Research Plan for the Dissertation of Natacha Pasche

How does nutrient cycling influence methane production in Lake Kivu?

Lake Kivu: the mouth of Ruhanga River in Rwanda

Ph.D Committee

Examiner:	Prof. Alfred Wüest (Eawag)	....
Co-Examiner:	Prof. Bernhard Wehrli (Eawag)	....
	Prof. Jean-Pierre Descy (FUNDP)	....
Supervisor:	Dr. Martin Schmid (Eawag)	....
Ph.D. Student:	Natacha Pasche	....

Abstract

Lake Kivu, one of the East African rift lakes, contains enormous amounts of dissolved carbon dioxide and methane. On the one hand, these gases are a tremendous hazard for this densely populated region since their sudden potential release, triggered by volcanic or tectonic activity, could have catastrophic consequences. On the other hand, the dissolved methane should become a valuable renewable energy source for the two bordering countries Rwanda and Congo. A recent study indicates that the CH_4 production in Lake Kivu has significantly increased in the past three decades. This increase could have been generated by changes in the nutrient cycling of the lake due to the fast-growing population in its catchment. Besides, the introduction of *Limnothrissa miodon*, the first pelagic and planktivore fish in Lake Kivu, could be responsible for significant changes in the nutrient fluxes.

This proposed Ph.D. project will examine the cycles of P, N and Si in the lake. In particular, the external nutrient sources, their internal fluxes and sedimentation will be quantified. The methane production, its oxidation and the methanotrophic bacteria will be investigated. A one-dimensional numerical model of Lake Kivu will bring together the methane production and the nutrient cycling.

The model will be a powerful tool for decision-makers, as it could predict the future development of the methane reservoir based on different strategies to limit eutrophication and to exploit the methane. As such, the scientific findings may assure a more sustainable management of the lake in the future. In addition, this project will build research capacities in Rwanda and Congo and provide a continuous scientific exchange, which is required for the monitoring of the lake to prevent a gas outburst.

1. Introduction

Lake Kivu is located in the East African Rift Valley, between the Republic of Rwanda and the Democratic Republic of Congo. Situated near the equator at an elevation of 1463 m, it has an area of 2370 km^2, a volume of 580 km^3 and a maximum depth of 485 m (Schmid et al. 2004; Tietze 1978). The lake consists of a main basin and four smaller basins: the Ishungu, the Kalehe, the Bukavu Basins and the Kabuno Bay (Botz et al. 1988). The Ruzizi River is the only outflow of the lake.

Sediment analysis (Haberyan and Hecky 1987) showed two stages in the formation of Lake Kivu: a shallow stage 1-5 millions years ago, followed by a deep stage about 10’000-50’000 years ago. This transition is marked by lavas flows from the Virunga volcanoes, which dammed the lake’s former outflow to the Nile about 12’000 years ago.

In 1937, a scientific expedition (Damas 1937) discovered that Lake Kivu contains exceptionally high concentrations of carbon dioxide and methane in its deep waters. These dissolved gases represent a considerable hazard for its riparian population, but at the same time a precious source of renewable energy. A recent study (Schmid et al. 2004) showed a significant increase of the methane concentration relative to measurements made 30 years before (Tietze 1978), probably due to changes in the lake-internal nutrient cycling. A better understanding of the nutrient cycling and the methane production in Lake Kivu is, therefore, necessary to efficiently protect this densely populated region.

1.1 The special hydrology of Lake Kivu caused by hydrothermal sources

The water in Lake Kivu can be described as a mixture of two end members: the surface water runoff from the catchment and a groundwater source. This was indicated by deuterium and ^{18}O isotopes water analysis, which both lie on straight lines with conductivity and temperature (Tietze 1978). Lake Kivu has no major river inflow, but is fed to approximately equal parts by precipitation and small rivers. Besides, several geothermal springs are supposed to emerge in its deep waters, which explains the strong gradients observed in the vertical profiles of salinity, temperature and dissolved gasses (Schmid et al. 2005). These inputs of water supply heat and salt to the bottom of the lake (Newman 1976; Tietze 1978), which maintain the permanent stratification of the lake.

This meromictic lake has several chemoclines, the strongest of which is at 260 m depth. The high density gradients within the chemoclines efficiently inhibit vertical mixing, and consequently the deep waters are isolated from the surface waters. This stable stratification, characterized by a N^2 of 10^{-4} s^{-2}, is due to the gradients in salinity and CO_2 concentrations. Salinity increases from 1g kg^{-1} at the surface to 6 g kg^{-1} at 450 m depth, causing a rise of water density of 0.75 g l^{-1} per added 1 g l^{-1} salts. The main dissolved salts are bicarbonates of magnesium, potassium and calcium. The dissolved CO_2 increases the water density with a contraction coefficient of $0.28 \cdot 10^{-3}$ kg g^{-1}. In consequence, these two stabilizing factors largely overbalance the two destabilizing factors, which are the increasing temperature and CH_4 concentration with depth (Schmid et al. 2004).

One special mixing process occurring in Lake Kivu is double-diffusive convection (Newman 1976). Between 120 m and 460 m depth, the temperature and salinity profiles show a staircase of 250-350 steps of well-mixed layers separated by interfaces of strong gradients (Schmid et al. 2005). This structure is due to the important difference between molecular diffusivities of heat and salt, and to the destabilizing effects of temperature. This pattern is sustained by the geothermal springs, which release warm and salty water into the deep part of the lake.

The intensity of double diffusive convection, characterized by the density ratio R_ρ between the stabilizing and the destabilizing forces, has recently changed. In 2005, this indicator ranged between 2 and 4 below 150 m, signifying a strong susceptibility of the water column to double diffusive convection. However, in the 1970s', double diffusion was more intense (Newman 1976) with 150 larger mixed layers separated by stronger temperature gradients. Within 30 years, the increase of R_ρ by 20 to 30% reduced the upward transport of heat, salt and dissolved gases (Schmid et al. 2005). But even in the 1970's, the upward transport caused by double diffusion could already be considered as negligible.

The upward transport of salts and gases is, therefore, dominated by the upwelling caused by the geothermal springs raising the water column. From this upwelling, the residence time of the methane below 260 m was estimated to be 870 years (Schmid et al. 2005). This analysis points out, that the waters below and above the chemocline are more isolated from each other than previously thought.

1.2 Origins of the dissolved carbon dioxide and methane in Lake Kivu

The deep waters of Lake Kivu contain exceptionally large amounts of carbon dioxide and methane. The dissolved methane has a volume of about 60 km^3 (at 0 °C and 1 atm), which is five times less than the volume of carbon dioxide. Different hypotheses have been put forward to explain the origin of these dissolved gases. The most recent model suggests a magmatic carbon dioxide origin and bacterial methanogenesis (Schoell et al. 1988).

Evidence for the magmatic origin of the carbon dioxide is provided by the geologic setting, the typical $\delta^{13}C$ (4-7‰) values of magmatic CO_2 and the presence of mantle derived ^3He. Carbon dioxide is introduced into the deep waters through hydrothermal vents and emanations (Schoell et al. 1988; Tietze et al. 1980).

In contrast, methane is thought to be generated by two biological processes: the reduction of magmatic CO_2 and the decomposition of organic sediment material. Methanogenic bacteria directly reduce the dissolved carbon dioxide near and in the sediments. Simultaneously, methane is formed from organic matter by acetate fermentation. A mantle origin of the methane was excluded, because unrealistic isotope values would result from the methane produced through fermentation (Schoell et al. 1988).

It was estimated that the reduction of carbon dioxide generates 67% of the methane, while the fermentation creates 33% (Schoell et al. 1988). These percentages agree with the isotopic composition of the dissolved methane ($\delta^{13}C$ = -58‰ and δD = -218‰) and with the difference in ^{14}C concentration between the sediments (27%) and the methane (9%). This model is also supported by culture experiments

made with an inoculum from the sediments of Lake Kivu, which contains strains of *Methanosarcina* and *Methanococcus* (Bochem et al. 1982).

1.3 An increased production of methane

Previously, the methane concentration was assumed to be in steady state (Tietze 1978). However, recent analysis (Schmid et al. 2005) indicates that the methane concentration has increased significantly by 15 to 20% since the 1970s' measurements. For carbon dioxide, the observed concentration increase was on the order of 10%, but was not statistically significant.

The main hypothesis for this increased production of methane is a rise of the nutrient inputs caused by the fast-growing population in the catchment of Lake Kivu. Actually, the city of Bukavu has grown from 60'000 inhabitants in 1959 to a recent estimate of about 500'000, and the city of Goma from 14'000 to 200'000 in the same time span. In addition, the intensified agriculture associated with biomass burning leads to dry and wet depositions containing high concentrations of nutrients (Langenberg et al. 2003). Similar increases in nutrient inputs are observed in the Great Lake region, in particular in Lakes Tanganyika, Malawi and Victoria causing their eutrophication (Bootsma and Hecky 1993).

These increased nutrient inputs lead to an intensified primary production. Evidence of a higher production and sedimentation of diatoms is provided by a comparison of the vertical distribution of biogenic elements between the measurements of Degens et al. (1973) and recent measurements by Eawag. Silica concentrations have drastically decreased in the surface waters, while largely increasing at 350 m depth. In addition, the greater productivity is confirmed by a significant augmentation of the Ca/Na ratio and of the phosphorus concentrations in the deep waters of Lake Kivu.

The increased sedimentation, due to the higher primary production, generates sediments containing a larger proportion of organic matter. This higher availability of organic material is assumed to lead to an increased production of methane from the decomposition of organic material by methanogenic bacteria.

The higher primary production may generate modifications in the sedimentation rate and composition. This higher availability of organic material in sediment is assumed to lead to an increased production of methane from the decomposition of organic material by methanogenic bacteria.

1.4 The introduction of Limnothrissa miodon and the nutrient cycling of Lake Kivu

Only 28 fish species live in Lake Kivu, in comparison to the Lakes Tanganyika, Edward and Victoria contain extremely high biodiversity (Snoeks et al. 1997). The impoverished fish fauna of Lake Kivu is explained by abrupt and cataclysmic volcanic and hydrothermal events, which were recorded in sediment cores some 5000 years B.P. (Haberyan and Hecky 1987).

In 1959, the introduction in Lake Kivu of *Limnothrissa miodon*, a sardine endemic to Lake Tanganyika, created major changes in its food web. For the first time, this introduced planktivore fish predated the pelagic resource, causing alterations in the zooplankton structure. In particular, the mesozooplankton size and abundance dramatically decreased and one of the main grazer, *Daphnia curvirostris*, disappeared (Dumont 1986).

A recent study (Isumbisho et al. in press) shows that zooplankton have evolved to a new state. Present mesozooplankton is dominated by cyclopoid copepods, with cladocerans and rotifers in smaller proportions. The larger copepods manage to reduce predation pressure by migration into the deep mixolimnion at daytime. However, the sardine predation affects the cladoceran *Diaphanosoma excisum*, whose size is significantly reduced. In general, the abundance of zooplankton seems to depend more on phytoplankton resource, suggesting a bottom-up control.

The phytoplankton changed from a cyanobacteria-chlorophyte assemblage (Hecky and Kling 1987) to diatoms and cyanobacteria as the dominant groups in the 2000's (Sarmento et al. in press.). However, the

evolution of the primary production biomass is difficult to assess, as previous studies were based on limited samplings over short period of time.

Lake Kivu has a higher phytoplankton biomass and a lower zooplankton production than Lakes Tanganyika and Malawi. This relatively high phytoplankton biomass may be explained by the modification of the predation due to *Limnothrissa miodon*. Actually, the zooplankton grazers, now predated by the introduced sardine, reduced their top-down control over the edible phytoplankton (Sarmento et al. in press.). Another factor responsible for this low trophic efficiency may be the disappearance of Daphnia, an efficient and large grazer (Isumbisho et al. in press).

The second hypothesis for the increased methane production in Lake Kivu is, thus, the change in the internal food web induced by the introduced sardine. The nutrient sedimentation depends on the phytoplankton community and the zooplankton composition (Darchambeau 2003). Zooplanktons tend to maintain their chemical composition constant, even when the chemical composition and availability of their resources is changing, a process known as homeostasis. Regulation is performed through excrements, which become enriched in the non-limiting nutrient. In particular, Daphnia has a high bodily demand in P, as opposed to cycloid copepods which need to consume more N. In Lake Kivu, it can therefore be expected that the sedimentation of P has increased since the disappearance of Daphnia. In consequence, the modification of the plankton species may have disturbed the nutrient cycling in Lake Kivu.

1.5 Increased probability of a gas release

The gas outbursts in Lake Monoun and Lake Nyos raised awareness of the considerable hazard caused by the gas accumulation in Lake Kivu. In 1986, Lake Nyos released a dense cloud of carbon dioxide, which flowed through the surrounding valleys asphyxiating more than 1700 people (Kling et al. 1987). In contrast, the gas accumulation in Lake Kivu is 1000 times more important and its nearby population is about 2 millions. In consequence, a gas release from Lake Kivu could have cataclysmic consequences.

The minimum requirement for a gas eruption is that the sum of the partial pressures of the dissolved gases locally exceeds the hydrostatic pressure, such that bubbles can be formed. The two majors probable risks for a gas outburst in Lake Kivu are a gas supersaturation or a volcanic event (Schmid et al. 2004).

Firstly, the concentration of the dissolved gas in the deep water could increase and their total pressure could, therefore, dangerously approach the hydrostatic pressure. In 2004, the maximum saturation was 55% of the hydrostatic pressure at 340 m depth (Schmid et al. 2004), while in 1978 it was only 48% at 290 m. Even though the methane concentration is five times less than that of CO_2, CH_4 contributes to 80% of the total pressure because of its lower solubility. With the estimated current methane production, the gas concentrations could approach saturation within this century (Schmid et al. 2005).

Secondly, a volcanic event could produce sufficient thermal energy to induce a rising plume, which could lift water with high gas concentrations to a level where it becomes oversaturated (Schmid et al. 2004). The high volcanic and seismic activities around Lake Kivu, illustrated by the three surrounding active volcanoes, the dry vents (mazukus) and the thermal springs, support this scenario (Degens et al. 1973). A sub-aqueous eruption could also occur, as ancient volcanoes cones were identified on the deeper part of the main basin lake bed (Lahmeyer and Osae 1998).

During the eruption of the Nyiragongo Volcano in 2002, about one million m^3 of lava entered Lake Kivu, which could have triggered a potential gas release. Three weeks after the eruption, an emergency expedition confirmed, that the deep layers containing the dissolved gases were not affected by the inflowing lava. Actually, plume simulations showed that a much larger heat input was needed (Lorke et al. 2004). However, this unusual eruption created a series of north-south oriented fractures, which only stopped 4 kilometres from Lake Kivu. It is yet not sure how this weakened tectonic fault-line, which continues under the lake, will develop in the future (Komorowski et al. 2004).

In consequence, it is important to monitor the concentrations of dissolved gases, as well as the seismic and volcanic activities, in order to protect the riparian population. A better understanding of how methane is produced and why its production increased is, therefore, urgently needed.

1.6 A renewable source of energy

The dissolved methane in Lake Kivu could become a valuable renewable energy source for the two neighbouring countries, Rwanda and Congo. Actually, the total content of the methane corresponds to more than 10 times the current annual commercial energy consumption of the two countries together (Sathyendranath et al. 1991). This exploitation would have the additional advantage of diminishing the risk of a gas outburst, thus protecting the riparian population.

The Government of Rwanda has shown great interest in the extraction of the gas deposit in Lake Kivu. Actually, the country energy consumption is based over 90% on wood resources. In particular, the national electricity production is not sufficient to cover even one of the lowest average electricity consumption per person in the world. As such, the exploitation of the lake methane represents a unique opportunity to enhance Rwanda's economy and to reduce its problem of deforestation (Halbwachs 2003).

In 1963, the first gas extraction plant at Cape Rubona in Rwanda was set up by the Belgian Chemical Union. Based on an auto-pump system, the gas is extracted from water taken at 300 m depth using 850 meters long columns. After its enrichment in methane, the compressed gas is transported into the Bralirwa Brewery. This on-shore station has worked well during 40 years, but some deficiencies have led to costly maintenance works.

During the past 30 years, numerous projects to exploit this unusual methane deposit were financed by international organizations. A safe and environmentally sound exploitation is essential to protect the equilibrium in the lake during the slow modification of its stratification (Tietze 2000). As such, three distinct options were investigated: an on-shore alternative, a semi-off-shore alternative (the extraction system on a barge with the treatment on-shore) and an off-shore alternative (Tietze and Lorke 2003). Different novel techniques, to treat this mixture of gases, had to be developed in order to maximise the methane richness in the extracted gas while diminishing its loss during exploitation.

In 2003, the Humanitarian Aid Office of the European Community funded a study on the feasibility of a pilot station (Tietze and Lorke 2003). The authors proposed an off-shore pilot extraction plant with a capacity of 2.5 million cubic metres per year. In the future, micro-power plants (500,000 m^3/yr) could be adapted for tea-drying plant, brickworks or hospital. More powerful plants (6.5 Mio m^3/yr) could supply larger needs such as the electricity production, the domestic supply in towns, breweries and cement works. But up to now, none of the exploitation plans have been implemented.

2. Objectives

The purpose of this study is to quantify the nutrient cycling and the Lake Kivu internal fluxes of nutrients and carbon, especially related to the production and the lake-internal fluxes of methane. In particular the goal is:

- To determine the external inputs and the lake-internal fluxes of the biogenic elements C, N, P, Si
- To elucidate the relative importance of different processes (riverine inputs, wet and dry atmospheric deposition, internal loading from sediment and deep water) on the nutrient availability for primary production
- To estimate the recent methane production as a function of nutrient availability
- To predict scenarios for the further development of the Lake Kivu methane reservoir based on different strategies to limit eutrophication, as well as to exploit the methane.

3. Work program

3.1 Work program 1: Lake-internal nutrient cycling

This work program will be studied in close collaboration with the Congolese PhD student, the Rwandan MSc student and the Belgium partners. Nutrient cycling in Lake Kivu will be assessed by quantifying the three main processes of the cycle: external nutrient inputs, internal loading of nutrients, and sedimentation. The first two processes will be assessed by the African partners, while sedimentation will be studied at Eawag. In this project, I will mainly perform the analyses of the nutrients in solid phase. I will also coach and follow up the African partners and assure that the collaborations work efficiently.

External nutrients inputs

Nutrient inputs from external sources will be evaluated by analysing nutrient concentrations in the main inflows, as well as in the dry and wet deposition. Water samples from the larger inflows will be taken on a monthly basis during the wet season and analyzed for total and dissolved P, N and Si, using standard titration and photometric techniques. The N and P concentration of the dry and wet depositions have already been measured on the Congolese side by Jean-Jacques Bagalwa, with whom we will further collaborate. Similar measurements will be implemented on the Rwandan side. The deposition of Si can be neglected (Bootsma and Hecky 1993). In addition, the nutrient outputs caused by the Ruzizi River will not be measured, as the concentrations in the river can be assumed similar to the concentration of the surface water.

The sampling and analyses of the dissolved nutrients will be performed by the Africans partners. I will be in charge of the analyses of nutrients particulate forms at Eawag, as those methods can unfortunately not be implemented in the Africans laboratories.

Internal loading of nutrients

The nutrient concentration within the lake and its fluctuations during the year will be determined by locally measuring their concentrations on vertical profiles on a biweekly schedule. The samples will be collected from the surface to the depth, which is reached by seasonal mixing. They will be analyzed for O_2, pH, alkalinity, silica, nitrate, ammonia, nitrite, total nitrogen, dissolved and total phosphorus.

The cycle of nutrients in the oxic layer is strongly linked with the food web of the lake, which is currently studied by the Belgian project ECOSYKI. Since 2004 and every two weeks, this team has been analyzing the nutrient concentrations in lake samples taken in the mixed layer, down to 90 m depth. They will therefore continue to do these measurements and be responsible for this section of the work program. They will also create an ecological model, representing the nutrient cycling within the mixed layer.

Sedimentation

The export of nutrients from the epilimnion (export production) will be quantified by analyzing the nutrient concentration in the material collected in sediment traps. Five sediment traps per mooring will be fixed in the eastern and the southern part of the lake and will be deployed in the anoxic zone where higher organisms are absent. The material collected in the sediment traps will be removed on a monthly basis by the African partners and analyzed at Eawag for total particulate dry matter, organic C and N, biogenic Si, total and organic P. Analyzing the isotopic composition of C and N will reveal changes in productivity and denitrification rates. Further, the recent production of methane through the decomposition of the sediments could be estimated by the input of organic material and nutrients to the deep waters, determined by the export production.

The recent history of net nutrient export to the sediments will be reconstructed by analyzing a sediment core. During the first expedition, short sediment cores will be taken within the anoxic deep water of the lake but at a depth where gas concentrations allow retrieving an undisturbed sediment core. The sediment core will be analyzed for organic C, N, P and biogenic Si concentrations. Core dating will be performed at Eawag using the radionuclide ^{137}Cs or ^{210}Pb, as ^{14}C dating is not possible due to the existence of magmatic carbon sources in the lake.

The analyses of C, N and P in solid phase will be performed at Eawag, under the supervision of Beat Müller and Ruth Stierli. Particulate biogenic silica will be measured under the supervision of Beat Müller and Bernhard Wehrli. Those methods can unfortunately not be implemented in the Africans laboratories. However, during stays from Africans partners at Eawag, they will learn how to perform these methods.

This work program will produce two scientific articles. One article will be written by the Belgian partners on ecological nutrient cycling in the oxic layer of the lake. Another article will be written by the African partners in collaboration with the Eawag, on the large-scale biogeochemical cycle of the entire lake. This paper will use data collected from the external nutrient input and the sedimentation sections. Collaboration and data sharing between all partners will be applied.

3.2 Work program 2: physical mixing processes

In this work program, the mixing and transport processes occurring in Lake Kivu will be quantified. The upward transport due to the hydrothermal sources as well as the double diffusive convection will allow understanding and modelling the internal cycling of nutrient. Double-diffusive convection is an absolutely outstanding phenomenon in Lake Kivu. This process is particularly fascinating in this case as not only temperature and dissolved solids but also the dissolved CO_2 and CH_4 contribute to the density stratification.

In the first part of the project, temperature microstructure profiles collected during previous expeditions will be analyzed to quantify the mixing by double diffusion. During the first expedition, 5 thermistors fixed at a sediment mooring line will be installed and will be used to record the water temperature quasi-continuously. In addition, a CTD profile with a very high accuracy will be taken in the deepest part of the lake. These measurements, together with vertical temperature profiles, will allow analysing the internal energetics (internal waves), the vertical diffusivity and the vertical advective movements of the water column, such as internal baroclinic motions and uplift. It is planned to collect the temperature data every month during two consecutive years.

The quantitative output of this physical analysis will be synthesized to the nutrient fluxes in the model. However, the advection is critical to evaluate, as neither the flux nor the salt concentrations of the hydrothermal sources are known. The model will therefore be used with vertical advection as fit parameter.

The double-diffusive convection will be studied in a diploma thesis or by an intern at Eawag, under the supervision of Alfred Wüest and Martin Schmid. I will be partly involved in this project and will be cited as a contributing author in the published scientific article. My main task will be the modelling of the

physical processes, under Martin Schmid supervision. This work will produce a second article describing the model calibration and the estimation of the advection.

3.3 Work program 3: Sources and sinks of methane

In Lake Kivu, CH_4 contributes to about 80% of the total gas pressures of the dissolved gases in the deep waters, although its volume represents only 20% of the total gases. This implies that a gas release would be triggered by a local supersaturation of CH_4. This work program will therefore investigate the processes that lead to the formation and the oxidation of methane. The detailed understanding of those processes is also required for the future development of a sustainable strategy to exploit the CH_4 deposit in Lake Kivu.

A deep profile of methane concentration has already been measured in the water column in 2004, showing an increased by 15% in 30 years. Other methane profiles won't be measured, as no significant increase over 2 years can be expected.

The sources of methane will be investigated by analysing its carbon isotopes and ethane concentration. For this, water samples will be collected in 250 ml gas-tied glass bottles, during the first measurement campaign. Carbon isotopes of dissolved methane will be measured every 20 m in two water column profiles. In addition, four sediment samples per cores will be taken every 5 cm at these two locations, and analysed for their carbon isotopes. The $\delta^{13}C_{CH4}$ values will allow us to understand where methane is produced and oxidized. These values should also confirm the biogenic origin of methane. This origin will be further investigated by measuring ethane concentration in water samples with a GC at Eawag. Actually, bacterial gas contains only 20 ppm of higher hydrocarbons, as opposed to thermocatalytic gas with higher concentrations (Tietze et al. 1980).

Schoell et al. (1988) estimated that the sources of methane were composed by two third from the reduction of magmatic carbon dioxide and by one third from the fermentation in the sediments. Similar measurements of carbon isotopes, deuterium isotopes and ^{14}C concentrations will be performed to identify eventual modifications. Pure gas samples will therefore be collected at two depths around 300 m during the first expedition, using a new device developed at Eawag. The $\delta^{13}C_{CH4}$ and δD_{CH4} values of these two samples will be measured at Eawag, as well as δD_{H2O} in water samples from the same depths. Sampling of dissolved methane for the measurement of its ^{14}C concentration will be done during the second expedition, as a sampling strategy needs to be explored. Time is also needed to find a laboratory, which can separate methane and carbon dioxide. Then, the separated methane will be oxidised to CO_2, so that its ^{14}C can be measured at the AMS ^{14}C laboratory at ETH in Zurich. Concerning ^{14}C concentration of the organic matter in the sediments, no further measurements are needed as they were already determined in the 1970's. ^{14}C concentrations of 26% were found with an age of about 11 000 +/- 250 years B.P (Schoell et al. 1988; Tietze et al. 1980). However, ^{14}C signal from the atmosphere needs to be estimated. For this, either a profile of a tracer, probably Neon, will be measured during the second expedition or surface samples will be analysed for ^{14}C. All these measurements will be put together and will allow us to determine the current proportion between the two biogenic processes of methane production. Detected changes could clarify the recent increase in methane concentration.

The location and organisms responsible for methane oxidation, which limits the methane accumulation, is still not clearly understood. Incubation experiments will be performed, in order to analyze the oxidation rates of CH_4 as a function of depth. To detect the organisms responsible for CH_4 oxidation in Lake Kivu, molecular tools such as FISH (fluorescence in-situ hybridization) will be used. This method is available at Eawag and will allow identifying and quantifying the bacteria or archaea responsible for aerobic or anaerobic methane oxidation. For the anaerobic methane oxidation, I will investigate the bacteria ANME-1, ANME-2, Eub and the archea Arch-915. For the aerobic oxidation, I will look for MOB type 1 and 2 in the samples. As bacteria use H_2S to oxidise methane, measurements of H_2S and its combination with C-cycle will be performed under the supervision of Bernhard Wehrli.

This work program will be used as an important input for the model, describing the behaviour of methane as a function of depth. I will perform all the experiments at Eawag under Carsten Schubert's supervision and with the help of Francisco Vasquez. This work will be the subject for a scientific article as first author.

3.4 Work program 4: Biogeochemical and physical model of Lake Kivu

In this work program, all the previous analyses will be summarized in a model linking the internal nutrient cycling within the lake with the methane production. Under the supervision of Martin Schmid, I will create the model at Eawag. The planning phase will start in the first year, to ensure that the needed parameters are accurately quantified during the measurement campaigns. The development of the model will be done in the second year, as soon as data are available. Model calibration, sensitivity analysis and parameters estimation for the various processes will be performed. The model will then be applied to predict effects on the future development of the methane deposit from various scenarios to limit eutrophication and to exploit the methane.

This one-dimensional model will be performed with AQUASIM, a lake simulation software designed to simulate physical mixing and biogeochemical processes in aquatic systems. Due to the long residence time of nutrients in the lake, horizontal homogeneity can be assumed at least in the deep waters of the main basin. A one-dimensional model should therefore be sufficient to describe the main features of nutrient cycling within the lake. However, this assumption will be verified by examining spatial homogeneity of chlorophyll using remote sensing. This task is the subject of a current diploma thesis, which started in February 2006 with the Remote Sensing Laboratories at the University of Zurich-Irchel.

Such a model will be a powerful tool for decision-makers, as it could predict the future development of the methane reservoir based on different strategies to limit eutrophication and to exploit the methane. It may also assure a more sustainable management of the lake in the future.

This model will be published in a scientific article.

4. Organization

During the Ph.D. one measurement campaign each year is planned in Kibuye (Rwanda) and Bukavu (Congo). The first campaign was three weeks in length. The second campaign will be longer about 2 to 3 months, as previous experiences showed that continuous formation of local partners is essential to assure good quality of the results. However, the length and the date of each stay will be adapted to the actual situation of the measurement campaign and the project work progress.

During stays in Rwanda and Congo, fieldworks, discussion of measurements, analytical methods and organizational details, as well as educational work will be performed.

In Switzerland, samples will be analyzed, collected data will be evaluated and discussed, publications will be written, the next campaign will be prepared and organizational issues (scientific exchange, technical support in Rwanda and Congo etc.) will be addressed.

A workshop will be organized towards the end of the project to disseminate the results to decision makers and Governmental representatives to discuss options for the future management of the lake, especially the CH_4 exploitation.

4.1 Cooperation between the different Institutes

Cooperation between ISP Bukavu (Congo), UNR Butare (Rwanda) and Eawag

Within this project, a strong cooperation between the three institutes is of greatest importance. ISP (Institut Supérieur Pédagogique) in Bukavu and UNR (Université Nationale du Rwanda) in Butare will contribute to the sampling activities and analytical work and provide the infrastructures needed for the project. The Eawag will provide expertise in fieldwork, physical and chemical analysis and quality assurance, and will perform analyses (isotopes, sediment material) and evaluations (numerical modelling, data analysis), which are not currently undertaken at both African institutes. Know-how transfer and instructions on these topics will be made during a first stay of the African students at the beginning of the project. A second stay in Switzerland is planned during the writing process.

The scientific outcome of the project will be published as joint articles in international, reviewed journals.

Collaboration with the ECOSYKI project

The project ECOSYKI aims at studying and modelling the functioning of the pelagic ecosystem of Lake Kivu, for the understanding and the description of the processes driving its productivity. This project started in 2004 and involves African and European scientific partners, from ISP in Congo and UNR in Rwanda and the Universities of Namur and Louvain-la-Neuve in Belgium.

The ECOSYKI project is focused on our second hypothesis: the modification of the nutrient cycling due to changes in the internal food web induced by *Limnothrissa miodon*. This PhD project will study the influence of external anthropogenic inputs on the nutrient cycling and will model the methane production as a function of the nutrient availability. As such, both projects are strongly linked and work will be performed in closed collaboration. Their ecological model and our biogeochemical model could then be combined.

4.3 Involved Eawag Personal

In its interdisciplinary approach, the Ph.D. thesis can only succeed with the help and involvement of specialists from the different fields addressed. At Eawag, the following people have agreed to support the Ph.D. thesis:

Prof. Bernhard Wehrli	Analytical (H_2S and SO_4) chemistry, nutrient chemistry
Dr. Beat Müller	Solid phase and sediment analysis, phosphorus speciation

Dr. Carsten Schubert	Microbiology, gas and isotopes analysis
Prof. Alfred Wüest	Physical processes
Dr. Martin Schmid	Numerical modelling

4.4 Additional manpower

As stated in the work program some working tasks of this project will be performed by other parties. So far the following people will be performing one task of the working section:

From FUNDP (Facultés Universitaires Notre-Dame de la Paix) in Namur, Belgium:

Prof. Jean-Pierre Descy	Ecological processes

From ISP (Institut Supérieur Pédagogique) in Bukavu, Congo

Prof. Boniface Kaningini	main foreign partner
Fabrice Muvundja	Ph.D student
Georges Alunga	technician

From the UNR (Université Nationale du Rwanda) in Butare, Rwanda:

Prof. Claudien Kabera	coordinator in UNR Rwanda

From the Remote Sensing Laboratory, at University of Zurich-Irchel, Switzerland:

Toni Frank	Diploma student
Dr. Mathias Kneubühler	Supervisor
Dr. Tobias Kellenberger	Research Scientist

5. Time schedule

Legend: tasks performed by
(orange) Natacha Pasche
(green) Fabrice Muvundja / Rwandan MSc student
(light blue) Intern or diploma student in physics
(orange/green stripes) Natacha Pasche and African partners
(orange/blue stripes) Natacha Pasche and Intern or diploma student in physics

Months	activities	work program 1: nutrient cycling	work program 2: physics	work program 3: methane, microbiology	work program 4: model	African collaboration
1.2006	literature reading					take contact, discuss workprograms
2.2006						
3.2006	preparing expedition					
4.2006						
5.2006	Expedition	analyse N,P,Si (deep profile) , install sediment traps, take sediment cores	CTD profiles, install thermistors	taking water samples, incubation		common fieldworks learn analytical methods
6.2006	analysis of collected samples	Anions/cations	CTD profiles	incubations		every month: receiving data of thermistor, N,P,Si conc from 0-100m
7.2006			prepare and treat the microstructure data	FISH		
8.2006		N,P, Si in sediment cores, dating		gas concentration	planning of the model	
9.2006				isotopes		Ph.D student at Eawag
10.2006		sediment collected in sediment traps	temperature series			
11.2006	inter-pretation of results	Interpret results	Interpret results	Interpret results		
12.2006						every month: receiving data of thermistor, N,P,Si conc from 0-100m
1.2007						
2.2007	preparing expedition					
3.2007	Expedition	analyse N,P,Si (deep profile), take sediment cores	CTD profiles, microstructure	water and gas samples, incubations, Neon profile, ^{14}C sampling		common fieldworks, formation, discuss measurements
4.2007						
5.2007						

Months	activities	work program 1: nutrient cycling	work program 2: physics	work program 3: methane, microbiology	work program 4: model	African collaboration
6.2007	analysis of collected samples		CTD profiles	incubations	creation of the model	every month: receiving data of thermistor, N,P,Si concentration from 0-100m
7.2007				^{14}C in CH4		
8.2007		N,P, Si in sediment cores, dating	temperature series	Neon concentration		
9.2007						
10.2007		sediment collected in sediment traps	Interpret results			
11.2007	inter-pretation of results	Interpret results		Interpret results	Improvement and sensitivity analysis of the model	
12.2007						
1.2008		quantify nutrient cycling	quantify transport processes	quantify CH_4 production/ oxydation		
2.2008						
3.2008	improve the model					
4.2008						
5.2008						
6.2008	End of measuring campaign	remove mooring	remove thermistors		test different scenarios in model	stop samplings
7.2008	test different scenarios in model	sediment collected in sediment traps	temperature series			discussions, work exchange
8.2008						
9.2008	preparing workshop					preparing workshop
10.2008						
11.2008	workshop	Presenting results and different scenarios. Advices on future management of the lake. Discussion about the monitoring of the gas concentration				
12.2008	writing processes					Ph.D student at eawag
1.2009						
2.2009						
3.2009						
4.2009						writing
5.2009						
6.2009						

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