

2 Establish a local scientific institute in a relevant city in Rwanda, e.g. in Gisenyi, that will be equipped and have technicians trained to undertake the yearly monitoring programme. It shall cooperate with the volcano institute in Goma. The institute and developer(s) will report on the results to the Monitoring Group. Ideally, scientists from both Rwanda and D.R. Congo should be among the staff.

3 Establish a contract with an internationally renowned group of scientists for the first complete baseline study of the pertinent lake variables, guided by the Monitoring Group. The scope shall include provision of the necessary instruments and training under item 2, as well as carrying out the actual base line monitoring with the assistance from the staff at the institute.

4 Once the results from the baseline study and the initial monitoring programme for the Pilot Plant are known, reported, and analyzed, the Monitoring Group should finish defining the scope for subsequent 5 to 10 year interval monitoring studies and enter into a contract with a relevant and capable body, that will also spot check the quality of the local scientific institute. This report shows clearly what is at stake, and it is therefore felt that a certain degree of double-checking is justified.

Obviously many of the above measures will require international funding. The requirements to the Pilot Plant and KP1 described in detail in Section 9.3 and summarized in Section 3.5 must be complied with before permitting either platform to start producing. Ideally, items 1 to 3 shall be completed before starting production from KP1.

9 Monitoring Programmes

9.1 Monitoring strategy

The monitoring programme comprises four main activities:

1. monitoring at the Pilot Plant at Gisenyi for as long as it operates,
2. continuous monitoring at the production facility KP1 at Kibuye (and subsequent facilities),
3. a baseline study of Lake Kivu at large(to be repeated mainly 10 years apart), and
4. Frequent monitoring of basic lake water variables all over the lake.

The key activity is monitoring changes in the physical, chemical, and biological conditions of Lake Kivu. This monitoring will allow the lake stability to be quantified, and will allow determination of the impact from the gas extraction projects on lake stability and thus on the risk of an uncontrolled gas release. The monitoring will also record and help minimize any harmful changes to the lake ecology. At the same time these monitoring data will provide a tool for intervention, optimisation, and regulation of the gas extraction project. The details of the required and recommended monitoring programmes are described below, and include specifications and requirements for monitoring instrumentation in Table 6.

Rationale for monitoring

These main activities in the monitoring programme are dependent on having the necessary and appropriate data from the lake. Previous sections in this report include descriptions of the mechanisms causing the accumulation of gases, the gas reserves, the methods for gas extraction, the lake stratification and stability, and the potential risks pertaining to loss of lake stability. However, a number of assumptions had to be made as the evaluation by necessity is based on the current, insufficient knowledge of the lake. This lack of information includes missing data or data that are of less than desired consistency and accuracy. This knowledge must be improved in order to determine the impacts and risks of gas extraction to the lake and to those living around the lake, to forecast future gas reserves, to guide the day-to-day production operations, and to develop a decision tool for the stakeholders of the project. For these reasons a monitoring programme of sufficient detail and accuracy is of the utmost importance.

Action plan

For practical and economical reasons the monitoring programme will have to be tailored to serve different purposes, with different time frames and different levels of sophistication and extent. The programme will address the Pilot Plant, the subsequent KP1 production facility (together with future addition of KP2 to KP6), other concessionaires, and a baseline or reference study of Lake Kivu *per se*.

The initial sequence of monitoring programmes is

- Pilot Plant monitoring
- Baseline study

and once a firm design basis has been established for the extraction platform (KP1) and that reference characteristics for lake are established the first full-scale platform will be built. When this (or other production platforms) moves to operation

- monitoring of production facilities in the lake simultaneous with a lake-wide regular monitoring programme.

Thus, the monitoring programmes also serve as feed-back to the overallaction plan for the extraction activities in Lake Kivu.

The Expert Committee has offered advice on the practical set-up of the different monitoring programmes but the quality, integrity, and benefit from these depend on considerable funding which currently is not in place. The Expert Committee further recognizes that efforts must be exercised in order to ensure that the different monitoring programmes are compatible, and that the responsibilities for these are clearly defined. The latter can only be resolved in dialogue with the stakeholders; in particular the lenders and the governments (see Section 8).

Monitoring parts

The monitoring programme consists of four parts that should be under the responsibility of different parties:

- A programme that must be carried out on and around any new extraction platform by the Developer, at start up as well as continuously.
- A programme that must be carried out by an independent party in order to continuously verify that the extraction procedures do not weaken the two main stability layers in the lake and to provide reports on lake stability. It is recommended that this activity be carried out by a local institute that should be established for this purpose. The local institute will also monitor for changes in lake ecology, as feedback will be required to assess the quantity of nutrients recharged in the biozone.

- A programme that must be carried out with regular but 5 to 10 year intervals that establishes the gas concentration and density profiles at different locations in the lake, and that at the same time verifies the results of the local institute (results of monitoring plus the accuracy and calibration of instruments and procedures).

- A programme that is recommended in order to verify whether, with a minute modification to the extraction platforms, it is possible to increase the fish stock in the lake. This programme should be carried out once only and as soon as practically possible.

Finally, as described in Section 5.7 it is challenging to establish a warning system for the population at large based on sensors for seismic activity, volcanic activity, and gas eruptions. A general warning system, addressing the above hazards, should only be installed in close cooperation with the relevant authorities (involving both Rwanda and DRC) and the disaster programme operated from Goma Volcano Observatory. Moreover, it should be ensured that this is accompanied by education and training, evacuation drills, and so forth.

The following describes the background necessary to understand the monitoring programmes, the programmes themselves, and finally the general requirements of all monitoring and the specific requirements of needed instruments and equipment.

9.2 Background for the monitoring programmes

In terms of the proposed extraction of gas reserves from Lake Kivu, the most fundamental characteristics of the lake that need to be understood and monitored are the upper and lower stability layers which protect the biozone in shallow waters and confine the gas deposits in deeper waters. Previous work on the lake and the analyses conducted in preparation of this report indicate that the density of the upper stability layer might be modified by the re-injection of water at a depth of -90 m. Because the stability of this layer controls the rate of nutrient movement upward into the biozone, any changes in its structure will potentially impact the primary production in the lake and subsequent rate of methane production at depth.

The second critical stability layer is at ~260 m depth, and serves as a lid to trap the bulk of the gases stored in the lake. Previous analyses and those in this report indicate that this layer is unaffected by wind-induced mixing. However, the near-neutral stabilities above and below this layer indicate that circulation cells may have been active in those regions in the past and may still be active. If changes in the depth of this stability layer occur due to the drawdown of water from the inlet of the gas extraction pipe, then changes may also occur in the stability of the layer and in rates of mixing and gas transport (mainly by double diffusive convection) at its upper or lower boundary. The authors believe this process will be slow since only 3.4 % of the water in the 10 m depth layer below the extraction point of -320 m is removed per year by KP1, but with several plants in operation and over the time scale of 10 years or more, this stability layer, which is at present only 8 m thick, would be drawn down ~10 m. This drawdown may modify the rates of mixing across the main layer, and also the mixing rates across the smaller stability layer which begins at 305 m and continues until 325 m. That is, changes in the layer stability and amount of mixing will affect the amount of the gas reserve that "leaks upward" and is lost from economic recovery, and will affect the resistance to an uncontrolled gas release in the face of some energy input as a trigger.

Given this important role of the two main stability layers, and the potential impacts on their function from the gas extraction, it is critical to first characterize these layers with highly accurate measurements, and then monitor the layers over time. The physical monitoring will be done mainly by the CTD profiles, where considerable attention must be paid to the process of double diffusive convection (see Lorke et al. 2004, Schmitt 1994, and Turner 1973). The chemical monitoring of nutrients and gas pressures will be done through water sampling and *in situ* instrumentation installed. Finally, the impacts of changes in chemistry on the biozone will be monitored by measures of lake ecology, including the biomass and production of algae, which could potentially impact the lake fishery.

The role of modelling

Although many of the important lake characteristics can be measured in real time and are relatively easy to interpret, the dynamic nature of the lake is quite complicated and requires models to improve our understanding or to make predictions of future conditions. For example, internal waves are likely to affect the upper stability layer, especially during the monsoon season, and these waves have the potential to increase mixing. This mixing may increase the amount of nutrients injected into the biozone, which in turn may stimulate growth of algae. As these algae die and sink to the bottom water, the carbon in their cells is used by bacteria to generate more methane and replenish the deep water gas reserve. Thus we have an inter-connected series of events that cannot be understood by simply monitoring each individual process, but that must be combined into a model that examines the interactions of processes in initially a conceptual formulation and eventually in a mathematical representation.

Perhaps the most important role of modelling is in the integration of many pieces of information into a useful prediction. In the example above, it would be important to project into the future the increased generation of methane in the lake for use in determining the number of extraction platforms that could be supported. In addition, it is likely that small changes in the stability layers even due to natural events will alter the time and length scales of double diffusive convection, and the stability or rate of gas loss across the lower layer. Monitoring these changes will detect any rapid or dangerous shifts, but modelling is required to look into the future and recognize the potentially large, eventual impact of an initially small deviation in lake structure or chemistry. Therefore it is recommended that modelling be used in conjunction with monitoring in order to insure the safe and efficient development of the gas reserves at Lake Kivu.

9.3 Developer's monitoring programme

The Developer must record a number of production variables onboard the platform and must monitor that there is no significant vertical disturbance in the lake as a consequence of the extraction and discharge activity:

9.3.1 Monitoring onboard platform

During the testing of the prototype, as well as of any other extraction platform later on, the following shall be tested and witnessed by a third party prior to start of any production test:

1 Send a signal to close the sub-surface valve and observe that flow stops.

2 Cut power (hydraulic or otherwise) to the subsurface valve and observe that it closes upon failure of signal and that the flow stops.

During test operations, measure and report the following (a third party shall be given the possibility to witness by being invited in due time):

3 Demonstrate that the density of the re-injected water is sufficiently similar to the *in-situ* density at the re-injection point to prevent major upwelling or downwelling of the re-injected water in the lake. Data obtained from profiles in the lake (see below) will be essential for the evaluation.

4 Controllability (turn-down ratio) of extracted water (maximum and minimum controllable flow rate).

5 Hourly flow rates as well as daily, monthly, and yearly total quantities of extracted water, washing water, re-injected water, produced gas, and vented gas. Hourly rates and daily quantities are required for the first two months of initial operation only.

6 Monthly averages of: Molar composition of produced and vented gas (methane, carbon dioxide, hydrogen sulphide, and nitrogen),salinity, conductivity, pH, temperature, and density of re-injected water and of washing water.

Among the above operating variables on the platform, the items 1 and 2 shall be witnessed once a year in order to ensure that the shut-down procedures will indeed function in an emergency. Items 3 through 6 shall be done continuously and shall be reported to the relevant parties (as defined elsewhere) once a month except for any data that are automatically transmitted.

9.3.2 Monitoring in lake

In order to assess the impact of gas extraction on the lake in real time, and to provide a more accurate forecast of the impacts, much information about the lake is required. In fact there is a real dearth of information about the lake because very few studies with very few data currently exist. The critical need is to develop a monitoring programme for the lake to provide information on lake stability and to guide shut-down of the extraction process if degradation of the two main stability layers develops. In addition, the monitoring data can be used in conjunction with models to forecast potential negative changes in the stability of the lake and increasing danger to inhabitants around the lake caused by the gas extraction, or caused by the natural build-up of gas in the lake bottom. Finally, a monitoring programme is necessary to insure that the lake ecology is not harmed by the gas extraction process.

Given this background, the key issue is to monitor the vertical water movement by CTD profiles of the lake as described below. The following variables must be measured in the lake in the vicinity of the pilot plant platform and any new platforms that are installed:

1 Conductivity, temperature, depth profiles taken as close to the re-injection pipes as possible, and every 25 m away from the re-injection pipe until no further disturbances in lake density (temperature and conductivity) structure are noted.

2 Depth profiles of total gas pressure in the lake near the platform and at distances as above to make sure that horizontal gradients in gases are minimal as their changes, along with temperature and conductivity, could trigger additional double diffusive convection.

3 Installation, use, and upkeep of a meteorological station on the platform which measures at least air temperature and wind speed and direction (One station at the pilot plant offshore Gisenyi, and one offshore from Kibuye).

4 Measurements of total nitrogen and total phosphorus in surface water (~2 metres depth) and of total nitrogen and phosphorus, and total dissolved inorganic nitrogen and phosphorus in water re-injected to ~90 m.

5 Measurements of light penetration into the lake (Secchi depth or light meter with underwater sensor).

In the beginning of platform operations, items 1, 2, 4, and 5 must be carried out prior to starting the pipe flow. After starting the (test) production, these measurements should be carried out once a week. Later on, once a month will probably suffice, but the frequency depends on the findings during the first month and should be agreed upon with (and approved by) the Monitoring Group once these data are available.

9.4 Baseline studies

Further to the above continuous monitoring, baseline studies should be carried out before any real production starts in the lake. This could be after the pilot tests, but before using the pilot installation at Gisenyi for continuous production, or before starting up the KP1 platform (whichever comes first).

The justification for these baseline studies is that very little is known about the true concentrations and amounts of gas throughout the lake, about the density structure and stratification in the lake, and about the lake productivity and ecology. In order to make any firm conclusions about how the gas extraction is affecting the lake and the risks of an uncontrolled gas release that could kill thousands near the lake, the current or “baseline” conditions must be established as a point of reference. Once this baseline is established the continuous monitoring at the platforms will detect any dangerous changes in the lake, or any changes that will impact the reserve of gas that can be exploited from the lake. However, because the baseline survey gives a synoptic, lake-wide picture of the state of the lake, it should be repeated at regular intervals. This updated picture will ensure the correctness of the monitoring and modelling by the local institute. The suggested time frame for this would be to repeat the 2006 baseline study every 5 years until 2016, and then every 10 years probably continuing until all gas has been extracted from the lake.

The baseline study consists of a repeat of the above continuous measurements, only at more locations in the lake, plus some additional measurements such as determining not only the total dissolved gas pressures but also the concentrations of individual gases such as methane and carbon dioxide. The measurements (see Table 6) should include the following at all positions (from a boat that has its position in all three dimensions determined with precision):

1 Conductivity, temperature, depth profiles (with oxygen, fluorescence, and pH).

2 Depth profiles of total gas pressure.

3 Measurements of light penetration (Secchi depth and light meter and underwater probe.

4 Measurements of algal biomass as estimated by concentrations of chlorophyll *a* or an equivalent method (e.g., algal cell counts and biovolume)

and of the following special measurements (at all stations):

5 Density profile, measuring *in situ* density every 10 metres

6 High resolution conductivity, temperature, depth profiling with a profiler also capable of measuring shear. This profiler will be essential for quantifying the enhanced mixing due to double diffusive convection.

7 Depth profiles of concentrations of dissolved methane and carbon dioxide every 10 metres.

8 Depth profiles every 10 metres for major ions in the water, and nutrients including total nitrogen and phosphorus, total dissolved nitrogen and phosphorus, and inorganic nitrogen (NH_4 and NO_3) and inorganic PO_4.

9 Measurements of primary production in the surface waters (3 depths) using the oxygen change method or an equivalent method (e.g., ^{14}C).

In addition, if required:

10 Bathymetry of the lake. We recognize that the Government of Rwanda has recently conducted a bathymetric survey of the lake, and the raw data from this survey must be made available or the survey must be re-done.

The sampling stations will include the sites of production platforms (two for the initial survey), and 4 additional locations roughly in the northern, central, and southern parts of the lake plus one at the deepest point of the lake. The station locations will be similar to those of Tietze (1978) for comparability (final decisions on stations will be made in conjunction with the Monitoring Group). The Kabuno Basin, forming the North-Western part of Lake Kivu, has high concentrations of carbon dioxide and must be sampled to assess the risk to people in the region. Primary productivity will be measured in pelagic and inshore waters at the northern, central, and southern portion of the main basin. Item 2 (total gas pressure) should be monitored once in the three other separate basins, and any further monitoring here would depend on the results.

9.4.1 Modelling

The data from the real-time meteorological and temperature measurements as well as from weekly CTD profiles can be used as inputs to the model of lake hydrodynamics, biogeochemistry, and productivity described above. The one-dimensional hydrodynamic model will be linked to real-time variables on withdrawal and re-injection rates of constituents, and other aspects of the functioning of the production plants. Data from the CTD profiles can be used to characterize the double-diffusive structures deeper in the water column and their impacts on mixing rates deep in the water column. The modelling effort will thus enable the effects of withdrawal rates on density, methane production, and biozone productivity to be followed in real time, and can be used to make predictions over time scales of decades. Modelling will also enable appropriate decision making regarding the number of future plants, the depths from which gas should be extracted, and the depths to which the bottom water should be re-injected. The modelling should be carried out by the local institute in association with the Monitoring Group and other scientists, and should be updated at least monthly.

As an initial recommendation, data from the baseline and continuing studies should be used to calculate critical diagnostic terms such as the Wedderburn and Lake numbers, coefficient of eddy diffusivity, and density ratio and other variables used to quantify double diffusive convection and be used in a model. The model should initially be a one-dimensional formulation (such as the Dynamic Reservoir Simulation Model, DYRESM, or a similar well-referenced and widely used model) that considers the rates of extraction of water and subsequent changes in density on lake stability particularly with respect to the upper and lower stability lids. The model should also include estimates of the effects of geothermal heating on density stratification, double diffusive convection, bubble plume formation, and mixing at the upper and lower density interface.

The model should be linked to processes at the gas extraction plant via extraction and re-injection rates of gases, salts, and nutrients. With appropriate tuning the model will predict if the re-injection strategies will disrupt the lake stability over time. In addition, the model output should include nutrient fluxes such that primary production and methane production can be assessed or predicted via a mass balance approach based on the number of power plants. This latter component will enable evaluation of the different recharge strategies with respect to improvements or degradation of the lake environment, and the potential for changes in productivity in the lake (which leads to impacts on fisheries).

9.5 Continuous lake monitoring programme

Because of the inherent risks involved in changing the structure and composition of Lake Kivu, there is a need to continuously for a third party to verify the impacts of gas extraction by the different plants (initially the Pilot Plant and KP1). This would be the role of the local scientific institute. In addition, the monitoring will evaluate the lake environment to determine if the plants are inducing eutrophication of the biozone, and whether conditions are changing in a way that would enhance the fisheries. It is suggested that this programme be carried out mainly by a local institute (details are defined in Section 8.2). Most of the measurements are identical or similar to those required for the Pilot Plant, and the programme should comprise the following (twice a year, dry and monsoon season) at all positions (from a boat that has its position in all three dimensions determined with precision):

1. Conductivity, temperature, depth profiles. CTD for lake sampling will be augmented with fluorometer, oxygen sensor, and pH sensor.

2. Depth profiles of total gas pressure.

3. Measurements of inorganic nutrients from the surface to the re-injection point at 10 m intervals. These include ammonium, nitrate, soluble reactive phosphorus, and silica.

4. Measurements of total nitrogen and phosphorus, and total dissolved nitrogen and phosphorus in surface water (~2 metres depth) and in water re-injected to ~90 m.

5. Measurements of light penetration into the lake (Secchi depth and a light meter with an underwater probe).

6. Measurements of algal biomass as estimated by concentrations of chlorophyll *a* or an equivalent method (e.g., algal cell counts and biovolume) at the same depths as the inorganic nutrients.

7 Measurement of primary productivity in the lake using the oxygen change in light-dark bottles or an equivalent technique.

The following continuous monitoring based on fixed installations should take place:

8 Installation, use, and upkeep of a meteorological station on the platform which (as a supplement to the station installed and maintained by the Developer) measures surface water temperatures, relative humidity, rainfall, and net radiation. Data will be relayed via radio to the local institute for upload to the web.

9 Installation and use of a combined thermistor-conductivity mooring to determine the internal wave response of the lake and to calculate the degree of mixing near the upper stability layer. The mooring should be attached to or near the platforms, with one at the Gisenyi pilot plant and one at KP1. Data will be obtained hourly and relayed via radio to the institute where it will be uploaded to the web.

Sites will include the same sites as for the baseline survey

Even after gas production ceases, items 1 and 2 should continue on a yearly basis at the deepest point of the lake in order to closely follow new accumulation of gases and the resulting increase in gas pressure and in risks in the lake.

9.6 Improvement in the lake fishery

As has been described in Sections 6.7 and 7.2 there is a possibility for increasing the number of fish in the lake by releasing controlled quantities of bottom water directly into the biozone. The risk involved is adding surplus nutrients that could result in the blooms of noxious blue-green algae instead. At present, fish stocks in the lake are low due to low algal biomass and correspondingly low biomass of zooplankton, both of which fish eat. In order to verify the potential of improvements in fish stock without negative consequences, it is recommended that as soon as possible, and hopefully in connection with testing of the pilot plant, biological tests are made based on samples of degassed water obtained from the pilot plant operation.

This testing programme will comprise:

1 Nutrient enrichment experiments to quantify enhancement of phytoplankton growth due to addition of bottom water, and to determine whether species composition shifts. These experiments will be conducted in cubitainers using ambient concentrations of inorganic nitrogen and phosphorus and concentrations up to those anticipated if all the water from depth were reinjected into the biozone.

2 Because over half of the species of fish in the lake are zooplanktivorus, similar experiments should be conducted to assess the affects of changes in

algal biomass and diversity on the growth and species assemblages of zooplankton in the lake.

3 Based on existing data of the physiology of tropical fish (representative of the fish in Lake Kivu), temperatures in the lake, and on results of the algal and zooplankton experiments, a bioenergetics or individual-based model can be constructed to help predict the likely outcome of increased growth in lower trophic levels on fish production.

9.7 Specifications and requirements for monitoring and instruments

There is a very distinct need for comparable and accurate data based on the monitoring programmes outlined above. Without such requirements of the data collection, it will not be possible to understand or predict changes in lake stability, or to accomplish a controlled intervention and gas extraction to prevent a disastrous eruption which would have catastrophic consequences for the inhabitants near the lake and the economy of the involved countries.

For each of the monitoring and measurement programmes there are several *Universal Requirements:*

- Equipment to be used is commercially available or sufficiently referenced (in refereed scientific or engineering journals) and easily constructed.
- Equipment to be used is accurate and precise enough to make robust comparisons over time (including with prior data) and thus to make viable conclusions on changes or dangers in the lake (see Table 6). Equipment must be re-calibrated at intervals indicated by the manufacturer.
- Precise determinations of sampling depth for all variables are required and extremely important, especially in zones of steep gradients in the lake. This requirement will necessitate the use of boats with sufficient power, size, stability, and emergency equipment to be safe on the lake.
- Precise determination of lake level (using land-referenced GPS) is required for each sampling to correct for changes in lake level that may affect the "relative" depth where samples are taken.
- Sampling and measurement techniques should be made in conjunction with local personnel and a local institute, and appropriate training should be provided.

In Table 6 the requirements in terms of accuracy, resolution, and reliability (stability of the instrument over time), the location and frequency of measurements, and the extent for the different monitoring programmes is summarized.

Table 6 Details of variables to be measured in monitoring programme.

Instrumentation	Station	Accuracy, Precision, Stability	Minimum Frequen[cy] of sampling
1. CTD - Conductivity, Temperature, Depth instrument (2 instruments required as backup is essential)	Gis1, KP1, Baseline	See specifications on individual sensors below; 4 Hz sampling rate; casing rated to exceed 500 m depth; all sensors rated to 500 m depth	Daily profiles of full w[a]ter column when pipe [i]s first started, Weekly thereafter
Temperature Sensor		0.001°C accuracy, 0.001°C resolution, 0.002°C stability (recalibrated following manufacturer's recommendation); Response time 0.07 sec at 0.5 m/s fall speed or faster. 2nd unit should also have a fast response FP07 thermistor.	
Conductivity Sensor		0.0003 Siemens/m accuracy, 0.00004 S/m resolution, 0.0003 S/m/month stability; requires pumping	
Pressure		0.1 % of full scale, 0.004 % of full scale/month; calibrated for maximum resolution in 500 m depth	
Fluorescence		0.02 µg/L and 0.05 NTU turbidity, 12 bit resolution digital. 1.2 mV analogue	
Dissolved Oxygen		2 % of saturation; calibrated for each deployment	
pH		0.05 pH unit accuracy and precision; calibrated for each deployment	
2. Thermistor and conductivity moorings	KP1	Sufficient for one site with loggers every 20 m	Continuous with real time or telemetered ou[t]put; output in 5 minute[s] averages
Conductivity and temperature loggers Pressure on loggers every 100 m.		Specifications as for T and C sensors above; capability to transmit data via an inductive modem or serial interface for telemetry applications. Battery life 5 years.	
3. Meteorology Station	Gis1, KP1	On lake with data telemetered to shore and with capacity to upload to the web. All sensors compatible with Data logger described below,	1 minute sampling, ou[t]put of data in 5 minute[s] averages
Wind Speed and direction		Equivalent to R.M. Young 03001-L Wind Sentry Anemometer -- Range 0-50 m/s, accuracy 0.5 m/s and threshold 0.5 m/s.	

Instrumentation	Station	Accuracy, Precision, Stability	Minimum Freque[n...] of sampling
Air Temperature and Relative Humidity		Equivalent to HMP45C-L Temperature and RH probe from Campbell Scientific	
Net Radiation		Equivalent to CNR1 Net radiometer with incoming and outgoing short and long wave radiation	
Photosynthetically Available Radiation		Equivalent to Licor LI190SB Quantum Sensor (measurement waveband 400-700 nm)	
4. Data Logger *Used for meteorological station, and potentially for thermistor chains and gas pressure probe*	Gis1, KP1	Equivalent to Campbell CR23X in terms of types of inputs, scan rate, and potential for telemetry but need capacity for additional sensors. (Campbell CR1000)	
5. Microstructure Profiler	Baseline	Shear based (specifications equivalent to VMP profiler of Rockland Instruments.)	Baseline studies to ass[...] mixing from double di[...] fusive convection.
6. Total Pressure of Dissolved Gases *Pressure transducer coupled with gas-permeable probe*	Gis1, KP1, Baseline	Equivalent to KPSI 700 Transducer; accuracy 0.05% full scale; depth rated 500 m; pressure rated 20 bar; gas permeable probe following Evans et al. 1993, Applied Geochemistry 8:207-221 (or equivalent).	Weekly water column profiles after pipe start[...] Monthly profiles of thereafter
7. Dissolved gas concentrations	Gis1, KP1, Baseline	Accuracy of 5%; precision of 3%	Once as each platform starts operation; Durin[...] each Baseline study
8. Major ions and nutrient concentrations	Gis1, KP1, Baseline	Ca, Mg, Na, K, Fe, Mn, HCO_3, SO_4, Cl, total nitrogen and phosphorus, total dissolved nitrogen and phosphorus, silica. Baseline study – NH_4, NO_3, PO_4 in addition to the above. All accuracy of 5%; precision of 3%	Yearly beginning with platform operation; Ba[...] line at multiple sites a[...] nutrients seasonally (monsoon vs. non-monsoon conditions)
9. Primary Productivity	Gis1, KP1, Baseline	*In situ* incubations using oxygen change or equivalent method; precision 10%	Seasonally (monsoon, non-monsoon) at insho[...] and offshore sites
10. Algal Biomass	KP1, Baseline	Measurements of chlorophyll *a* or an equivalent measure (e.g., cell counts or biovolume); accuracy 10%.	Biozone profiles seaso[...] ally (monsoon, non-monsoon)

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