

# PRELIMINARY REPORT ON THE JUNE 2012 FIELD EXPEDITION TO LAKES NYOS AND MONOUN, CAMEROON



*Japanese-Cameroonian SATREPS Project on Safety, Rehabilitation, and Development of the Lakes Nyos and Monoun areas in Northwest Cameroon. American participation by the U.S. Geological Survey and the University of Michigan*

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## SUMMARY

In 1984 Lake Monoun released carbon dioxide gas that killed 37 people, and in 1986 Lake Nyos released a burst of gas which killed over 1800 people. Scientists and engineers have been working since the Nyos disaster in 1986 to safely remove the gas from these lakes and make them safe.

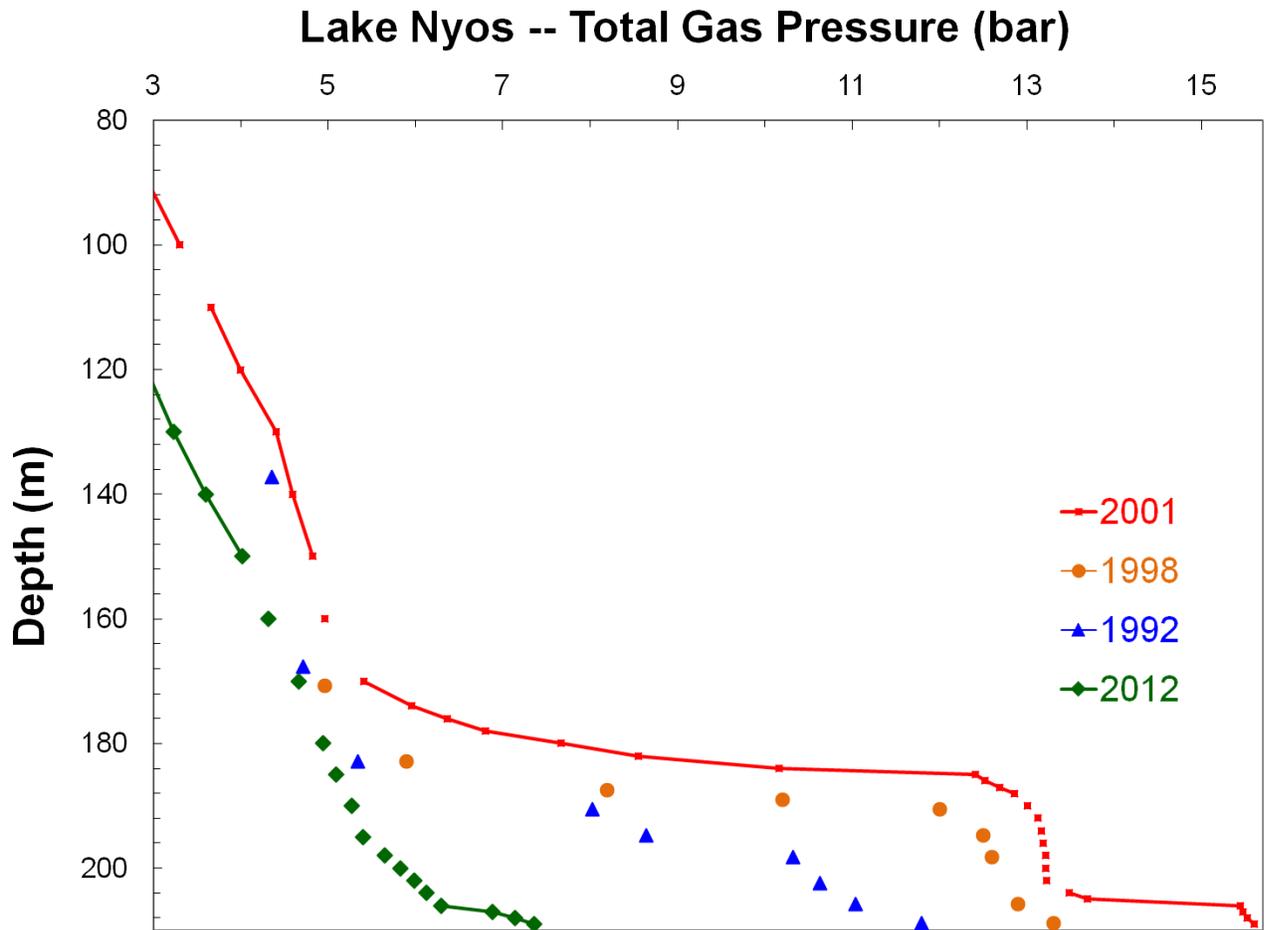
As part of the 5-year SATREPS project funded by the Japanese government (JICA, JST) and supported by the Cameroonian government (MINRESI, IRGM), American scientists Bill Evans (USGS) and George Kling (Univ. Michigan) traveled with Japanese and Cameroonian scientists to Lake Nyos from 1-10 June 2012. Here we provide a brief report on our preliminary findings.

- (1) We installed a floating platform on Lake Nyos to measure basic climate variables such as air temperature and humidity, wind, and solar radiation. Sensors were installed to monitor the water temperature, salt content, and the pressure of dissolved gases (carbon dioxide, CO<sub>2</sub> and methane, CH<sub>4</sub>) at two depths in the lake (Figure 1).
- (2) Measurements of the total gas pressure in the lake showed that the degassing operation is steadily reducing gas amounts in the bottom of the lake. The gas pressure at the deepest part of the lake has been reduced by ~2.5 times from a maximum content in 2001 when the first pipe was installed (Figure 2). The total CO<sub>2</sub> in the lake has been reduced by 40% since 2001, from ~710,000 to 425,000 metric tons (Figure 3).
- (3) The gas concentrations in Lake Monoun are now negligible – the degassing operation is complete in this lake. In 2013 the team of scientists will return to install a climate monitoring station in Lake Monoun similar to that installed in Lake Nyos in order to verify that the gas concentrations in the lake remain low and safe.
- (4) Operations have begun at Lake Nyos to strengthen the weak natural dam impounding the upper 40 m of the lake (supported by the EU). This strengthening will reduce the danger of the dam failing and creating a flood that could reach into Nigeria and affect up to 5-10,000 people below the lake.

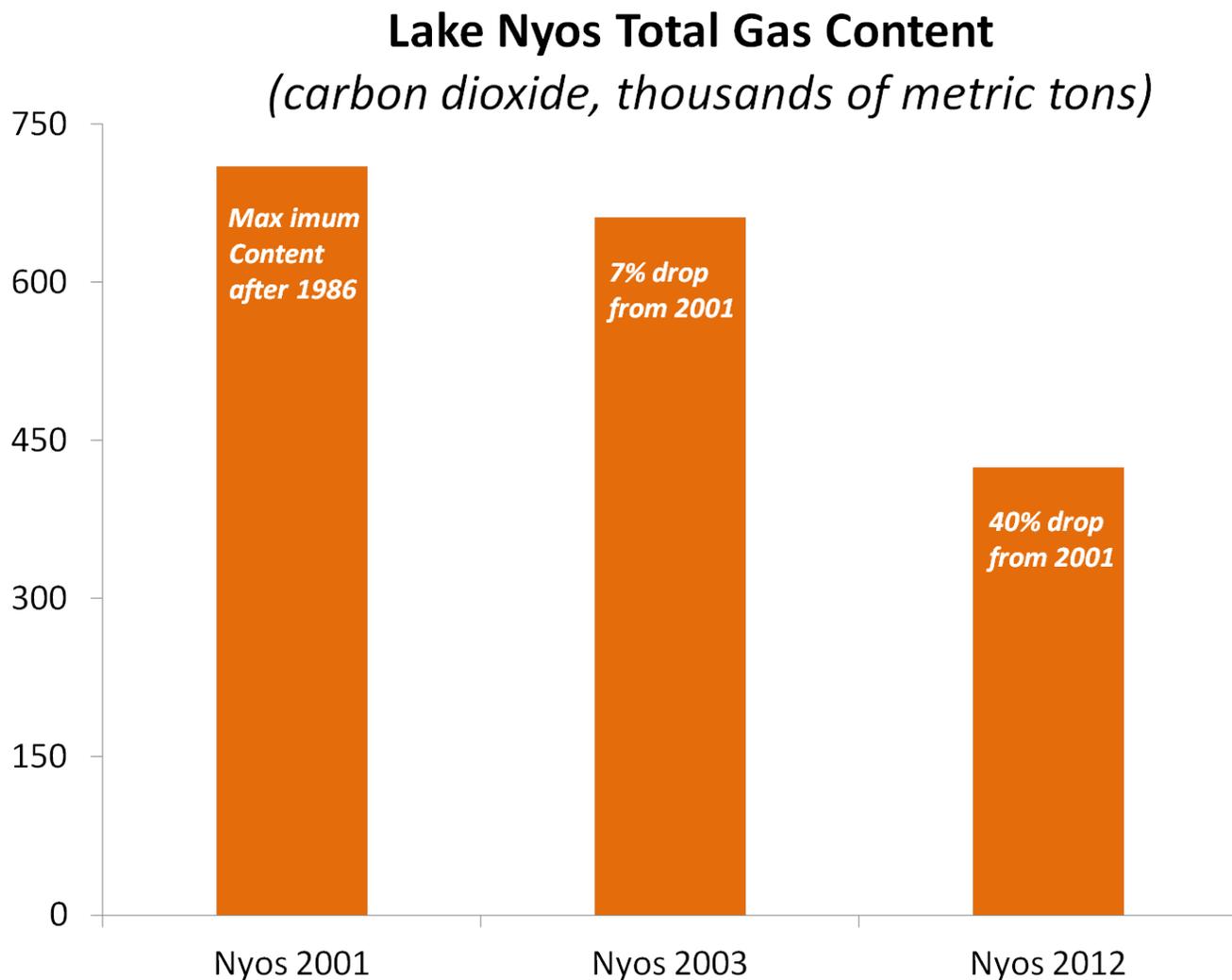
**Figure 1. Climate monitoring station installed at Lake Nyos.**



**Figure 2. Profile of total gas pressure (CO<sub>2</sub> plus CH<sub>4</sub>) in the bottom waters of Lake Nyos. The gas pressures increased from 1992 to 1998 to a maximum in 2001 when the first degassing pipe was installed. In June 2012 the profile shows the gas pressures at the bottom of the lake have been reduced by ~2.5 times from the maximum in 2001.**



**Figure 3. Total amount of CO<sub>2</sub> in Lake Nyos in 2001 (maximum content after the 1986 gas disaster) was reduced by ~ 7% by 2003 with the pipe installed in 2001. Two more pipes installed in March 2011 have further reduced the gas content to 40% of the maximum held in the lake in 2001.**



# TECHNICAL REPORT ON THE JANUARY 2006 FIELD EXPEDITION TO LAKES NYOS AND MONOUN, CAMEROON

*Follow-up Report of the U.S. OFDA Technical Project, Cameroonian Nyos-Monoun  
Degassing Program (NMDP), January 2006.*



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## EXECUTIVE SUMMARY

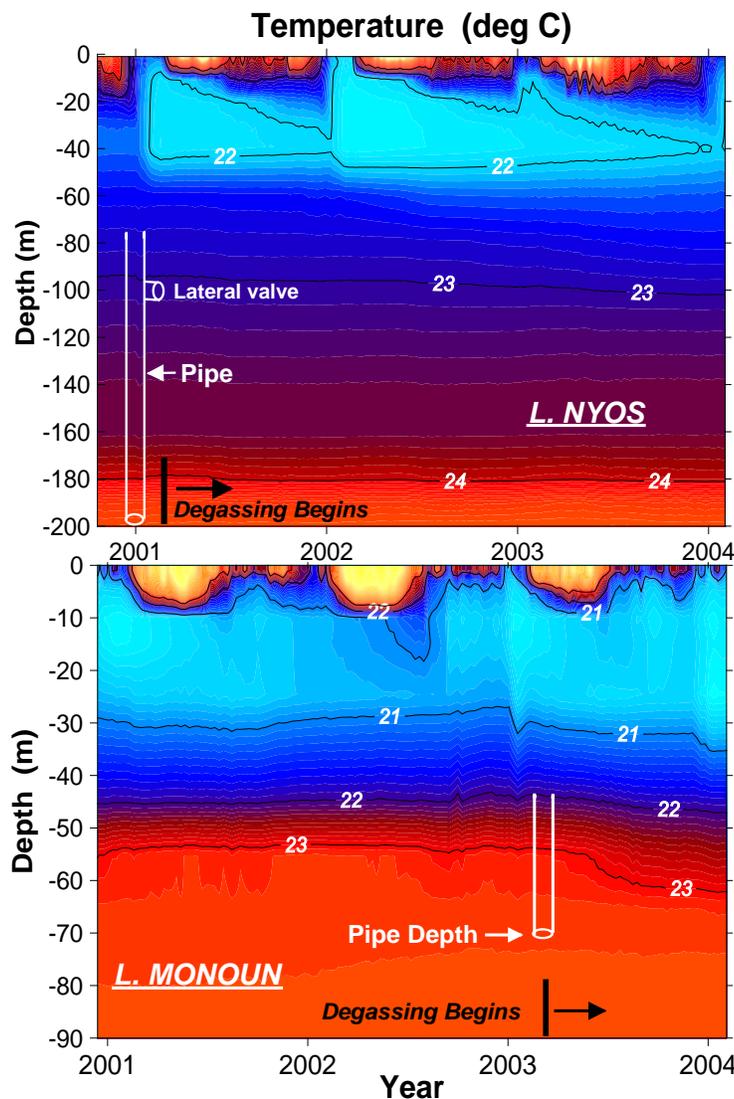
- (1) The degassing pipes installed in Lake Nyos in 2001 and in Lake Monoun in 2003 have reduced the gas content in both lakes compared to pre-degassing conditions. The strength of layering and stability in the lakes remains high, indicating that the gas removal is not destabilizing the lakes, and is not increasing the likelihood of another disaster.
- (2) Even with gas contents lowered, the lakes will still contain more gas than was released in the 1980s disasters and thus still pose grave dangers to local populations. A model of future status predicts that only ~30% of the gas remaining in Monoun can be removed, and by 2015 only ~25% of the gas remaining in Nyos will be removed. This slow removal extends the time window of risks for local populations. New pipes installed in Monoun in 2006 should solve the problem if the inlet is at the lake bottom, but in Nyos additional pipes are required to reduce the risk of repeat disasters.
- (3) The role of CO<sub>2</sub> degassing in contributing to greenhouse gas emissions and climate warming is negligible. The output of CO<sub>2</sub> from cars and trucks alone in Yaoundé each year is ~4 times greater than the maximum output of the pipe at Lake Nyos, and is ~20 times greater than the natural recharge of gas into the lake annually. The released CO<sub>2</sub> is mixed rapidly with the atmosphere and there is no threat to air quality for people on shore or fishermen on the lake. In addition, oxygen levels in both lakes are acceptable and there is no sign of harmful effects on the fish in the lakes.
- (4) All evidence indicates that there is no economic benefit to recovering the CO<sub>2</sub> gas from Lake Nyos. Delaying the gas removal to wait for gas recovery and business opportunities simply increases the danger and risk faced by people living near the lake. Economic and social development in the region would be stimulated by removing the risks from natural hazards, reconstruction of the ring road, and promoting tourism which includes the educational and training opportunities at the lakes themselves.
- (5) The danger from the weak dam at Lake Nyos still exists, and a flood could reach into Nigeria and affect up to 5-10,000 people below the lake. The dam can be strengthened immediately, and once the majority of gas has been removed from the lake the water level may be lowered to completely eliminate the flooding threat.

# I. EFFECTS OF DEGASSING

The degassing pipes were installed as part of the U.S. OFDA project started in 1999, supplemented by funding from the governments of Cameroon, France, and Japan. A subcontract from the OFDA grant funded the pipes themselves, which were designed and built solely by Michel Halbwachs and his engineering company Data Environnement in France. Another subcontract to Yutaka Yoshida and the Yoshida Engineering firm in Japan produced the rafts for the degassing pipes and instruments. Once the pipes were installed the main reason for monitoring the effects of degassing was to ensure that the lake stability, which is a measure of the resistance to a catastrophic gas release, remained strong. In addition, the gas content is monitored to gauge the degassing progress. This monitoring is accomplished by measuring the gas content of bottom waters, and the temperature and salt content within the lakes.

## (1) Temperature

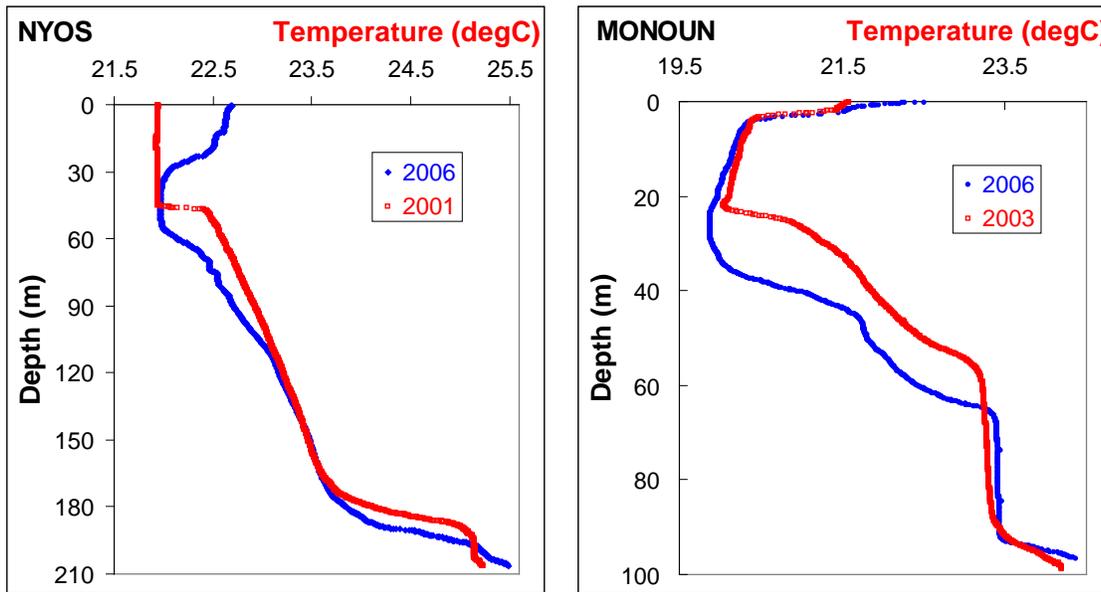
The long-term changes in lake temperature vary seasonally at the surface, but at the middle and bottom depths the temperatures have remained fairly constant even after the degassing. *Figure 1* shows the relatively constant temperatures over time in the middle and bottom layers for both Lakes Nyos and Monoun. In Lake Monoun, there was a slight lowering of temperature from 2003 to 2004 between 55 and 65 m depth. This lowering was



expected, and it is due to the degassing pipe which has its inlet at ~70 m depth. The temperatures decrease because the water removed by the pipe is lowering the layers in the lake, and the upper layers had cooler temperatures. This change in the thermal structure of the lake is similar to what is happening in Lake Nyos, but is more pronounced because L. Monoun is smaller and the degassing pipe is having a greater relative effect. This lowering of layers can be seen more clearly in *Figure 2*, which compares the pre-degassing profiles with those from measurements made in January 2006. Note that the temperatures below the pipe intake have remained fairly stable or increased slightly, which is what is expected given the inputs near lake bottom of slightly warm, CO<sub>2</sub>-rich spring water. Thus there is no indication that the thermal structure of the lake has been negatively disturbed by the degassing.

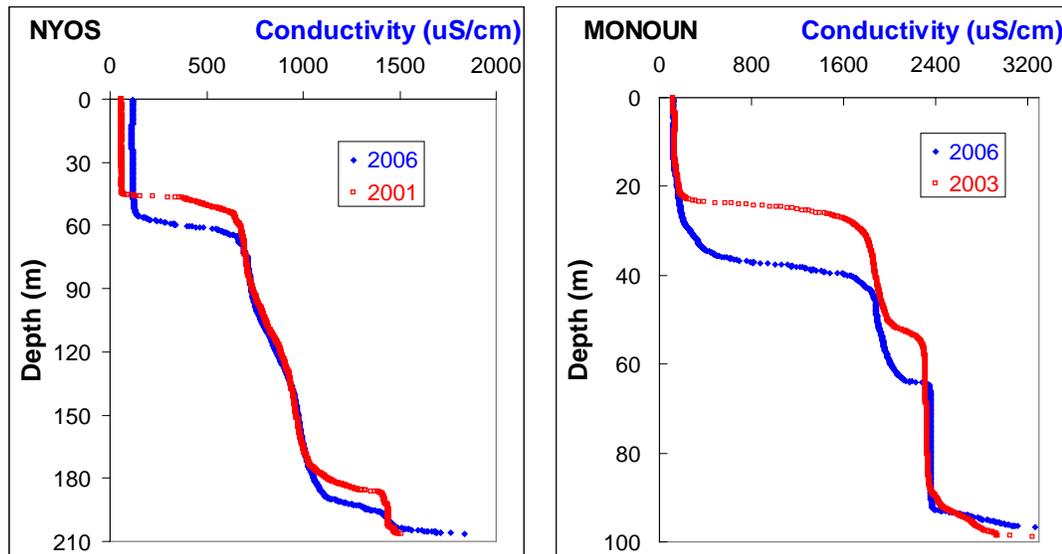
**Figure 1.** Temperature versus depth in Lakes Nyos (top) and Monoun (bottom).

**Figure 2.** Temperature versus depth profiles in Lakes Nyos and Monoun showing the lowering of thermoclines and chemoclines today (2006) compared to before degassing.



## (2) Conductivity

The stability of stratification can also be measured by the electrical conductivity of the water. The higher the salt content of the water the higher the conductivity, and the greater the density of the water. *Figure 3* shows the differences in conductivity profiles between 2001 and 2006 in Lake Nyos, and 2003



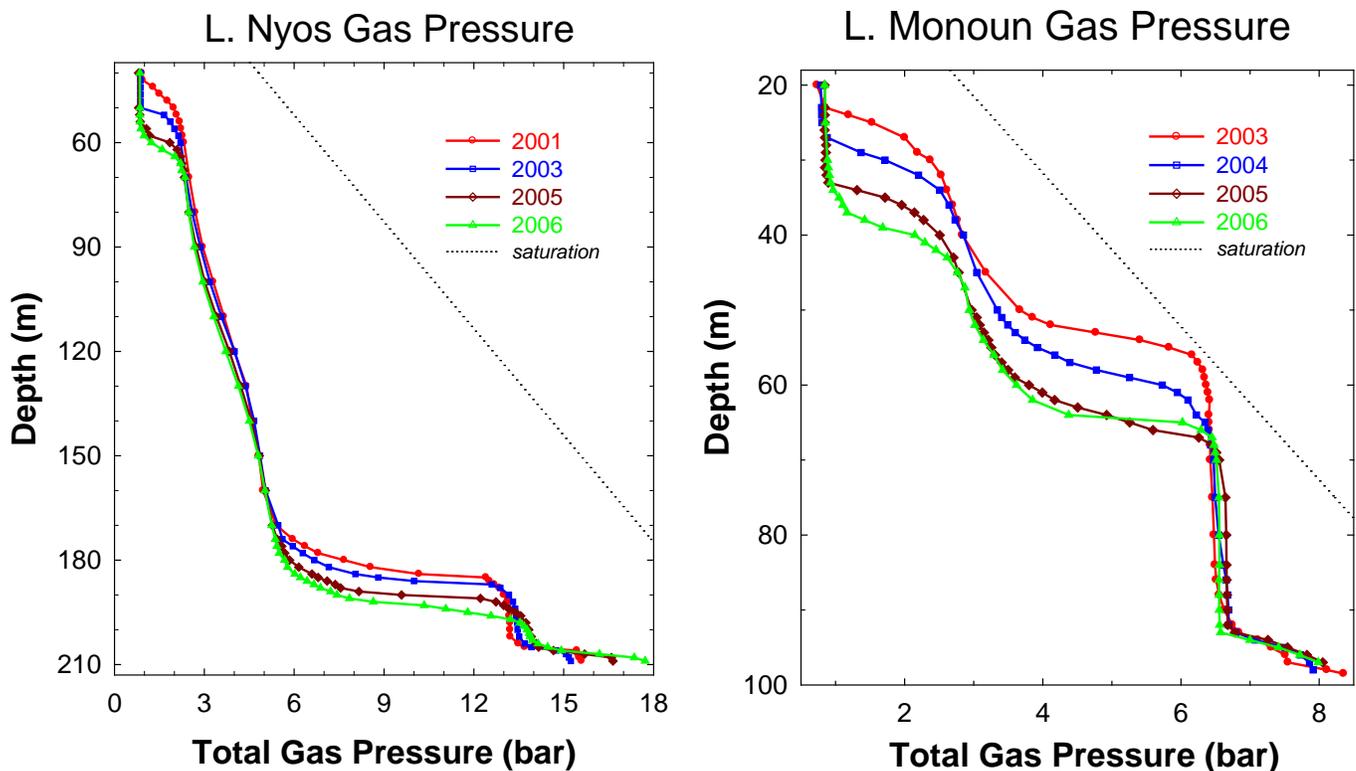
**Figure 3.** Water conductivity versus depth in Lakes Nyos and Monoun. The profiles from January 2001 (before degassing in Nyos) and January 2003 (before degassing in Monoun) are compared to the post-degassing profiles (blue lines) in 2006.

and 2006 in Lake Monoun. In Lake Nyos, the conductivity of the surface water is slightly higher today than it was before degassing, due to the release of high-conductivity bottom water at the surface through the pipe. Second, the rapid increase in conductivity with depth (the chemocline) that occurred at about 45 m depth in 2001 (red line) has been lowered to ~60 m depth in 2006. A similar lowering occurred at the bottom chemocline around 180 m depth. This lowering was expected because of the withdrawal of

water by the degassing pipes, and the same lowering is seen in Lake Monoun at about 30 and 55 m depth. Although any increase in conductivity in the surface water lowers the strength of stratification, this is more than offset by the fact that the rise in conductivity with depth is now more abrupt. Thus, overall the strength of this stratification barrier to an uncontrolled gas release has increased.

### (3) Gas Pressure

The measurement of total gas pressure is required to estimate the potential for rapid degassing and to estimate the total amount of gas in the lakes; gas pressures have decreased in both lakes over time (*Figure 4*). In Lake Nyos, gas pressure decreased from a high in 2001 before the pipe was installed (red line) to lower post-degassing values. The most noticeable changes are between 40-60 m and 175-190 m depth, where the lowering is caused by the removal of gas-rich water at depths of ~100 m and ~200 m. The gas content has not dropped consistently over time in Lake Nyos. For example, *Figure 4* shows that the drop in gas pressure seen around 180 m between 2001 and 2003 was about half of the drop seen the following two years between 2003 and 2005. This difference is a result of several design and equipment



**Figure 4.** Total gas pressure profiles at Lakes Nyos and Monoun prior to the degassing (maximum pressures, red lines), and for the post-degassing years. The dotted “saturation line” shows the maximum gas pressures that can be held in the lake, and gas pressures closer to that line indicate a greater danger of a disastrous gas release.

flaws in the pipe installed by M. Halbwachs. These problems caused the pipe to function at full capacity only 50% of the time between 2001 and 2003 (~343 out of 686 days), which explains the lower rate of gas removal during that period. In Lake Monoun the gas reduction in the first two years was more dramatic (2003 to 2005), especially near the ~25 m and ~55 m depths (*Figure 4*). However, the gas content in January 2006 is slightly higher at some depths than it was in 2005 (up to 13% higher at 65 m depth), and overall there has been little change in gas content between 2005 and 2006. The reason for this is the fact that the pipe in Monoun has malfunctioned for all but 5 days of the last year (99% of the

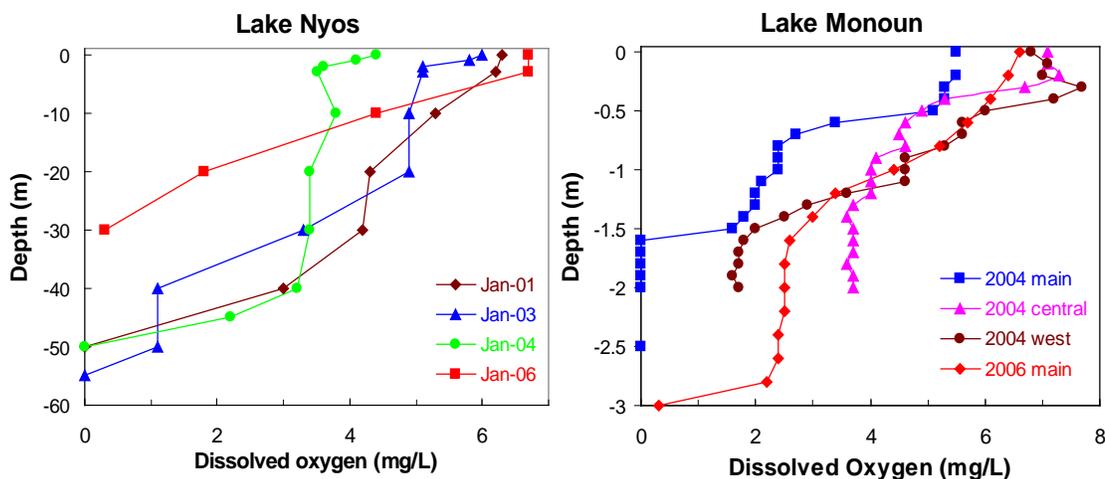
time). As in L. Nyos, this malfunction is due to pipe design and implementation flaws and results in only small amounts of gas being removed through a lateral valve at shallow depths. This explains the observation that between January 2005 and January 2006 there was a reduction of gas only around the shallow depth of 35-40 m near the location of the lateral valve (*Figure 4*).

In both lakes the profiles show that gas pressures at the bottom of the lakes are remaining constant or increasing (*Figure 4*). This is due both to the natural recharge into the lakes and the production of methane within the lake, especially at Nyos. At the bottom of Nyos the gas pressure now exceeds 17.7 bar, and  $\sim 1/3^{\text{rd}}$  of that pressure is probably due to methane gas. In L. Monoun the original design of the pipe inlet to be placed at only 73 m depth means that the pipe cannot remove gas below that depth and gas pressures at the bottom have not dropped over time. For L. Monoun we anticipate that this situation and the problems with the pipe will be corrected in January-February 2006 as two new but smaller pipes are installed in the lake by Data Environnement. In L. Nyos the overall reduction in gas content with the single pipe is slow, and it is imperative that more pipes be added to Lake Nyos in order to reduce the gas pressures at a much quicker rate (see section below).

One question often asked is why are the lakes still dangerous if the gas is being removed, the lake “stability” is high, and the gas pressures are far away from the saturation line, especially at Lake Nyos? The answer is that there is still a tremendous amount of gas in both lakes, more than was released in the initial disasters, and at Lake Nyos a rockfall or landslide from the cliffs around the lake could supply a tremendous amount of energy that could mix bottom waters upward and trigger another gas burst.

#### (4) Environmental Effects on the Lakes

We investigated the environmental effects of degassing, which were the most difficult to predict in advance. One concern was that when the bottom water rich in iron was brought to the surface, oxidation of the iron would consume the dissolved oxygen normally present in surface water, which would harm fish and other lake organisms. *Figure 5* indicates that overall the depletion of oxygen has been small, and that there is still plenty of oxygen for fish down to at least 20 m depth in Lake Nyos. The



*Figure 5. Oxygen concentration in the surface waters of Lakes Nyos and Monoun are currently sufficient for fish populations.*

distribution of oxygen varies naturally over time. In 2006, oxygen concentrations were higher at the lake surface than in 2004, but dropped to zero at a shallower depth.

Lake Monoun currently supports an active local fishery, and reduction or loss of this fishery is a source of concern. The fishermen have been restricted from working in the main basin where the degassing pipe is located so as not to interfere with its operation. Fishing is still unrestricted in the other two

basins of the lake (central and west). Only the upper few meters of Lake Monoun contain oxygen, which decreases rapidly with depth. In 2004, after a year of piping, oxygen was clearly depleted in the main basin relative to the other basins. Between 2004 and 2006, the pipe only worked at a low rate of flow due to valve malfunctions, and oxygen concentrations in the main basin recovered to levels comparable to the other basins. Note that in the central and west basins there is still plenty of oxygen in the surface waters, which is important for the fishing activity in the lake. However, with the two new pipes installed in L. Monoun this year, and if the original pipe is also repaired, it is likely that oxygen concentrations will be very low in the main basin due to the larger amounts of anoxic bottom water high in iron brought to the surface by the pipes. We do expect that the central and west basins will still retain sufficient oxygen to maintain the fish, and the fishing industry, in the lake.

#### **(5) Greenhouse Gases and Air Quality Impacts of Degassing**

Recently a concern voiced in the media has been that releasing the CO<sub>2</sub> gas from the lakes will contribute negatively to the greenhouse effect and climate warming. This is *NOT* a valid concern because the amount of gas released by the degassing pipes is far too small to have any noticeable impact at any scale. For example, at the most local scale we have information from the CO<sub>2</sub> warning stations located on the spillway of Lake Nyos and near the town of Njindoun at Lake Monoun that monitor the CO<sub>2</sub> concentrations in the atmosphere (and to warn the local people in the case of a gas release). Analysis of the continuous records of data collected from these stations shows that the gas concentration in the atmosphere is always near ambient, and investigations near the pipes also show that the CO<sub>2</sub> concentrations are at safe levels and there is no reduction in air quality around the pipe itself. Even if the releases of CO<sub>2</sub> from the pipe discharge are integrated over time, the contribution to greenhouse warming is negligible. For example, we calculate that the long-term recharge of CO<sub>2</sub> into Lake Nyos (~5,000 tons of CO<sub>2</sub> per year) is about 20 times less than the amount of CO<sub>2</sub> put into the atmosphere each year by the cars and trucks in Yaoundé. The output by vehicles alone (no contributions from industry) is also ~4 times higher each year than the maximum output of the degassing pipe in Lake Nyos. Note that the degassing output of CO<sub>2</sub> from L. Monoun is about 5 times less than the output from Nyos. At the global scale, the total of all natural volcanic emissions (0.05 x 10<sup>9</sup> tons of CO<sub>2</sub> per year) is 160 times less than the yearly anthropogenic emissions. Furthermore, the total amount of gas in Nyos and Monoun is only ~0.2 % of the annual volcanic emissions. Thus it is clear that even volcanic emissions, and especially these lakes, pose no threat to the environment through greenhouse warming.

#### **(6) Potential Economic Benefits from the Gas**

An often-mentioned concern is that the CO<sub>2</sub> stored in Lake Nyos has economic value and it should be developed. Although there are no published assessments of value that we are aware of (although proprietary reports may exist), it is highly unlikely that the extraction of gas would be profitable. In part this is based on the fact that there is no infrastructure around Lake Nyos (e.g., serviceable roads, available power or transmission lines) to support a gas extraction plant and bottling facilities. More importantly is the fact that the amount of CO<sub>2</sub> available in the lake (about 572,000 tons total, of which 335,000 tons is extractable, plus ~5,000 tons of recharge per year which may or may not be easily extracted) has been published and known for almost 20 years. Despite this knowledge there has been no interest in development. This lack of interest is not due to the appropriate companies being unaware of the gas. For example, Gaz de France is a large company with the capability and interest to develop such a resource, but they have declined this opportunity and instead they have actually helped to fund the tests on gas removal through piping with no economic recovery. It is therefore clear that there is no economic potential from the gas, and that degassing should proceed immediately and quickly so that people in the area can be safe and can return to their homes. The real economic benefit for this area will

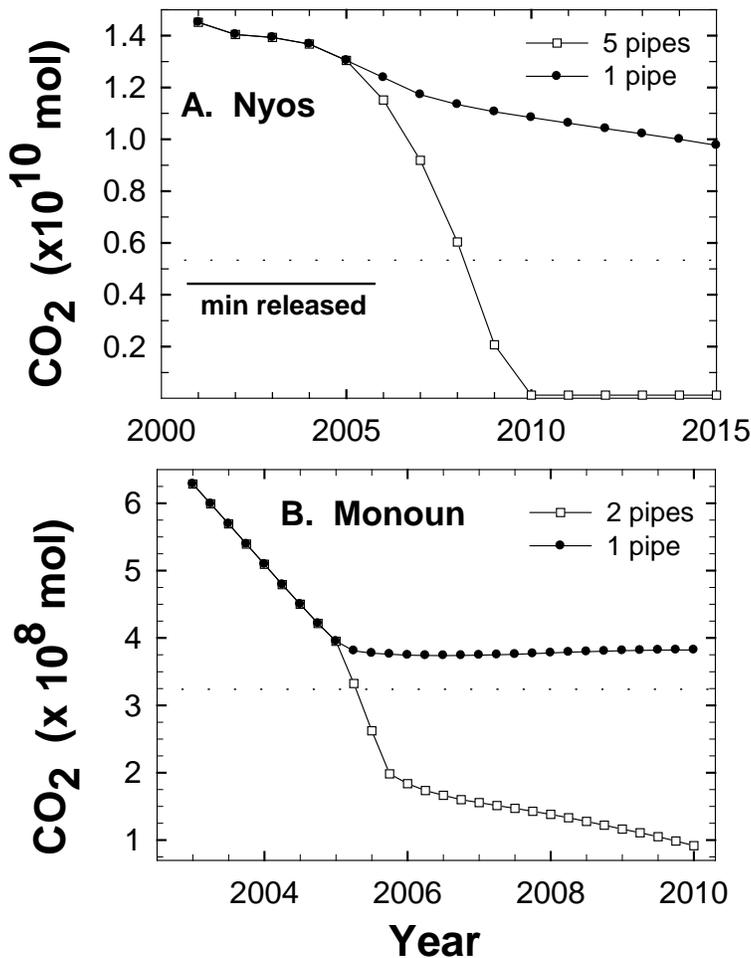
come from eliminating the hazards and rebuilding the roads, which will allow commerce, agricultural, and tourism to thrive.

## II. HAZARD PREDICTION and MITIGATION

### (1) Gas Hazard

The inevitable trajectory of these lakes toward massive gas bursts resulting in the loss of human life has been altered, but future hazards depend on the balance between controlled gas removal and natural recharge. Because the removal rate is driven by the gas pressure at the pipe inlet (the energy of gas exsolution lifts the fluid up the pipe), as gas pressures drop the rate of removal also declines. To predict the future state of the lakes we modeled the gas content over time, assuming that recharge rates and surface losses remain constant. Gas removal is estimated using the measured relationship between the maximum flow rates in both lakes and the gas pressures at the pipe inlets (*Figure 4*). As gas is removed the chemoclines subside and a new, lower gas pressure drives flow at the pipe inlet. To check the validity of the model we compared model results to actual measurements between the time that degassing began and our samples in 2004. The model performed very well – the predicted CO<sub>2</sub> removal was within 1% of the measured values in both lakes.

With the single pipe now operating in each lake, this model predicts that within the next 5 years the rates of CO<sub>2</sub> removal and recharge will become essentially equal (within ~1%; *Figure 6*). At this point, the



piping becomes ineffective at further reducing the gas content, and 69-75% of the initial (2001) CO<sub>2</sub> content will remain in Nyos, and 59-64% of the initial (2003) CO<sub>2</sub> content will remain in Monoun. The CO<sub>2</sub> pressure at the pipe inlet at Lake Nyos will be ~ 6 bar, and further degassing will fail to remove substantially more gas than is replaced by natural recharge. In Lake Monoun the gas content will actually increase slightly due to greater recharge gain than pumping removal (*Figure 6*). This situation arises because first, as the chemoclines drop the maximum gas pressure is decreased in the layer around the pipe inlet. Second, the gas

**Figure 6.** Predicted gas contents in Lakes Nyos and Monoun over time given the current installation of 1 pipe in each lake, and the proposed installation of additional pipes. The dashed lines indicate the amount of gas remaining at atmospheric pressure (0.9 bar), and the “min released” shows the amount of gas released in the 1986 disaster at Lake Nyos.

recharge is distributed relatively evenly in the lower water column (based on the observed rise of CO<sub>2</sub> over previous years, Kling et al. 2005) rather than concentrated into a high-pressure layer at the bottom of the lake.

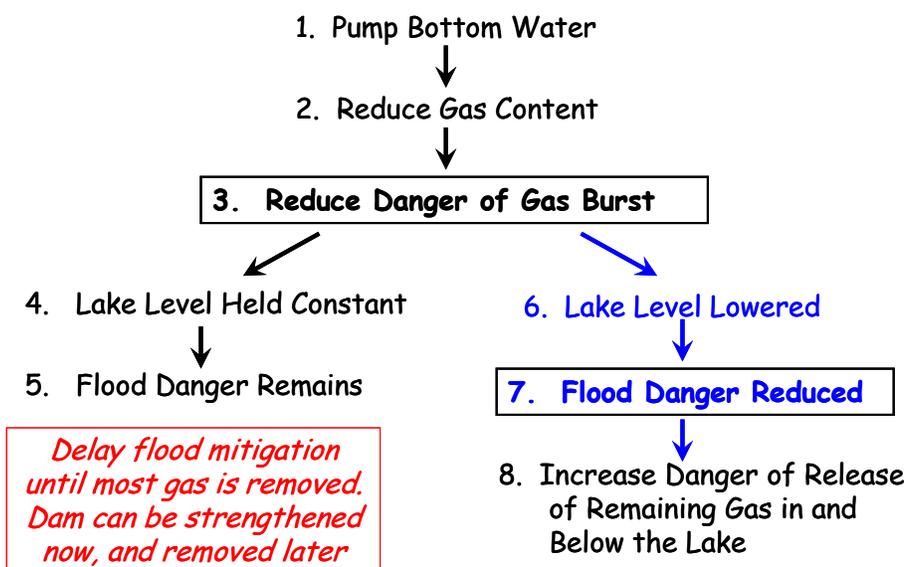
In order to evaluate the effectiveness of other degassing configurations, we modeled the impact of adding more pipes to the lakes. For Lake Nyos the model included one additional pipe installed each year starting in 2005 for a total of 5 pipes in the lake by 2008, and the inlet depth for all pipes was at 206 m. For Lake Monoun one additional pipe was incorporated into the model in 2005 with the pipe inlet depth at 97 m, and the existing pipe inlet was lowered from 73 to 97 m. Both configurations resulted in a much greater reduction in gas content and a longer time period of effective operation than the currently operating single pipes (*Figure 6*). In this scenario the amount of CO<sub>2</sub> remaining in Lake Nyos below 50 m when the degassing becomes ineffective would be about 0.016 km<sup>3</sup> (at Standard Temperature and Pressure), which is an order of magnitude smaller than the minimum gas cloud thought to have been released in 1986. Only about 0.005 km<sup>3</sup> of CO<sub>2</sub> would remain below 20 m in Lake Monoun. Although the amount of gas released from Monoun in 1984 is unknown, it is unlikely that a substantial release could occur given the low gas pressures that would exist in the lake (<2.5 bar). Thus the model verifies the need for additional pipes, and illustrates that future research should concentrate on methods of transitioning from raft-mounted degassing pipes to installations that operate at lower concentrations of gas and permanently prevent gas build-up in the future, such as mechanized circulators or passive drain pipes.

**(2) Flood Hazard at Lake Nyos**

For nearly 20 years scientists have recognized that a severe flood from L. Nyos could result from collapse of the weak natural dam (spillway) holding back the upper 40 m of the lake. Plans for remediation of the flood hazard must include the associated hazard of gas releases, because it is the weight of water in the upper part of the lake that acts as a lid on the gas dissolved in the lake’s bottom waters. Lowering the lake to reduce the flood hazard would remove this lid and increase the likelihood

of another gas release; thus the plan for remediation includes first removing most of the gas from the lake (*Figure 7*).

**Remediation for Lake Nyos Hazards  
Gas Bursts and Flooding**

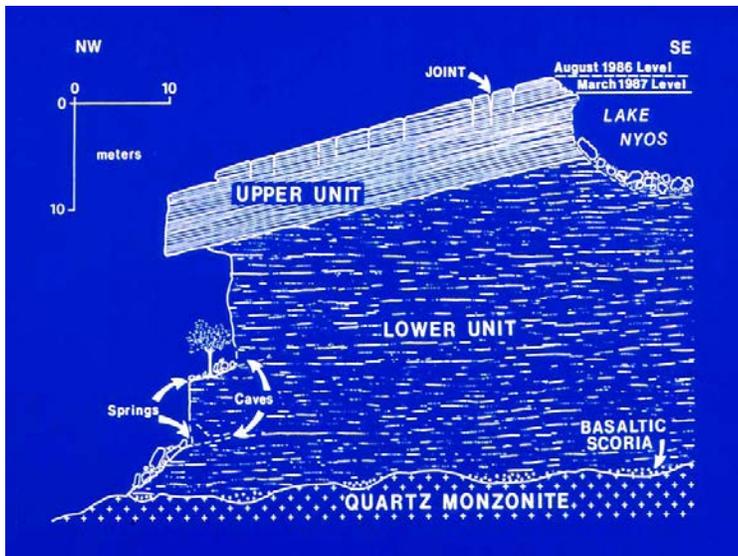


*Figure 7. Remediation plan for natural hazards of gas bursts and flooding at Lake Nyos. Lowering the lake level to remove the flood hazard before most of the gas is removed could depressurize bottom waters or gas pockets in the sediments and trigger a gas burst. In addition, lowering the lake level could result in landslides or rockfalls of newly exposed materials on cliffs around the lake, which could also trigger a gas release.*

Several studies and publications (see references in *Appendix I* of this report) have examined the dam hazard, and here we summarize the critical aspects common to any solution to this problem. It is well-documented that the dam is composed of loosely consolidated volcanic materials that are eroding rapidly. The weakest part of the dam is the narrow spillway in the middle (*Figure 8*), which is covered by a slightly harder, indurated cap of volcanic materials (*Figure 9*). This cap is also eroding, and any dam failure will be initiated at this narrow septum. Several springs exit from the downstream wall of the dam, indicating that the dam is leaking and could fail at any time.



**Figure 8.** Photo of Lake Nyos just after the 1986 disaster. The dam is located in the lower right corner of the picture, and the narrow septum of the spillway is defined by the outflow of water from the lake (white strip). The inlet to the lake is at the upper part of the photo. The lake level could be lowered by diverting inlet water outside the catchment before it reaches the lake (upper left in photo), or by drilling through hard rock beneath the dam or to the east of the dam (left side of photo).



**Figure 9.** Geological cross-section of the weak natural dam at Lake Nyos that was created when the lake basin was formed (from Lockwood and Rubin 1989). The dam is about 40 m thick and consists of an upper unit of welded volcanic materials that contain joints and erosion pits, and a lower unit of weakly consolidated volcanic materials. The dam rests on hard rock (quartz monzonite). The upper unit is the strongest part of the dam, and should not be removed unless the entire dam is removed down to the level of the hard rock.

Currently the mitigation process is removing gas but holding the lake level constant (step 5 in *Figure 7*), which is required until most of the gas is removed. At that point the lake level could be lowered by 40 m and a pipe placed at the base of the dam on the hard rock, or a hole could be drilled into the lake at the appropriate level at least 40 m below the current lake surface elevation. This pipe or hole would allow the lake to drain and maintain a new, lower lake level beneath the weak dam, which would eliminate the flood hazard. Several methods could be used to lower the lake level, including (1) diverting the inflow streams at a high point in elevation in the watershed before they reach the lake, (2) pumping water out of the lake, or (3) drilling a hole into the lake from low-lying areas downstream of the lake. Suggestions to lower the lake level by using the degassing pipes may be unworkable due to the difficulties of moving gassy water horizontally and the fact that as the lake level lowers, the water must still be pumped upward and over the spillway (“cutting a slot” down through the dam to allow for horizontal water removal as the lake is lowered is ill-advised because of the fragile nature of the dam).

It is also possible to strengthen the dam before the gas is removed and while the lake is held at its current level. One proposal was to inject concrete into the dam, but this would require drilling into this weak structure which may be risky. A safer option would be to construct a barrier upstream of the dam (i.e., placed in the lake) that would serve to reinforce the dam. The details of these options can be explored relatively quickly and cheaply (a detailed study may only cost ~\$50,000 to \$100,000 USD), and from the U.S. perspective we recommend that the U.S. Geological Survey is requested to guide or make an assessment of the situation; this is warranted in part because most of the published scientific studies on the dam have been conducted by U.S.G.S. personnel (e.g., Lockwood and Shuster). In any case, it is important to recognize that strengthening the dam while the gas is being removed is a prudent measure that will only reduce the risks of hazards in a shorter period of time. Finally, in *Appendix I* of this report we comment on a recent UNEP/OCHA assessment report on the dam, which also found that the dam is fragile and an imminent flood danger exists.

### III. SUMMARY

- Further work should be initiated as soon as possible to ensure the safety of those living near the lakes. This work includes installing more pipes in Lake Nyos, upkeep and refurbishment of the lake monitoring stations, removal of the flood hazard, and placement of drainage systems at both lakes to continuously remove gas inputs to the bottom waters once the main degassing is complete.
- This coming August 2006 will mark the 20-year anniversary of the gas disaster at Lake Nyos. The technical solutions to these natural hazards have long been understood and are of reasonable cost, and although progress has been made the dangers still exist. People near the lakes still live in fear, and at Lake Nyos an entire generation has grown up as refugees from their homes. At least 12,000 people are currently displaced, and up to 10,000 others still could be affected by a flood from the lake. The entire Nyos region has suffered, and beyond the issues of safety for two decades the region has been denied the basic elements of roads and commerce, business and agricultural development, and social and cultural pride and well-being. In fact this blight is so visible and well-known that it casts a shroud over all of Cameroon. Agencies within the Cameroonian government are currently planning to commemorate this anniversary in August with cultural and scientific activities and events. These events will be a wonderful opportunity for those with the greatest influence and power to affirm their will to solve the problems, and to highlight their accomplishments to a local and world media that have never tired in their fascination with these very special natural hazards.

### ACKNOWLEDGEMENTS

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## APPENDIX I

### Technical Updates to the UNEP/OCHA Lake Nyos Dam Assessment Report

In September 2005 a team from the UNEP/OCHA Unit visited Lake Nyos to assess the natural dam and potential flood hazard at the lake (Report published in Switzerland, October 2005 by the Joint UNEP/OCHA Environment Unit). Although the visit to Lake Nyos was brief (~3 hours), the report accurately reflects the fragile nature of the dam and the severe flood hazard it represents when it fails. These conclusions are similar to all other assessments of the dam that we are aware of, and highlights that remediation of this natural hazard along with the hazard of another gas release is of paramount importance for the safety of people near the lake. Because of the brief nature of the field investigation, the full benefit of previous scientific and technical work done on the dam was unrealized. Below we provide several technical updates or corrections to the UNEP/OCHA report based on our ~20 year association with research on these hazards. For each point we identify the location and original statement in the report, and then provide our comment or correction.

1. p. 4, Executive summary. “A breach of the natural dam is imminent within the coming 10 years, with a high likelihood for this to occur within the next 5 years”. *Actual – it is true that the dam could fail at any time, and that is the great danger. However, predicting the time to failure within a specific number of years is difficult.*
2. p. 5, paragraph 2. “...Lake Nyos is a 200-meter deep lake”. *Actual average depth is 208 meters (Kling et al. 1987), and nearly 210 m may be reached at high lake level in the rainy season.*
3. p. 6, para 2. “...lake formation some 400 years ago”. *Actual age is at least 400 years old (Lockwood and Rubin 1989, Dalrymple and Lockwood 1990) and it could be up to ~8,000 years old (Festus Aka and Minoru Kusakabe, unpublished U-Th dates).*
4. p. 6, para 2. “...there are even indications that landslides will occur at the section of the dam just east of the spillway”. *Actual – when the scientific storehouse building was constructed in 2001 on the spillway, the bulldozer moved materials into a pile on the dam just east of the spillway. It is this loose material that is sliding, not the dam itself.*
5. p. 6, para 3. “...the dam is kept between the adjacent soil bodies and derives part of its stability from these”. *Actual – the dam consists of volcanic materials throughout, and some very shallow soil on the top. There is older and deeper soil material behind the widest parts of the dam (downstream of the lake) to both sides of the narrow septum located in the middle of the dam. This older soil may provide some stability to the widest parts of the dam, but, it is this narrow septum that is weakest and will fail.*
6. p. 7, para 2. “...the adjacent soil structures appear to be the weakest spot in the dam area.” *Actual – as mentioned in point 5 above, the dam consists entirely of volcanic materials; it is not a sandwich of soil on the east and west sides and volcanics in the middle. It is volcanic material across the entire dam from east to west, and the only thick soil structures are downstream to the north of the dam (see Lockwood et al. 1988; Lockwood and Shuster 1991).*
7. p. 9, para 2. “...strengthening the dam would be a logical solution, but this is hardly feasible, very costly, and considered uneconomical”. *Actual – there exists one engineering study on dam*

*strengthening, and they concluded that strengthening the dam was feasible. Clearly another assessment is required before dismissing the solution of dam strengthening.*

8. p. 9, para 2. “...the recommended solution of reducing the level of the water by 20 meters”. *Actual – the dam consists of a 40 m thick section of weak volcanic material, below which is solid rock (Lockwood and Rubin 1989).*
9. p. 9, para 2. “After the water level has dropped by 20 meters the top of the dam can be removed”. *Actual – the top of the dam is the strongest part (an indurated cap), and thus the entire 40 m of the dam must be removed. Removal of only one part of this section (e.g., the upper 20 m) will still leave the weak lower part of the dam.*
10. p. 9, para 4. *The stepwise plan of action is fundamentally sound, but some specifics are unworkable. For example, it is doubtful that the gas content can or should be lowered so quickly (3-6 months) by any method. In addition, removal of only one part of the dam, as mentioned above, is unsound.*
11. p. 10, para 2. “The design of the discharge system is based on a discharge of 50 m<sup>3</sup>/sec, assuming that this is close to the maximum discharge over the spillway...”. *Actual – our measurements of discharge in the wet season indicate a maximum of <5 m<sup>3</sup>/sec.*
12. p. 10, para 2. “A lower rate of e.g., 0.25 m/day will be applied”. *Actual – at this rate of lake lowering the flow of water in the pipes would need to be almost 100 times greater than the flow in the currently installed pipe (Kling et al. 2005). It is a difficult engineering problem to maintain this high flow rate, and it is likely not needed. For example, such rapid lowering of lake level could lead to other problems such as slumping of sediments in the south end of the lake into the main basin, or to landslides and rockfalls which if large enough have the potential to destabilize the lake and trigger another gas burst.*
13. p. 11, para 1. “The horizontal discharge of the gas water mixture over the surface of the lake should also be verified.” *Actual – this is a method that is untested and may not work, mainly because the horizontal discharge may be blocked by gas pockets forming in the horizontal sections of the pipes. In addition, as the lake level drops, the “horizontal” flow would be more and more uphill to the top of the spillway.*
14. p. 12, Table of organizational structure. *Our comment here is that of course there must be oversight, but this appears to be an excessive number of committees which will most likely result in administrative burdens and financial drains on the project.*
15. p. 14, Annex I. “...3 hours visiting Lake Nyos.” *The fact that the team was able to correctly assess that the dam is very fragile in just a 3 hour visit (consistent with all other assessments), highlights the danger of this natural hazard.*
16. p. 17, Annex II. “To degas the entire lake, approximately 600,000 tons of carbon dioxide will have to be removed. It is estimated that this will take 30 years [with the current pipe].” *Actual – only about 335,000 tons need to be removed (Kling et al. 2005) to drop the CO<sub>2</sub> to safe levels, and with 4 more pipes similar to the one in operation this could be done in only 3-5 years.*

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## *APPENDIX II*

### **LAKES NYOS AND MONOUN DEGASSING PROJECT (NMDP)**

#### **Scientific Background**

Lakes Nyos and Monoun, which exploded in the mid-1980's killing about 1800 people, still contain large amounts of carbon dioxide dissolved in their bottom waters, and another lethal gas burst could occur at any time without warning. The lethal release of large amounts of gas from lakes is very rare. Only three lakes in the world are known to contain high concentrations of dissolved gas in their bottom waters: Lakes Nyos and Monoun in Cameroon and Lake Kivu in East Africa. Only two of these lakes, Nyos and Monoun, are known to have recently released gas resulting in the loss of human life. Two conditions are necessary for CO<sub>2</sub> accumulation in lakes to reach dangerous levels. First there must be an abundant source of CO<sub>2</sub>, and second a lake must be strongly stratified, a situation where the bottom and surface waters do not mix, in order to trap the CO<sub>2</sub> in bottom waters. Geological conditions in much of Cameroon are favorable for the generation of CO<sub>2</sub> gas. This gas is discharged harmlessly to the atmosphere in many soda springs found throughout the country. In most of Cameroon's crater lakes, sheltering from the wind and great depth help to create stable stratification. The combination of gas-rich springs feeding into strongly stratified lakes led to the buildup and eventual violent release of gas from the bottom waters of Lakes Nyos and Monoun. Our previous investigations have shown that these conditions do not occur in any other Cameroonian lakes, and no other lakes contain dangerous amounts of CO<sub>2</sub>.

The gas content of these two lakes continues to build, supplied by the input of CO<sub>2</sub> from underground springs that discharge into the bottom of the lakes. The trigger for a gas burst is unknown although any disturbance that moves deep, gas-rich water closer to the surface could result in a gas release. As that deep water rises, the weight of water above it (the hydrostatic pressure) decreases, and at some point the dissolved gas pressure will become equal to the hydrostatic pressure. At this point there is nothing to force the gas to remain in solution, and gas bubbles begin to form. This process is identical to the removal of the cap from a bottle of soda – when the cap is removed there is no more pressure to keep the gas dissolved in the soda, and bubbles are formed. Once bubbles are formed in the lake they rise rapidly and drag the deep water toward the surface, at which point additional deep water is drawn upward and depressurized. This leads to a chain reaction that eventually results in the violent release of enormous amounts of lethal CO<sub>2</sub> gas. Because the gas content of these lakes is currently very high, catastrophes similar to those in 1984 and 1986 could occur at any time.

The natural hazards presented by these lakes are unique in that remediation is possible before a disaster occurs. The plan involves pumping of gas-rich bottom waters to the surface of the lakes through pipes. As the bottom water moves toward the surface the dissolved gas comes out of solution and forms bubbles. These bubbles lower the density of the gas-water mixture and the fluid begins to rise rapidly through the pipe. The energy released during degassing is sufficient to drive the pumping operation without any external power source. In addition to removing the gas currently in the lakes, it is possible to prevent future gas buildups using a pipe that continuously flushes bottom water out of the lake. After most of the gas is removed from Lake Nyos, it is also possible to lower the lake level so that the threat of flooding from the weak dam is eliminated.

Until the lakes are degassed using the method described above, the people living around the lakes are at risk, and increased awareness and education about the risks are needed. In addition, relocation of survivors from the Lake Nyos event has already occurred. However, people are moving back into the

evacuated region, and they should be made aware of the risks. There was no relocation of survivors around Lake Monoun; however, the population around the lake has increased in recent years and thus the need for risk education is as important here as it is in the Nyos region.

### **History and Political Situation Leading to the Current Degassing Project**

Because of the continuing danger of these lakes, the Government of Cameroon initiated the Lakes Nyos and Monoun Degassing Project (NMDP). The NMDP is guided by an International Advisory Committee of 7 scientists: Greg Tanyileke, Institute for Geological and Mining Research – IRGM, is the Cameroonian representative, and other members include Bill Evans and George Kling (U.S.), Minoru Kusakabe (Japan), Klaus Tietze (Germany), Alain Bernard (Belgium), and Jean-Christophe Sabroux (France). The project has three main goals: (1) continuously monitor the physical, chemical, and biological conditions in both lakes, (2) install CO<sub>2</sub> monitoring stations at both lakes to provide an audible and visual warning in the event of a gas release, and (3) install permanent degassing pipes to remove the gas from both lakes. The main funding for these three items has come from a U.S. AID-Office of Foreign Disaster Assistance grant (~\$680,000 total), and the support funding for road improvement and the construction of permanent science-support structures at the two lakes has come from the Cameroonian government (see below); additional funding has also come from the French and Japanese governments.

Continuous water and gas monitoring stations (goals 1 and 2) are now in place and operational, and a degassing pipe has been deployed and is operating in each lake. Although the risk of another gas burst is no longer increasing at the lakes, there is an acute need for a lowering of the pipe at Monoun and more pipes (up to 4-5) to be installed in Nyos in order to quickly drawdown the gas content to a safe level. The details of this work are given in our present and previous reports sent to the U.S. Embassy and MINRESI.

The long-term success of mitigating these natural hazards involves a broader program that includes building roads to the lakes, constructing permanent work facilities, educating the local people about the dangers and the remediation, and ensuring that Cameroonian scientists and technicians receive proper training to manage the degassing equipment and procedures in the future. To help coordinate these diverse tasks, in 2000 an Inter-Ministerial Committee was formed under the direction of the Prime Minister. Several important Ministries are represented on the Committee, but the vice-chairmanship was assigned to Minister H.H. Nlend of MINREST (now MINRESI). This choice recognizes the important role that scientific research plays in this effort.

Coordination of the project at the ministerial level operated well (with some transient difficulties), and the infrastructure of roads, power generation, and buildings required to support the degassing was in place by 2001-2003. With this infrastructure, future work can focus on funding and deploying a degassing pipe in Lake Monoun and additional pipes in Lake Nyos. The goal is to complete the degassing process within ~10 years and install passive drainage pipes or mechanical mixers that will prevent gas from building up in these lakes ever again.

The NMDP has been financially supported by the governments of Cameroon, the U.S. (through the Office of Foreign Disaster Assistance), France, and Japan. Our (Kling and Evans) ability to carry out the required work has been greatly facilitated by encouragement and logistical help from the U.S. Embassy for the past 19 years, and we gratefully acknowledge this contribution.