Modelling the reinjection of deep-water after methane extraction in Lake Kivu

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Abstract

The deep-water of the East African Lake Kivu contains large amounts of dissolved methane (~60 km^3 STP) and carbon dioxide (~300 km^3 STP). To utilize the methane as an energy resource valued at many billion dollars and to reduce the risk of an uncontrolled gas eruption, the governments of the Democratic Republic of the Congo and Rwanda have decided to begin extracting the methane. The Government of Rwanda has issued first concessions for pilot plants to start extraction in the fall 2008.

There are two major risks involved with extracting methane from Lake Kivu: (i) disrupting the lake stratification, which could increase the probability of a gas eruption, and (ii) enhancing the transport of nutrients from the deep-water to the surface water, which could negatively affect the lake ecosystem. These two risks should be kept in mind while trying to (iii) minimize the methane loss and maximize the extraction of the naturally produced methane in the lake. In this study, a one-dimensional model was developed and applied to predict the stratification, in addition to the gas and nutrient concentration profiles, for a 100 year period of various methane extraction *Scenario*s in Lake Kivu. The goal of the modelling is to find an optimal strategy that acceptably fulfils all three concerns (safety, lake ecology and socio-economic benefit).

The resulting simulations let us conclude that (a) the deep-water **MUST NOT be diluted** with surface water to adjust its density before reinjection into the lake, and that (b) the degassed deep-water can **not be reinjected above 200 m depth**, where this would lead to both strongly increased nutrient fluxes into the surface layer and unacceptable algae growth. Despite these two restrictions it is possible to harvest ~90% of the maximal possible methane without risking a gas eruption and without sacrificing the ecological integrity of the lake. The key findings are listed in the executive summary.

How to read this report?

This report consists of two parts: (PART I) a summary (Sections 1 and 2), which contains the conclusions (executive summary) and an outline of the decision-making approach; and (PART II) a technical part, where the lake data (Section 3), the modelling approach (Sections 4), the evaluation procedure (Sections 5 and 6) and the model simulations (Section 7) are given in detail. The Appendix contains useful technical details (such as formulas). Readers interested only in the outcome and implications can refer to PART I of this report. PART II serves as a detailed documentation of (i) the model input data, (ii) the interpretation of the simulation results and (iii) for further planning and future revisions of model calculations.

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PART I: Summary of Results

1. Executive summary

The deep-water of the East African Rift Lake Kivu contains ~60 km^3 (STP) of dissolved methane and ~300 km^3 (STP) of dissolved carbon dioxide. While the gases pose a serious risk to all oxygen-dependent life in the vicinity of the lake, the methane gas also provides an accessible (and partly renewable) energy resource, valued at many billions of dollars, for the Kivu region.

The Governments of Rwanda and DR of the Congo decided to award concessions for methane extraction to private investors under specific management prescriptions (MP 2009). These requirements will (i) ensure the safety of the population, and (ii) conserve the integrity of the lake ecosystem while (iii) maximizing the methane harvest by minimizing the methane loss to the atmosphere and to the oxic surface water. This report summarizes the results of model calculations that aim at supporting the development of an optimal strategy of methane extraction from Lake Kivu.

Most of the methane is stored in the deep part of the lake, indicated as the *Resource Zone* in Figure 1.1. The principle for extracting the methane from this Zone is straightforward (Figure 1.2): initially a tube is placed vertically into the Resource Zone. As the deep-water moves upwards in the tube it experiences decreasing pressure and bubbles are formed. The bubbling water is lighter (buoyant) and drives an upward flow through the tube. Deep-water is pulled upward while

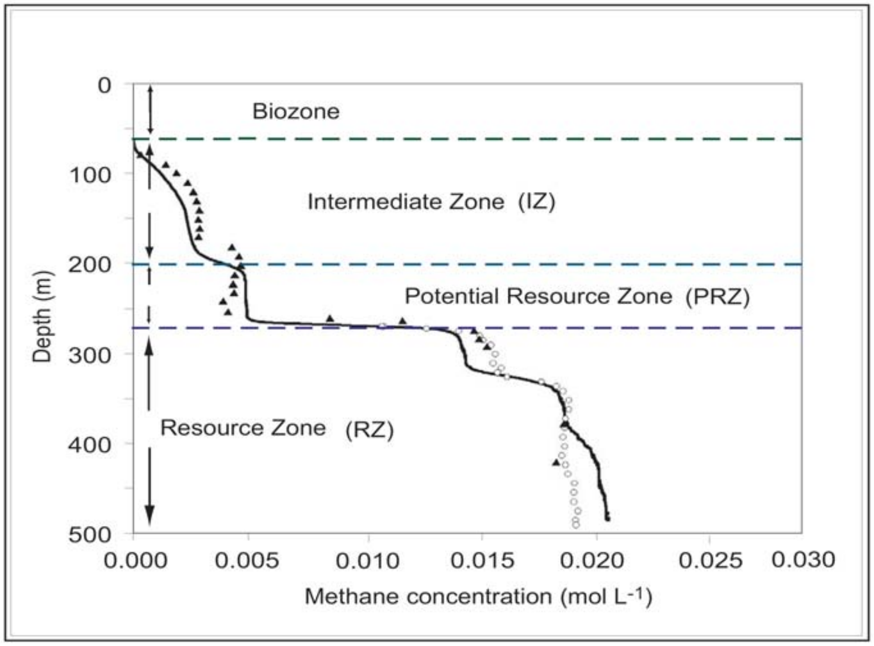


Figure 1.1 *Definition of the terms for the identification of the water bodies, as listed in Table 1.1. The boundaries are drawn according to the vertical structure of the methane profile. For volumes of water and methane, see Table 1.1. The triangles and circles depict observed methane concentrations; the black line represents a continuous methane profile, assuming that methane concentrations are proportional to CO_2 concentrations.*

continuously forming bubbles, which results in a self-sustaining (self-siphoning) flow. The gases are then stripped from the withdrawn deep-water using a separator near the lake surface. Following the washing of the extracted raw gases, the refined gases are transferred in underwater pipelines to the shore, where the methane can be used for distribution, bottling or electricity.

The gas-depleted deep-water then needs to be reinjected into the Lake. This reinjection could potentially lead to long-term negative changes including: (1) excessive algae growth causing nuisance to the population and damage to the lake (such as (i) zones deprived of oxygen and related fish kills, (ii) changes in the composition of the plankton, which is the food base for fisheries, or (iii) toxic algae blooms) as a result of enhanced nutrient fluxes from the deep-water to the surface, and (2) weakening the extremely stable density stratification (i.e. salty/heavier water at depth, underneath of fresher/lighter water at the surface), which is presently preventing the gases from diffusing (and mixing) upwards and is therefore crucial for safety as well as for the methane accumulation in the lake.

The concept of the gas extraction described above is schematically identical for the different proposed projects that may vary in design and operation parameters. Therefore, the aim of this study is to estimate the effects of different extraction *Scenarios* on the development of Lake Kivu's density stratification, nutrient fluxes and gas concentrations. The vertical distribution of the gases is of particular concern as this affects the safety. The extraction *Scenarios* (Table 2.3.2) were developed in co-operation with engineers working on Lake Kivu methane extraction projects. These *Scenarios*, as well as the "no extraction" *Scenario* (O) without methane

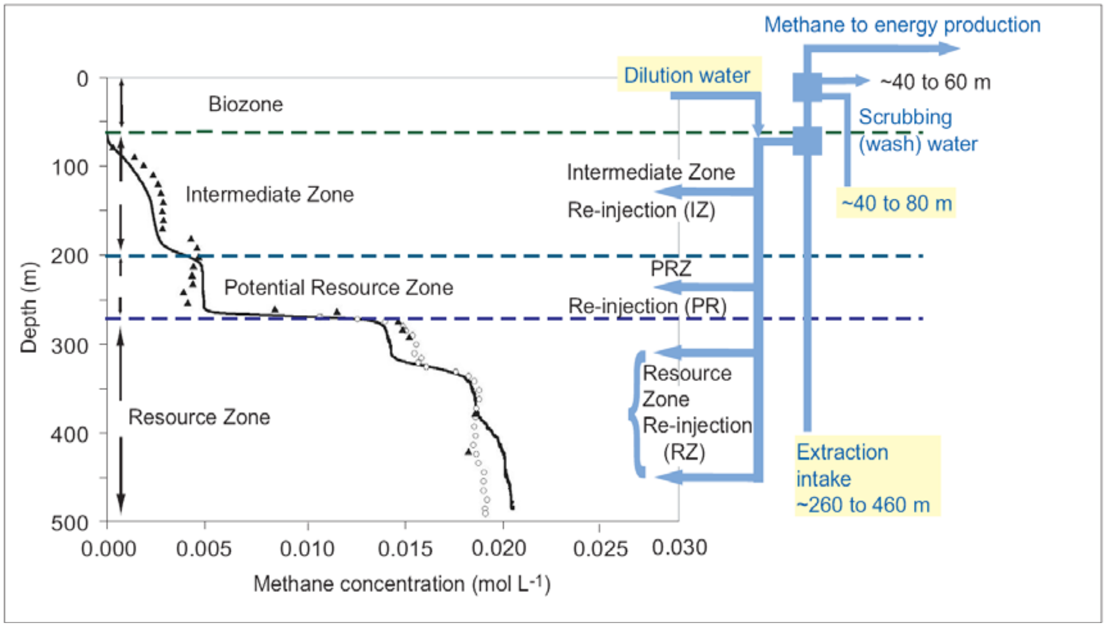


Figure 1.2 *Methane-rich deep-water is extracted from the RZ. After stripping the gases the methane-depleted deep-water is reinjected into the lake. This report studies the consequences for different reinjection Scenarios releasing the methane-depleted water into the IZ (Scenarios IZ1 to IZ5), into the PRZ (Scenario PR1) and the RZ (Scenarios RZ1 to RZ6).*

exploitation, were simulated with a one-dimensional model specifically designed for this purpose and implemented with the software AQUASIM. Density stratification, gas concentrations and nutrient fluxes were simulated for extracting operations over a 100 year period.

In order to understand the simulation results, it is important to take into account a few particularities of Lake Kivu's stratification. These specialties comprise: (1) As a consequence of the density stratification, the deep-water of Lake Kivu is decoupled from the surface waters, i.e. there is almost no exchange of water mass between the deep waters below 260 m depth and the surface water. (2) Due to this confinement gases as well as nutrients and other dissolved substances accumulate to very high concentrations in the deep waters. (3) Despite the strong stratification and the suppressed vertical exchange of water, there is still upward transport of the nutrients and gases from the deep-water towards the surface. This upward flux is due to the slow movement, so-called upwelling of the water layers (i.e. uplift) of up to ~1 m per year. This upwelling is caused by the inflow of subaquatic sources at various depths within the deep-water. In this report it is assumed that ~36% of the lake water outflow to the Ruzizi River stems from such subaquatic inflows.

The results of the simulations can be summarized as follows:

A) Guiding Principle *"Safety"*

(1) ***Maintaining stable lake stratification*** - The best approach to eliminate any risk for a gas eruption would be to completely remove all the gases from Lake Kivu immediately. However, this would not permit the utilization of methane as a resource during the next few decades and is therefore not considered an option. The most ideal approach is to the keep the lake stratification as stable as possible in order to minimize the risk of a gas eruption and furthermore to minimize the loss of the methane resource. Most of the *Scenarios* (Table 2.3.2) simulated here will be able to maintain 50% of the natural stability, which we consider more than acceptable in view of the decreasing gas contents due to the extraction operation.

(2) ***Disadvantage of shallow reinjection*** - The lake stratification is drastically weakened when water is reinjected into the *Biozone* (not acceptable) or into the *Intermediate Zone.* This disadvantage is reduced with deeper reinjection (*Potential Resource Zone)*.

(3) ***Advantage of deep reinjection*** - Reinjecting water into the *Resource Zone* is the *Scenario* with the least disturbance to the density stratification.

B) Guiding Principle *“Lake Ecological Integrity”*

(4) ***Minimizing nutrient fluxes into the Biozone*** **-** The best approach for conserving the lake ecological integrity would be to extract methane from the *Resource Zone* water and then to reinject this water back into the same zone. The deep-water would then be depleted in methane but the stratification of all other water properties would remain almost unchanged. Particularly the nutrient fluxes into the *Biozone*, which affect algae growth, would remain at their natural level.

(5) ***Release into the Biozone*** **-** Methane-depleted reinject-water, which consists of extremely nutrient-rich deep-water, must **STRICTLY NOT** be released into the *Biozone*. Its release would increase the nutrient flux into the *Biozone* (and subsequently cause algae growth) to an unacceptable level even for a small rate of methane extraction (equivalent to a few MW of electrical energy production).

(6) ***The role of upwelling by subaquatic springs*** - Subaquatic springs in Lake Kivu induce a continuous upward flow of water (~1.3 km^3 per year) and cause an upwelling (uplift) of the lake water layers towards the surface (~0.7 m per year into the *Biozone*). If methane-depleted reinject-water is released directly below the *Biozone* into the *Intermediate Zone*, the nutrient content below the *Biozone* would increase. The upwelling water would consequently flush an increased amount of nutrients into the *Biozone*.

Despite that upwelling is slow, the nutrients would reach the *Biozone* already after a few decades. Therefore, the reinjection of nutrient-rich water into the *Intermediate Zone* (defined as layer from 60 to 200 m depth) would only be **acceptable for small extraction rates** of less than a few 10 MW of equivalent electricity production, which is much less then the anticipated extraction of several 100 MW of equivalent electrical energy. For those high methane extraction rates, **reinjecting deep-water into the middle-to-upper *Intermediate Zone* is not acceptable.**

(7) ***Dilution of reinject-water*** - If reinject-water is to be re-stratified in the *Intermediate Zone* (small amounts only, such as during pilot plant operations or for short periods of time), then the density of the methane-depleted deep-water has to be decreased to meet the density of the lake water in the *Intermediate Zone***.** This density adjustment can be achieved by diluting the reinject-water with near-surface (lighter) water. Removing water for dilution from the surface and releasing it at a greater depth would **immediately increase** the upward flow of deep-water into the *Biozone*. Therefore, dilution-water (if used at all) has to be taken from **STRICTLY BELOW 80 m** depth in order not to increase the upward flux of nutrients.

However, any dilution, including with water from below 80 m depth, will increase the flux of nutrients to the surface in the long term. Extraction operations **without dilution-water** have a clear **advantage for the ecological integrity of the lake**. Furthermore, using dilution-water only negligibly benefits the amount of harvestable methane, and therefore we conclude that there is no justification of using dilution-water.

C) Guiding Principle *"Economic benefit"*

(8) ***Maximum methane harvest*** **-** The maximum methane harvesting would be achieved if the reinject-water were released at the surface, which would prevent any dilution of methane-containing deep-water. Additionally, this approach would minimize the loss of methane to the *Biozone*. However, the deep-water is enormously nutrient-rich and therefore this *Scenario* is unacceptable. From the tested *Scenarios*, we found that the maximum methane harvest would be achieved for the *Intermediate Zone* reinjection *Scenario*. This *Scenario* serves, therefore, as a reference for the maximum methane harvest. Depending on the formation rate of new methane, ~50 to ~70 km^3 can be harvested during the next 100 years.

D) Finding a compromise among the three Guiding Principles

(9) ***Structured decision-making*** - A so-called structured decision-making approach (Reckhow 1994; Reitsma 1996) has been chosen to compare the advantages and disadvantages of the different possible extraction *Scenarios* (Table 2.3.2). This allows a comprehensible and transparent way of comparing the *Scenarios* along well-defined *Objectives* (Table 2.2.2). Our approach is to stipulate that the overall lake stability shall never be lowered by more than 50% relative to natural (undisturbed; no extraction) and that the upward flux of nutrients are never enhanced by more than 25% relative to natural conditions. Several *Scenarios* fulfil the requirements of these *Objectives* (Table 2.4.1).

(10) **Optimal Scenario –** There are some limited differences among the *Scenarios* that fulfil the *Objectives* to maintain "Safety" and "Lake ecological integrity". We concluded that reinjection **without dilution into the *Resource Zone*** carries the most advantages. This *Scenario* allows almost a maximal amount of methane to be extracted. In addition, this *Scenario* is not sensitive towards the "completeness" of methane extraction at the extraction facility. Methane that is not effectively extracted, and which is released back into the lake (with the reinject-water), would thereby return back into the *Resource Zone*. Therefore, such incompletely extracted methane could be harvested in the (far) future and would not be lost as a resource. Therefore, **it is not acceptable diluting the Resource Zone** with water which is from outside the **Resource Zone** (such as by using dilution-water).

It is realistic to harvest the methane from Lake Kivu while following the three *Guiding Principles* concerning safety, maintaining the lake ecological integrity and achieving high methane output. The ideal *Scenario*, which fulfils these restrictions on internal nutrient cycling and maintaining the lake stratification, will most likely access reduced amounts of methane. The ***available methane*** in the lake will be reduced by ~2% whereas the maximal ***methane harvest*** can be reduced by up to ~12%, relative to the economically most favourable *Scenario*. The differences of ***methane harvest*** among the *Scenarios*, which fulfil the *Principles* concerning safety and lake ecological integrity, are only a few %.

Due to this optimization potential of a few % in ***methane harvest***, we recommend to analyze the best strategy in more details. Such a study has to include: (i) the optimization of the methane extraction efficiency and of the power conversion efficiency, (ii) the flexible removal of CO_2 and (iii) the optimized vertical stacking of the reinjection water.

(11) ***Robust strategy*** - Some of the assumptions included in the model simulations, are not well-known (or not yet defined) and need to be reconsidered in future modelling, after an understanding of the lake processes and the extraction processes has improved and more planning information has become available. The two most relevant uncertainties with respect to the model output are (i) the rate of new methane formation, and (ii) the discharge-rate of the subaquatic sources. Furthermore, (iii) the rate of methane extraction, which is dependent on political and economic developments, is not yet well-defined. Fortunately, the comparison of the different *Scenarios* (evaluation procedure in Section 6) show that the "ranking" of the different *Scenarios* does not depend sensitively on these three assumptions.

Probably the most important uncertainty is the concentration level at which methane can still be efficiently and economically harvested. In this report, we assumed this level at 5 mol m^{-3}. If practical experience should turn out that this **level is significantly different**, then the details (especially the timing) of the **extraction strategy** (as described in RZ6) **need to be adapted**.

(12) ***Future strategy adjustment*** - The results of the simulations presented in this report are sufficiently robust to be used as a guide for projecting the methane extraction from Lake Kivu into the upcoming decades. Nevertheless, adjustments to the strategy or to the targets will be necessary in the future. The model contains unknowns and the simulation output carries uncertainties (see item 11) including the two most important internal lake processes: the water inflows from the deep-water sources, and the new methane formation in the lake. Furthermore, their constancy is not guaranteed in the future (natural

variability). It is therefore **essential to continuously monitor** the evolution of the stratification as well as the gas and nutrient concentrations in the lake. Such monitoring will allow for a reaction to unforeseen developments by adjusting the methane harvesting. We recommend **re-evaluating** the **optimal strategy** whenever **major concessions** are granted and the simulations should be repeated at least every 10 to 20 years by using the newest profiles and adjusting the model parameters according to the latest knowledge on the functioning of the lake. The harvesting strategy should then be optimized based on these new observations and simulation results, as well as the experience gained from the ongoing gas extractions and the technology improvements in methane harvesting methods.

Table 1.1 ***Water bodies of Lake Kivu (terms as used in report)***

Lake-internal water body	Area [km^2]	Water volume [km^3]	CH_4 volume [km^3]	Estimated CH_4 new formation [km^3 yr^{-1}] (*)
Biozone (0 to 60 m depth)	2'370 to 2'020	134		
Intermediate Zone (60 to 200 depth)	2'020 to 1'280	229	11.7	0.17 (*)
Potential Resource Zone (200 to 260 m)	1'280 to 1'050	70	8.5	0.05 (*)
Resource Zone (260 to 485 m depth)	1'050 to 0	118	44.7	0.24 (*)
Total	**2'370**	**550**	**63.9**	**0.45** (*)

(") *This new CH_4 formation rate (120 g-C m^{-2} yr^{-1}) was used to reproduce concentrations measured by Tietze (1978) and Schmid et al (2005a,b). The most recent data (Pasche et al submit), however, indicate that this new CH_4 formation rate is an overestimate. For planning purposes, we recommend using 50% of the above listed values as the most probable new CH_4 formation rate.*

2. Background to executive summary

This Section provides background on the Lake Kivu functioning (internal lake processes), the definition of the extraction *Scenarios*, the model simulations, and the evaluation of the extraction *Scenarios*. In addition the procedure for determining the optimal *Scenarios* is explained.

Information on the modelling approach (Sections 3, 4, 5), the decision-making process (Section 6) and the model simulations (Section 7), as well as the Appendix (Section 8) is presented in more detail in the second part of the report.

2.1 Lake Kivu: stratification of methane and nutrients

Vertical structure of lake water - Lake Kivu is one of the most fascinating lakes on earth. Surrounded by mountains, this Rift Lake is located at an altitude of 1462 m between Rwanda and the Democratic Republic of the Congo (DRC). The lake water body has a maximum depth of 485 m, contains a volume of 550 km^3 and covers a surface area of 2370 km^2. During the dry season the lake surface cools off, causing convective mixing (cooler water is heavier than warmer water) from the surface down to ~50 to ~70 m depth. This surface layer - called the *Biozone* in this report (Table 2.1.1) - is oxygenated every year during convective mixing in the dry season. The *Biozone* ecosystem hosts all the “higher” life in Lake Kivu, such as fishes, zooplankton, etc. that cannot survive without oxygen. The oxygen originates from the atmosphere and the algae, which grow in the *Biozone.* Below the *Biozone* (i.e. below ~60 m) the lake water body is permanently density-stratified and anoxic (free of oxygen) at all times. Enormous amounts of gases have accumulated there during hundreds of years; about ~300 km^3 (STP) of carbon dioxide (CO_2) and ~60 km^3 (STP) of methane (CH_4), are trapped in the deep waters of the lake (STP: gas volume at 0 °C and 1 atm). The gasses are dissolved in the water similar to the carbon dioxide dissolved in bottled mineral water.

Methane in Lake Kivu - The CH_4 in Lake Kivu is a renewable energy resource, as new CH_4 is continuously formed. Due to the unusually stable stratification and the large depth of Lake Kivu, the CH_4 remains stored in the deep water for a term of several hundred years. CH_4 is transported to the *Biozone* via upwelling water, where it is either consumed by microorganisms or diffused into the atmosphere. The microorganisms need either oxygen, sulphate, or nitrate to degrade CH_4. Because these three substances are only available in the upper layers, CH_4 is well preserved in the deep-water and can accumulate undisturbed.

The CH_4 stems from (i) bacterial fermentation of settling organic matter (mainly in the IZ and PRZ) whereas in the RZ in addition also (ii) CO_2 reduction and/or (iii) inflow of geogenic CH_4 contribute to the build-up of the CH_4 resources. The exact composition of these three different sources is still the subject of scientific research.

Table 2.1.1 Definition of the terms used for the lake water bodies

In this report, we use consistently the following terms to distinguish the different vertical layers of the Lake Kivu water body:

***Biozone (BZ)* -** This is the upper, oxygenated water body of Lake Kivu (~50 to ~70 m deep; Figure 1.2), where algae provide food for zooplankton and fish. The *Biozone* becomes homogenised during the dry (cooler) season but is strongly stratified during the rainy (warmer) season. The *Biozone* water contains oxygen, reaching to ~60 m during the dry (cooler) season. During the rainy (warmer) season the oxygen is partly depleted in the lower *Biozone*. The CH_4 content in the *Biozone* is negligible. If not indicated otherwise, the *Biozone* refers to the top 60 m.

***Intermediate Zone (IZ)* -** This zone is located between the *Biozone* and the *Potential Resource Zone* and ranges from 60 to 200 m depth. The *Intermediate Zone* contains 11.7 km^3 of CH_4 (Table 1.1), which is not expected to be harvestable within the 100 yr of simulation.

***Potential Resource Zone (PRZ)* -** In this zone, which is confined by the *Intermediate Zone* above 200 m and by the *Resource Zone* below 260 m depth, a significant part of the CH_4 is stored (8.5 km^3, Table 1.1). Some of this CH_4 may become harvestable within the next few decades, if CH_4 accumulation is continuing or if future technologies advance.

Resource Zone (RZ)* -** The *Resource Zone* contains the entire water body below the *Potential Resource Zone* from 260 m to the maximum depth of 485 m. This water body not only contains most of the CH_4 at harvestable level (~44.7 km^3) but also enormous amounts of nutrients. This deep-water is CO_2-rich and salty and therefore significantly denser (heavier) than the upper water layers. In this report we occasionally distinguish between ***Upper RZ (260 to 320 m depth) and ***Lower RZ*** (320 to 485 m depth).

***Main Density Gradient* -** The steep gradient from 255 to 262 m depth forms the highest density difference within the vertical structure of Lake Kivu. Although there are other density interfaces in the lake, this gradient at 260 m is special as it distinctly separates the *Resource Zone* (extractable CH_4) from the rest of the lake above.

***Reinject-water* -** The nutrient-rich deep-water, after CH_4 extraction, plus the added dilution-water (if used) needs to be reinjected into the lake (Fig. 2.3.1). Although the deep-water is gas-depleted, it still contains large amounts of CO_2 and some traces of CH_4. The core of this report addresses the question on how to best manage the "undesirable" reinject-water. Reinject-water is unwanted in the upper lake layers as it contains too much nutrients and reinject-water is unwanted in the deep-water layers due to dilution of the CH_4 resource.

***Dilution-water, dilution factor* -** see Table 2.3.1.

However, we know, that above the RZ, the formation of CH_4 can be explained by the settling organic matter only, whereas in the RZ ~40% of the CH_4 is produced from fresh sediment material and ~60% contains “old” carbon. The scientific background addressing the sources and sinks of CH_4 in Lake Kivu are available in: Deuser et al (1973), Tietze (1978), Tietze et al (1980), Schoell et al (1988), Jannasch (1975) and Pasche et al (2009, 2011, submit).

The current rates of CH_4 new formation and of CH_4 accumulation are not accurately known (Pasche et al submit). Therefore, the harvesting strategy has to be designed **robustly** such that the economic viability (such as the maximum CH_4 harvest) or important *Design Parameters* (Table 2.2.1) should not sensitively depend on these not well-defined *Planning Parameters* (Table 2.2.1). The present technically extractable amount (of the CH_4 stored below 200 m depth) is ~42.3 km^3 (STP). For a typical conversion factor of 2.6 TWh km^{-3}, this amount of CH_4 equals an electrical energy of ~110 TWh. If harvested over 50 yr, this energy corresponds to an electricity power of ~250 MW. For the model simulations we used an annual CH_4 new formation rate of 0.45 $km^3\ yr^{-1}$ (= 120 g-C $m^{-2}\ yr^{-1}$) for the volume below the *Biozone* (Table 1.1). Thereof ~0.24 $km^3\ yr^{-1}$ is produced within the *Resource Zone* below 260 m depth. This CH_4 new formation is equivalent to a steady-state energy generation of ~68 MW. This assumed new CH_4 formation rate is based on the analysis in Schmid et al (2005a), available at the time of the simulations. However, from recent investigations of the lake-internal carbon fluxes by Pasche et al (submit), we conclude that the true rate of new CH_4 formation is probably approximately half the value given above (~0.23 $km^3\ yr^{-1}$ for the entire lake; ~0.12 $km^3\ yr^{-1}$ for the RZ).

Risk of gas supersaturation - The downside of the gases in Lake Kivu is the danger which they expose to all oxygen-dependent life in the lake region. A gas eruption in the lake could lead to an unimaginable disaster of an apocalyptic dimension, far beyond the events at the comparable “killer lakes” Monoun in 1984 (Sigurdsson et al 1987) and Nyos in 1986 (Kling et al 1987; Sigvaldason 1989) which claimed 37 and more than 1700 lives, respectively. The gases present in Lake Kivu could replace more than a 100 m thick air layer if suddenly released from the lake water (this height is calculated by dividing the total amount of lake gas by the lake surface area). Although the probability of such a catastrophic chain reaction leading to a complete degassing of the lake is presently low, the gases need to be removed from the lake in the future decades. Without CH_4 extraction, the gas accumulation - at the current estimated rate of new formation - could reach dangerous (saturation) levels towards the end of this century (Schmid et al 2005a).

Although CH_4 concentrations are only ~21% of CO_2, the probability of an eruption is mainly determined by CH_4. This is because of the low solubility of CH_4; its contribution to the total gas pressure exceeds that of CO_2 (Tietze 1978; Schmid et al 2004). Consequently a gas release from Lake Kivu would be triggered by supersaturation of CH_4. However, CO_2 would thereby be stripped into the newly-generated gas bubbles and would account for most of the released gas volume. The origin of the CO_2 is mainly from the volcanically active underground, and to a smaller part, from the degradation of organic matter (carbon in algae).

Vertical fluxes of methane - The CH_4 and CO_2 remain trapped in Lake Kivu to an extent which is unique compared to other lakes and ocean basins on Earth. Why Lake Kivu's CH_4 concentrations reach such high levels is still a poorly answered question (Pasche et al submit). Besides the high rate of CH_4 new formation, the strong density stratification of the lake is another important reason. As a result of this stratification, water masses are only very gently (almost not) stirred in the vertical direction. Therefore the upward flux of CH_4 is small and it can reside for long in the deep layers. In addition, the CH_4 trapped in the deep anoxic zone, is preserved and microorganisms can not degrade or remove it from those deep layers. Under such confined anoxic conditions, CH_4 could remain for hundreds or thousands of yr. However once CH_4 has been transported upwards into the oxic (oxygen-containing) *Biozone*, then CH_4 is oxidized to CO_2. This transformation can only take place in the top ~80 m, as the microorganisms need oxygen (or sulphate or nitrate; here a minor part) for the oxidation. There are two transport mechanisms by which CH_4 moves upwards:

(1) Deep subaquatic inflows into the lake push water, and all the substances dissolved therein, upwards. This so called "**upwelling"** is a slow vertical upward movement with a velocity determined by the subaquatic water discharge (up to ~42 $m^3\ s^{-1}$ or ~1.3 $km^3\ yr^{-1}$, details in Section 4.3 and Appendix 8.2) divided by the cross sectional area of the lake (< 2000 km^2, decreasing with depth, details in Appendix). The upwelling velocity is varying with depth, but is in the range of up to 1.0 m yr^{-1} (Figure 4.3.4). The upward transport of CH_4 (or any other substance) can then be calculated by the upwelling velocity times the concentration. As an example: the CH_4 upward flux at 260 m depth (= loss from the *Resource Zone*) is 23 g-C $m^{-2}\ yr^{-1}$ * 1050 km^2 = 24'000 t-C yr^{-1} = 0.045 $km^3\ yr^{-1}$ = ~0.1% yr^{-1} of the CH_4 contained in the *Resource Zone* (Table 1.1). Therefore we can conclude that CH_4 would remain almost 1000 yr in the deep-water despite the continuous upwelling by the subaquatic sources.

(2) As water masses in lakes are never at complete rest, there are always some (that are especially slow in Lake Kivu) currents caused by storms, atmospheric pressure changes or other external forces. These (slow) horizontal currents lead to friction between water layers that lie on top of each other and flow at slightly different velocities. This friction causes some **turbulent vertical mixing**, which leads to an upward diffusion from higher to lower concentration (CH_4 is increasing with depth). As an example, this turbulent upward transport of CH_4 in 260 m depth (i.e. the loss from the *Resource Zone*) is ~11 g-C $m^{-2}\ yr^{-1}$ * 1050 km^2 = 11'000 t-C yr^{-1} = 0.021 $km^3\ yr^{-1}$ = ~0.05% yr^{-1} of the CH_4 contained in the *Resource Zone* (Table 1.1). This flux implies that CH_4 would reside for ~2000 yr, if turbulent diffusion were the only process to transport CH_4 out of the deep-water layers.

When comparing these two types of upward fluxes, which occur simultaneously and independently of each other, it becomes evident that upwelling (subaquatic sources) is generally more important than the turbulent upward diffusion below ~100 m depth (in the previous example, the diffusion was about the largest in the entire lake, as there the gradient is the strongest). The vertical fluxes in Lake Kivu are unusual compared to other lakes for two reasons: (i) The turbulent mixing in the deep-water is unusually weak, as highlighted by the presence of about 340 so-called "double-diffusive" homogeneous layers (forming an unprecedented double-diffusive staircase; Schmid et al 2010) below 120 m depth, which would quickly be destroyed if the deep waters were to contain much turbulence. (ii) The subaquatic springs comprise a significant flow both in absolute terms (~42 $m^3 s^{-1}$ = 1.3 $km^3 yr^{-1}$) as well as in relative terms of the lake throughflow (~⅓). These subaquatic springs cause the unusual upwelling of water, CH_4 and nutrients.

Vertical fluxes of nutrients - During the decomposition of settling organic matter (predominantly algae in Lake Kivu), phosphate (PO_4) and ammonium (NH_4), assimilated during algae growth, are released back into the deep-water. Over the decades, the accumulation of nutrients leads to unusually high concentrations, similar to CH_4. The upwelling (subaquatic springs), described above, transports the nutrients into the *Biozone* and supports algae growth at a medium intensity (so-called mesotrophic). In absolute terms, the current estimate of the upward transport is about 1900 t-P yr^{-1} of PO_4 and about 15'900 t-N yr^{-1} of NH_4. Such a mesotrophic level of algae growth is usually considered as an indicator for a healthy ecosystem and a desirable water quality.

If the extraction operation would release nutrient-rich deep-water at or near the lake surface, the algae growth would increase. The amounts of released deep-water of a full-scale CH_4 extraction would enhance the nutrient fluxes into the *Biozone* by factors (!) and these nutrients would stimulate a tremendous algae growth over the entire lake surface (and not only near the release site). Subsequently, the oxygen-containing *Biozone* would shrink in depth, while the oxygen-free deep-water masses below would expand by the same volume. It is not possible to predict the impact on such a complex aquatic system in detail, but adverse effects, such as occasional fish-kills, toxic algae blooms, changes in species composition, and degradation of the already poor fish biodiversity would be expected. **Releasing large amounts of deep-water** (i.e., releasing large amounts of nutrients) **into the *Biozone*** is ultimately against the *Guiding Principle* of "conserving the lake ecological integrity" (next Section) and **is** therefore **unacceptable** as a planning option.

2.2 Guiding Principles for sustainable methane extraction

Motivation - After the March 2007 stakeholder meeting in Gisenyi (NCEA 2007, http://www.eia.nl/lake_kivu/), focussing on the monitoring during the upcoming CH_4 extraction, it was realized, that principles, technical requirements and prescriptions are needed to responsibly guide the extraction planning and operations of the different investors. The ministries in charge of the Governments of Rwanda and DR of the Congo asked a group of experts to develop ***Management Prescriptions for the Development of Lake Kivu Gas Resources*** **(MP 2009)** in order to achieve safe, environment-friendly and economic ways of CH_4 extraction. These discussions revealed a set of agreed-on basic principles, which need to be maintained during the entire CH_4 extraction. Some of these principles concern the extraction technology per se, which has to comply with "safe, environment-friendly and efficient procedures and operation of the CH_4 extraction". These technology-related principles and guidelines are part of MP (2009) and are not subject of this report.

Guiding Principles - We adopt the same agreed-on basic principles for our analysis. These principles, which we call "*Guiding Principles*" in the following, are used for the evaluation and inter-comparison of the different extraction *Scenarios*, which represents the core of this report. These *Guiding Principle*s are (in priority (i) to (iii)):

(i) Reduce the probability of a catastrophic gas release from the lake;
(ii) Conserve the ecological integrity of the lake;
(iii) Maximize the benefit from the CH_4 resources in the lake.

There are evidently industry-specific professional standards (best practice, codes of conduct) aimed at preventing harm to people and the environment, which could be caused by the operation. Foremost, the operation has to avoid any risk of causing a catastrophic gas release (such as by breaking pipes, etc). This report is **not addressing** these issues, which are part of the Impact Assessment and have to be observed independent of the adopted extraction approach. The aim of this report is to identify an optimal extraction *Scenario*, by estimating the implications and the consequences that those different *Scenarios* (Table 2.3.2) might have.

Objectives and their measures - In order to perform such an assessment in a comprehensible and transparent way (Table 2.2.1), we need to define *Objectives*, against which the outcome of the different *Scenarios* can be numerically measured. For this particular problem, we defined seven *Objectives* ((a) to (g) in Table 2.2.2):

(a) Keep lake stratification as stable as possible, at least at 50% of natural
(b) Reduce content of the gases in the lake, at least by 25% over the next century
(c) Increase required activation energy for (and thereby reduce chance of) initiation of bubble formation
(d) Minimize additional nutrient input to Biozone, at maximum 25% increase
(e) Minimize loss of CH_4 (i) to Biozone and (ii) by the extraction operation
(f) Allow new formation of CH_4 in deep-water
(g) Avoid dilution of CH_4 resources.

In order to measure how well these seven *Objectives* are fulfilled, we assign eight quantifiable *Attributes* to these *Objectives* (Table 2.2.2). These *Attributes* are well-defined, measurable, physical quantities, which can be calculated at any moment for all *Scenario* simulations. The definitions of the eight *Attributes* are summarized in Table 2.2.2 and detailed explanations are provided in Section 6.2. The quantitative evaluation (comparison, etc) of these *Attributes* for the various *Scenarios* follows in the next Section.

Table 2.2.1 *Terms for structured decision-making framework*

We use the following terms for the structured decision-making process:

***Guiding Principles* -** the three basic principles to follow while extracting the CH_4 from the lake. These principles concern specifically the “safety of the population”, the “lake ecological integrity” and the “economic benefit” from the CH_4 resource.

Objectives* -** the goals of the extraction project are expressed in a practical / operational way, such that the ***Objectives become easily comprehensible, quantifiable and finally measurable.

Attribute* -** the physical term, with absolute units, which is used to measure to which degree each ***Scenario fulfils an ***Objective.***

Scenario* -** there are many alternative options to construct and operate extraction plants. The ***Scenarios are those extraction approaches, which we analyzed in this report. A ***Scenario*** is specified by a well-defined set of ***Design Parameters.***

Consequence Table* -** for each ***Scenario model simulations are performed. The ***Consequence Table*** is the inter-comparison of the ***Attributes***, which resulted from the simulations of these *Scenarios*.

Trade-offs* -** discussion of the advantages and disadvantages for those ***Scenarios that fulfil the ***Objectives*** (and consequently also the ***Guiding Principles*)**.

***Design Parameter* -** the key parameters of an extraction plant defining the extraction operation, such as withdrawal and reinjection depths, the extraction water flow, etc (Table 2.3.1).

***Planning Parameter* -** the managerial boundary conditions, such as: location of the plant on the water surface, number of extraction plants, licensed CH_4 harvesting rate, assumed rate of CH_4 new formation.

Table 2.2.2 *Guiding Principles, Objectives and measurable Attributes*

Guiding Principles	Objectives	Attributes to Objective	Physical measure and unit (1)
(i) Safety Reduce probability of catastrophic gas eruption from lake	(a) Keep lake stratification as stable as possible	Energy required for complete mixing (vertically) of the entire stratified lake water body (higher value = more stable)	Schmidt stability [J]
	(b) Reduce gas content in lake	CO_2 content in lake = Integral of CO_2 over entire lake volume	Content of CO_2 [km^3]
		CH_4 content in lake = Integral of CH_4 over entire lake volume	Content of CH_4 [km^3]
	(c) Increase activation energy for (and reduce chance of) initiation of bubble formation	Minimal energy required for initiating bubbles (at the most critical depth) in water column below 200 m depth (higher value = more stable and safer)	Safety margin [J m^3]
(ii) Lake ecological integrity Conserve ecological integrity of the lake	(d) Minimize additional nutrient input to *Biozone*	Vertical upward flux of P at 80 m depth (= input into *Biozone*) (lower value = more sustainable, less disturbance)	Vertical upward flux of P [t-P yr^{-1}]
		Vertical upward flux of N at 80 m depth (= input into *Biozone*) (lower value = more sustainable, less disturbance)	Vertical upward flux of N [t-N yr^{-1}]
(iii) Economic benefit Maximize benefit from lake CH_4 resources	(e) Minimize loss of CH_4 (i) to *Biozone* and (ii) by operation (f) allow accumulation of newly formed deep-water CH_4	**Available CH_4** = Harvested(2) CH_4 (= amount of CH_4 extracted from deep-water) plus remaining CH_4 content in lake	Sum of already harvested CH_4 plus remaining CH_4 content in lake [km^3]
	(g) no dilution of CH_4 resources	**CH_4 harvest** = sum of already harvested(2) and still harvestable(3) CH_4	Sum of harvested and harvestable CH_4 [km^3]

(1) *Definitions and calculation formula of the Attributes are detailed in Section 6.2.*

(2) *Harvested CH_4 = integral of CH_4 already extracted (to power production) for entire simulated operation period*

(3) *Harvestable CH_4 = integral of harvestable CH_4 over entire lake volume (harvestable: CH_4 > threshold concentration; here arbitrarily assumed as 5 mol m^{-3} (Figure 1.2).*

2.3 Modelling and Scenario evaluation procedure

(i) Goal and procedure - In this Section we explain the procedure to identify the optimal approach for extracting the CH_4 from Lake Kivu, while observing the *Guiding Principles* formulated in Section 2.2. To achieve this goal, we proceed by the following steps (order 1 to 6):

(1) definition of the *Scenarios*
(2) definition of the modelling approach
(3) definition of the *Attributes* for evaluating the *Scenarios*
(4) evaluation of the simulations
(5) evaluation of the robustness of selected *Scenarios*
(6) choice of the optimal *Scenario*.

(ii) Basic elements of the extraction operation - A large variety of approaches for CH_4 extraction are conceivable. Many of them may not be of interest, as they would not meet the three *Guiding Principles* (safe, sustainable and efficient). Here we focus only on plant designs, which are qualitatively similar to the currently projected plants, i.e., water is taken to the surface, degassed, and reinjected into the lake. Other options are conceivable but currently not thought to be economical. We also do not discuss the technology applied (independent of the option chosen), which is not relevant to the analyses of the lake system response, but may be relevant to the economic benefit.

There are five “plant-defining” parameters, in the following called *“Design Parameters”*, which are basic elements of all considered *Scenarios*, and which determine the outcome of the extraction, both regarding the achievable CH_4 harvest as well as the change of the lake stratification. These five *Design Parameters*, defined in Table 2.3.1, comprise:

(1) withdrawal depth and depth range
(2) reinjection depth (of the depleted deep-water) and depth range
(3) dilution-water flow (% of extraction flow) and dilution-water intake depth
(4) removal (%) of CH_4
(5) removal (%) of CO_2.

Further “plant-defining” parameters are conceivable, but we conclude that these five *Design Parameters* are the most relevant because (i) they comprise the key elements of an extraction operation and because (ii) the *Attributes,* used for the *Scenario*s evaluation, are sensitive towards these parameters.

(iii) Scenario definitions - In the past much analyzing was performed to establish an extraction concept that would fulfil the core ideas of the *Guiding Principles* and the MP (2009). There are three extreme options, which would each fulfil one of the respective three *Guiding Principles* (i) to (iii) in Section 2.2:

Table 2.3.1 ***Definitions of the five Design Parameters***

The *Design Parameters*, used for the *Scenario* analysis, are defined as follows:

Withdrawal depth **-** CH_4-containing water is withdrawn from the *Resource Zone* below 260 m depth. If water is taken in over a vertical range, then the *withdrawal depth* refers to the centre of the intake. The withdrawal range refers to the vertical extent of the intake. Some *Scenarios* have two intakes indicated by ***withdrawal depth 1, 2*** and ***withdrawal range 1, 2*** (Table 2.3.2).

Reinjection depth - After stripping CH_4 (and other gases) from the extracted deep-water, the depleted deep-water is returned to the lake. The ***reinjection depth*** indicates the vertical centre, if the release occurs over a vertical ***reinjection range***. The ***reinject-water*** contains also dilution-water (if used for density adjustment; see below). If the density of the reinjection water is different from the lake water density at the reinjection depth, then the released water restratifies above (less dense) or below (denser) the reinjection depth. Some *Scenarios* have two return outlets, indicated by **reinjection depth 1, 2** and **reinjection range 1, 2** (Table 2.3.2).

Dilution-water **-** If the reinject-water needs to be restratified within a narrow or precise vertical range, it was usually considered as necessary to add less dense surface water to the CH_4-depleted deep-water in order to adjust the density before release into the lake. As the density of the dilution-water depends on the withdrawal depth, the ***dilution intake depth*** needs to be specified as well. The ***dilution factor*** is the ratio of dilution-water flow divided by extraction-water flow. The reinject-water is the sum of the extracted deep-water plus the dilution-water.

Removal of CH_4 **-** During the initial gas stripping and the scrubbing (gas washing) processes not all the gases are completely separated. The ***removal of*** CH_4 gives the percentage of the CH_4 that is removed from the CH_4 contained in the deep-water (typically 70 to 96%). The rest of the CH_4 is returned with the ***reinject-water*** into the lake. Depending on the re-stratification depth, the returned CH_4 is lost (if reinjection is shallow) or can be harvested later (if reinjection is deep).

Removal of CO_2 **-** After the initial gas stripping, most of the CO_2 is washed back into the scrubbing-water (Figure 1.2). However the gas-washing process is not perfect and some deep-water CO_2 will be removed together with the harvested CH_4 (via power production) or released to the atmosphere. The ***removal of*** CO_2 gives the percentage of the CO_2 that has been removed from the CO_2 contained in the deep-water (typically 40 to 90%). The rest of the CO_2 is returned with the reinject-water and the scrubbing-water back into the lake (Figure 2.3.1).

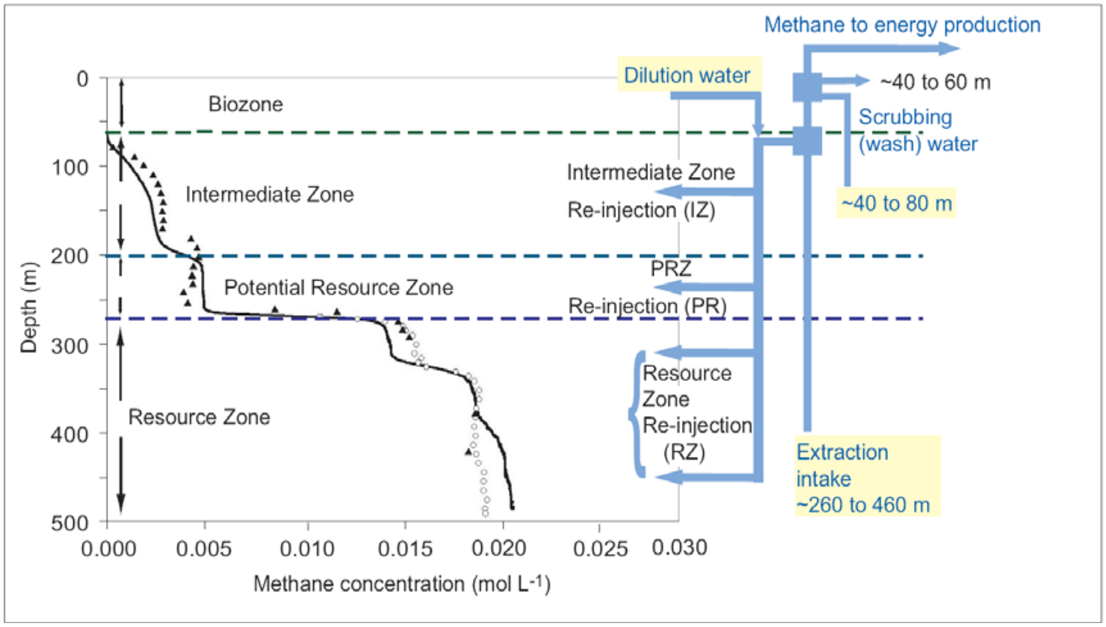


Figure 2.3.1 *Using self-siphoning, CH_4-rich deep-water is extracted from the RZ. After stripping the gases, CH_4-depleted deep-water is reinjected into the lake. The gas mixture is washed using scrubbing-water to redissolve H_2S and CO_2 back into lake water (see scrubbing-water outlet at 40 to 60 m depth). The remaining CH_4 is piped to power production onshore.In this study, we analyse the effect of releasing the reinject-water into the Intermediate Zone (Scenarios IZ1 to IZ5), into the Potential Resource Zone (Scenario PR1) and into the Resource Zone (Scenarios RZ1 to RZ6). The Scenarios are defined in Table 2.3.2 and detailed in Section 5.*

- The approach for maximum risk reduction (i) would be to rapidly extract all CH_4 and to remove all CO_2
- The best approach for conserving the lake ecological integrity (ii) would be using the CH_4 from the *Resource Zone and* reinjecting the extracted deep-water back into the same *Resource Zone*, without removing the CO_2 in order not to change the lake stratification. The deep-water would then be depleted in CH_4 but the stratification of all other water properties would remain unchanged.
- The most economical (iii) approach would be to draw the deep-water entirely down to the deepest zones and to return the reinject-water into the *Biozone* in order to prevent any dilution of the CH_4-containing deep-water and to allow complete removal of all CH_4 contained in the deep-water.

It appears obvious that none of these three options fulfils a-priori all three *Guiding Principles* and therefore an optimal, feasible and acceptable concept may consist of a compromise among those three positions. In addition, a viable extraction *Scenario* has to also meet management aspects - here called *Planning Parameters*, such as extraction location on the lake (accessibility) or rate of CH_4-harvesting.

Prior and during the establishment of this report we consulted with interested engineers and MININFRA and established a list of extraction approaches. We analysed those options for similarities and differences and condensed them into a shortlist of extraction "*Scenarios*". We expect these *Scenarios* to be distinct enough that the sensitivity of the *Attributes* (of the *Objectives*) towards those *Scenarios* can be estimated. The analysis in this report was performed for the following *Scenarios* (summarized in Table 2.3.2 and detailed in Section 6):

O	no extraction
IZ1	intake: Lower *RZ*; reinjection: middle part of *IZ*; with dilution-water
IZ2	intake: Upper *RZ*; reinjection: upper part of *IZ*; less CH_4 removal, with dilution-water
IZ3	intake: Lower *RZ*; reinjection: upper part of *IZ*; with dilution-water
IZ4	intake: Lower *RZ*; reinjection: middle part of *IZ*: no dilution-water
IZ5	intake: Upper *RZ*; reinjection: lower part of *IZ*; less CH_4 removal, no dilution-water
PR1	intake: *RZ*; reinjection into *PRZ*
RZ1	intake: Lower *RZ*; reinjection: Upper *RZ*
RZ2	two intakes from RZ (Upper and Lower); two reinjections into *RZ* (Upper and Lower); withdrawal and reinjection over entire RZ
RZ3	same as RZ2, except for higher gas removal
RZ4	two intakes from RZ (Upper and Lower); two reinjections into *RZ* (Upper and Lower); preparation step for RZ5
RZ5	intake: entire Lower *RZ*; reinjection: Upper *RZ*
RZ6	first RZ4 until Upper *RZ* exploited; then RZ5 until completion.

(abbreviations: *RZ = Resource Zone; PRZ = Potential Resource Zone; IZ = Intermediate Zone; BZ = Biozone; see Figure 1.1).*

(iv) Modelling approach - The stratification of Lake Kivu is modelled as a function of (extraction) time by using the software AQUASIM (http://www.aquasim.eawag.ch/). The following natural processes are included (details in Section 4 and Appendix 8.1):

- inflow, outflow and upwelling (caused by the subaquatic discharges)
- turbulent diffusion (vertical mixing of water masses; slow process)
- CH_4 new formation at the lake sediment surface
- CH_4 oxidation in the oxygen-containing *Biozone*
- nutrients (PO_4, NH_4) assimilation (algae growth) in *Biozone*
- nutrients redissolution from settling matter at the lake sediment surface
- exchange of CH_4 and CO_2 with the atmosphere
- lake-internal water dislocation induced by the extraction operation

Table 2.3.2 ***Methane extraction Scenarios O, IZ1 to IZ5 and PR1***

Scenario	Aim	Realization	Advantages	Disadvantages
O	no CH_4 extraction	no vertical water movement in lake, except upwelling by subaquatic springs	natural	gases would accumulate up to eruption
IZ1	stacking reinject-water above the *PRZ*; maximizing CH_4 harvest by drawdown of entire CH_4-containing deep-water to deepest zone	CH_4 withdrawal at 475 m and release at 150 m (*IZ*); reinject-water density adjusted by dilution-water taken at 40 m depth	clear separation of harvestable water (*RZ*) and reinject-water (*IZ*), well below *BZ*	enormous (up to 5-fold) nutrient fluxes and enhanced salt flux into *BZ*; massive reduction of stratification
IZ2	Extraction close to shore; else as *Scenario* IZ1	CH_4 withdrawal at 320 m (Upper *RZ*) and reinjection at 90 m (*IZ*); reinject-water density partly adjusted by dilution-water from 10 m	clear separation of harvestable water (*RZ*) and reinject-water (*IZ*), well below *BZ*	60% increased nutrient fluxes into *BZ*; loss of ~8 km^3 of CH_4 (relative to IZ4); poor CH_4 extraction; reduction of stratification (1)
IZ3	Extraction close to shore; else as *Scenario* IZ1	CH_4 withdrawal at 350 m (Lower *RZ*) and reinjection at 90 m (*IZ*); reinject water density adjusted by dilution-water from 50 m depth	clear separation of harvestable water (*RZ*) and reinjecting water into *IZ*, well below *BZ*	Up to 2.6-fold nutrient fluxes into *BZ*; loss of ~4 km^3 (relative to IZ4) of CH_4; large reduction of stratification (2)
IZ4	maximizing CH_4 harvest by drawdown of entire CH_4-containing deep-water to deepest zone; no dilution-water	CH_4 withdrawal at 475 m (*RZ*) and release at 150 m (*IZ*); reinject-water will sink further, as density is not adjusted (no dilution-water)	clear separation of harvestable water (*RZ*) and reinject-water (*IZ*) well below *BZ;* high CH_4 harvest	doubling of the nutrient fluxes and enhanced salt flux into the *BZ*; lake stratification reduced to half of natural
IZ5	Extraction close to shore; stacking the reinject-water directly above *PRZ* (no dilution-water)	CH_4 withdrawal at 320 m (Upper *RZ*) and reinject at 190 m (lower *IZ*); reinject-water sinks, as density not adjusted	clear separation of harvestable water (*RZ*) and reinject-water (*IZ*), well below *BZ*	20% increased nutrient fluxes into *BZ*; loss of ~7 km^3 (relative to IZ4) of CH_4 due to poor extraction (1)
PR1	high CH_4 harvest by drawdown of entire CH_4-containing deep-water to deepest location; avoiding high nutrient flux into *BZ*	CH_4 withdrawal at 475 m (*RZ*) and release at 240 m (PRZ); reinject-water will sink but not beyond the *Main Chemocline;* expansion of the *PRZ*	*RZ* remains undiluted; nutrient fluxes to *BZ* not affected; stability reduced by only ~20%	modification of stratification; loss of ~2.5 km^3 CH_4 (relative to most economic IZ4); *PRZ* diluted

(1) CH_4 below 320 m depth not harvested; (2) CH_4 below 350 m depth not harvested. We consider this not as an important disadvantage, as CH_4 can still be harvested at a later term.

Abbreviations used: *RZ = Resource Zone; PRZ = Potential Resource Zone; IZ = Intermediate Zone; BZ = Biozone*.

Table 2.3.2 ***Methane extraction Scenarios RZ1 to RZ6 (continuation)***

Scenario	Aim of *Scenario*	Realization	Advantages	Disadvantages
RZ1	protecting the *PRZ and retaining the stratification* by stacking reinject-water to the Upper *RZ*	CH_4 withdrawal at 475 m (Lower RZ) and reinjection at 290 m (Upper RZ); reinject-water will remain in Upper *RZ*	CH_4 can build up within *PRZ* during 100 yr to harvestable level	loss of ~2.5 km^3 CH_4 (relative to most economic IZ4); parts of *RZ* diluted
RZ2 RZ3	extraction of CH_4 from entire *RZ* without changing stratification of the lake	homogeneous CH_4 withdrawal below 275 m (RZ) depth over entire *RZ*	no changes to the lake ecological integrity; high flexibility in harvest rate	at end of extraction, lake left with large amount of CH_4; CH_4 concentration and CH_4/CO_2 ratio decreasing over time; reduction in power production efficiency (Halbwachs 2009)
RZ4	extraction of CH_4 from the entire *RZ* by stacking reinject-water into Upper and Lower RZ separately	CH_4 withdrawal at 310 m (Upper RZ) and reinjection at 270 m (Upper RZ); CH_4withdrawal at 410 m (Lower RZ) and reinjection at 325 m (Lower RZ)	no changes to the lake ecological integrity; flexibility in harvest rate	accurate depth compliance for reinject-water required; accurate adjustment (with CO_2) of reinject-water density required; parts of *RZ* diluted
RZ5	drawdown of CH_4 in the entire *RZ* by stacking the reinject-water into Upper *RZ*	CH_4 withdrawal at 400 m (Lower RZ) and reinjection at 270 m (Upper RZ)	no changes to lake ecological integrity; flexibility in harvest rate	accurate depth compliance for reinject-water required; accurate adjustment (with CO_2) of reinject-water density required; parts of *RZ* diluted
RZ6	harvesting the Upper *RZ* before diluting it with reinject-water originating from the Lower RZ	First *Scenario* RZ4 until CH_4 used up in Upper RZ; thereafter *Scenario* RZ5	no changes to lake ecological integrity; flexibility in harvest rate	accurate depth compliance for reinject-water required; needs operational flexibility: change of withdrawal and reinjection depths (RZ4 to RZ5) after ~25 yr; parts of *RZ* diluted

Abbreviations: *RZ = Resource Zone; PRZ = Potential Resource Zone; IZ = Intermediate Zone; BZ = Biozone*.

In order to simulate (i) the stratification, (ii) the gas contents and (iii) the nutrient fluxes, all relevant quantities need to be included as dynamic model variables. The simulated quantities comprise the following output (all as a function of depth):

- all density variables: temperature, salinity, CO_2 and CH_4
- concentrations of dissolved gases: CO_2 and CH_4
- concentrations of nutrients: PO_4 and NH_4
- turbulent diffusion and upwelling.

We use the term CO_2 for dissolved gaseous CO_2, which is less than the total dissolved inorganic carbon ($CO_{2,total}$, including carbonic acid, bicarbonate and carbonate; details in Section 4.10 and Appendix 8.3). The latter ions are included in the salinity. Both contributions (CO_2 and ions) are included in the density calculations.

Also lake-internal processes induced by the extraction operation are included in the model: The two most relevant are the water withdrawal (leading to downwelling between the withdrawal and the reinjection depths) and the reinjection (leading to upwelling above the reinjection depth). Beside the water masses, the constituents in the withdrawal and reinject-water are also accounted for. The *Design Parameters* directly influence the properties of the reinject-water and thereby affect the lake stratification in the long-term, especially the vertical distribution of the gases.

The one-dimensional advection-diffusion-reaction model is run for **100 yr** from 2004 to 2104 for all *Scenarios* (IZ1 to RZ6) listed in Table 2.3.2. ***Scenario* O** (no extraction, no intervention) is used for model calibration as well as a reference for comparing the *Scenarios* (see evaluation below). The simulation time frame of 100 yr is adequate for the entire extraction of Lake Kivu. A choice of 50 yr for the same volume of extracted water would double all fluxes and rates of change, but would not alter the lake system response or the structure of the results. Therefore, the chosen time frame has no influence on the evaluation of the outcome.

The lake stratification data (six dynamic model variables and related quantities) have been evaluated (Table 7.1 to 7.12 and 7.13) after 0 (2004), 50 (2054) and 100 yr (2104). Details of the model construction are given in Section 4.

(*v*) *Definition of Attributes measuring the Objectives* - The planning of the large-scale CH_4 extraction unfolds a list of questions concerning the effects that the operation may have on Lake Kivu and the risks related to its gases. Obvious questions on any of the different extraction *Scenario*s are:

- How does the long-term stratification of Lake Kivu develop?
- How does the long-term risk for gas outburst develop?
- Are there critical layers with a high probability for gas outburst?
- How large are the changes of the lake-internal nutrient fluxes in comparison to the undisturbed (natural) fluxes?
- What is the maximal total amount of CH_4 to be possibly harvested?
- What amount of CH_4 is “lost” (by oxidation) as a result of the extraction in addition to the naturally occurring oxidation?
- How does the vertical distribution of the CH_4 change during extraction?

The model simulations provide answers to such questions. To perform the trade-offs between the different *Scenarios* quantitatively and comprehensively, we specified eight *Attribute*s, which are well-defined physical quantities (Table 2.2.2; Section 6.2). These *Attribute*s basically measure to which degree the *Objectives* are fulfilled. The *Attribute*s comprise:

- **Schmidt stability** = the mechanical energy required for complete (vertical) mixing of the entire stratified lake water body. Unit: [J]
- **Safety margin** = the minimal mechanical energy required to initiate bubbles (at the most critical depth) in the water column below 200 m depth. Unit: [J m^{-3}]
- **Phosphorus upward flux** = vertical upward flux of P into the Biozone (at 80 m depth). Unit: [t-P yr^{-1}]
- **Nitrogen upward flux** = vertical upward flux of N into the Biozone (at 80 m depth). Unit: [t-N yr^{-1}]
- **CO_2 content** = CO_2 content in entire lake. Unit: [km^3]
- **CH_4 content** = CH_4 content in entire lake. Unit: [km^3]
- **CH_4 harvested** = CH_4 led to production since start of extraction. Unit: [km^3]
- **CH_4 harvestable** = total amount of CH_4 left in the lake at concentrations exceeding the economically viable (harvestable) concentration, presently assumed as 5 mol m^{-3}. Unit: [km^3].

All eight *Attributes* (Table 2.2.2; Section 6.2) have a value at any given point in time for any of the *Scenario* simulations. As indicated above, the evaluation was carried out for 2004 (0 yr), 2054 (50 yr) and 2104 (100 yr).

To potentially limit the complexity of the optimisation by reducing the number of *Attributes*, we checked for interdependencies among the *Attributes* and found that the Schmidt stability, the safety margin and the CO_2 (or total gas) content are correlated. This implies that one of these three *Attributes* alone is enough to characterize the *Guiding Principle* "*Safety*". Also the PO_4 and NH_4 upward fluxes are strongly correlated, and consequently one of those two *Attributes* already contains the full information related to the *Guiding Principle* "Lake ecological integrity". Therefore we base the final evaluation on a reduced set of the following four independent *Attributes*:

- Schmidt Stability
- P flux into *Biozone*
- Sum of "CH_4 harvested" (production) plus "CH_4 content" (remaining in lake)
- CH_4 harvest = sum of "CH_4 harvested" plus "CH_4 harvestable".

In the next Section, we apply these four *Attributes* to all model simulations and list the results in the *Consequence Table* (2.4.1). Subsequently, this table is used as a base for determining the optimal *Scenario*.

2.4 Evaluation of the extraction Scenario simulations

The eight *Attribute*s for all *Scenarios* simulations (Section 7) are summarized for 0, 50 and 100 yr of extraction in Table 7.13. An excerpt for the essential four *Attribute*s is provided In Table 2.4.1, which allows a first triage to be made, based on how well the *Scenarios* meet the *Objectives*. The comparison of the *Scenarios* O to RZ6 in Table 2.4.1 reveals the following findings:

(i) Safety (*Guiding Principle* (i)): The largest modifications of the lake stratification occur when reinject-water is released into the *Intermediate Zone* (*Scenario*s IZ1, IZ2, IZ3, IZ4; Table 2.4.1). Reinjection into the *Potential Resource Zone* (or the lower reaches of the *Intermediate Zone*) reduces the stratification much less (*Scenario*s IZ5, PR1). In contrast, the changes to the stratification are small, as long as water is reinjected into the *Resource Zone* (*Scenario*s RZ1 to RZ6). In these *Scenarios*, CH_4 is allowed to further accumulate in the PRZ and the IZ, which implies that a solution for degassing these zones may be required at a later stage.

(ii) Lake ecological integrity (*Guiding Principle* (ii)): For this *Objective*, the distinction between *Intermediate Zone* reinjection and deep reinjection is even more pronounced than for the *Guiding Principle* “Safety”. Whereas the *Potential Resource Zone* and *Resource Zone* reinjection (PR1 and RZ1 to RZ6) cause almost no change in the (natural) nutrient upward fluxes, the *Intermediate Zone* reinjections (IZ1 to IZ5; Table 2.4.1) cause a significant unwanted enhancement of the fluxes.

The addition of dilution-water - if dilution-water is taken from the *Biozone* – enhances **immediately** (with the onset of the extraction) the nutrient upward fluxes into the *Biozone* (*Scenario*s IZ1, IZ2, IZ3; Table 7.3.1). The dilution-water withdrawal from the *Intermediate Zone* enhances the nutrient fluxes eventually as well, but only after several decades and much more gradually.

In several hundred years the nutrient upward fluxes will gradually increase independently of the extraction and of the *Scenario* chosen. This increase is unavoidable given the enormous reservoir of nutrients in the deep-water.

(iii) Economic benefit (*Guiding Principle* (iii)): The maximum CH_4 harvest would be achieved, if the deep-water would be reinjected at the surface. This option is however not acceptable. Of the analyzed *Scenarios*, the maximum CH_4 harvest would occur for the *Intermediate Zone* reinjection (*Scenario* IZ4, Table 2.4.1). Although this *Scenario* IZ4 fails on grounds of the other two *Guiding Principles* (Table 2.4.1), it serves as an ideal reference for the maximum CH_4 harvest (set to 100% for the comparison in Table 2.4.1).

Fortunately, for the concession and planning process, the **available CH_4** (sum of CH_4 let to power production and CH_4 still in the lake) varies only within 1% among the *Scenarios* (PR1 and RZ1 to RZ6), as there is almost no additional loss of CH_4 to the *Biozone*. There are however significant differences concerning the CH_4 harvest among the *Scenarios* (Tables 2.4.1 and 2.4.2). The reason is related to the different

Table 2.4.1 ***Consequence Table relating Attributes of all Scenarios*** *(1).*

Sce-nario	Objective "Safety"	Objective "Lake ecology"	Objective "Economic benefit"	Objective "Economic benefit"	Assessment
	Schmidt stability	**Nutrient fluxes**	**Available methane**	**Methane harvest** (2)	
O	stability intact, but gas accumulating to dangerous level	natural	no benefit	no benefit	no option
IZ1	only 19% of natural after 100 yr, lake homogenized, salty surface	4.9-fold of natural after 50 yr	90 % of maximum	97 % of maximum	failed on Obj. "Safety" and on Obj "Lake ecology"
IZ2	61% of natural after 100 yr	1.6-fold of natural after 50 yr	92 % of maximum	84 % of maximum	failed on Obj. "Lake ecology" and poor on Obj. "Economic benefit"
IZ3	48% of max. after 100 yr	2.6-fold of natural after 50 yr	96 % of maximum	89 % of maximum	failed on Obj. "Lake ecology" and poor on Obj. "Safety"
IZ4	48% of max. after 100 yr,	2.0-fold of natural after 50 yr	100 % of maximum	100 % of maximum	failed on Obj. "Lake ecology" and poor on Obj. "Safety"
IZ5	82% of natural after 100 yr	1.2-fold of natural after 100 yr	93 % of maximum	83 % of maximum	weak on all three Obj.
PR1	81% of natural after 100 yr	natural	97 % of maximum	92 % of maximum	option
RZ1	100% of natural after 100 yr	natural	97 % of maximum	90 % of maximum	option
RZ2	100% of natural after 100 yr	natural	98 % of maximum	96 % of maximum	option
RZ3	87% of natural after 100 yr	natural	98 % of maximum	96 % of maximum	option
RZ4	91% of natural after 100 yr	natural	98 % of maximum	88 % of maximum	option
RZ5	85% of natural after 100 yr	natural	98 % of maximum	89 % of maximum	option
RZ6	87% of natural after 100 yr	natural	98 % of maximum	88 % of maximum	option

(1) Dark shading indicates failure fulfilling the Objective, intermediate shading indicates weak performance compared to best scenarios.
(2) Methane harvest = CH_4 harvested plus CH_4 harvestable (Table 2.2.2) relative to maximum of Scenario IZ4 (100%).

vertical distributions of CH_4 (Figures 7.1.5 to 7.12.5) that result for the different *Scenarios* and the definition of the level at which the remaining CH_4 is still economically harvestable. The advantages and disadvantages of those *Scenarios* are evaluated in Table 2.4.2 and in Section 2.6.

In addition to the *Attributes* of the "economic benefit" (**available methane**, **methane harvest**, Table 2.4.1) other factors will be equally important for the overall economic benefit of the CH_4 harvesting process. Such factors will include the temporal development of the CH_4 concentration and the CH_4/CO_2 ratio at the extraction depth, the percentage of energy consumption for the plant operation, the conversion efficiency of CH_4 to electrical energy, or the required distance from the shore to reach a certain extraction depth.

2.5 Evaluation of the robustness of selected Scenarios

(i) Role of model assumptions - It is important that the optimal (chosen) *Scenario* is not only fulfilling the *Guiding Principles* and the associated *Objectives*. In addition the optimal *Scenario* should also be robust towards the critical uncertainties in the model assumptions. The model simulations and the *Consequence Table* (2.4.1) are most sensitive to three model assumptions:

- upwelling flow (rate of uplift, caused by the subaquatic springs),
- CH_4 new formation rate, and
- CH_4 harvesting rate.

The first two assumptions are not well-known and the third has not been decided yet. For the evaluation of potential influences, robustness tests have been performed. Therefore, we varied the assumptions for the simulations as follows:

- The present in-situ CH_4 new formation rate (assumed: 120 g-C m^{-2} yr^{-1} is equivalent to 0.29 km^3 yr^{-1} within the *Resource Zone* + *Potential Resource Zone*; Table 1.1), was varied from 32 to 120 g-C m^{-2} yr^{-1}.

- The subaquatic water inflows (sources at several depths with estimated total flow of 42 m^3 s^{-1} (Table 8.2.2), corresponding to a vertical upwelling advection of 0.7 m yr^{-1} in 80 m depth) were varied from 10.5 m^3 s^{-1} to 42 m^3 s^{-1}.

- A constant water flow rate of 70 m^3 s^{-1} (corresponding to an approximate energy equivalent of ~100 to ~200 MW over 100 yr) was used in all *Scenarios*. For the robustness test, we further assumed a faster extraction rate of ~600 MW equivalence, which is assumed to be reached after 15 yr of gradual increase (and constant extraction flow afterwards).

(ii) Results of the robustness tests - The simulation runs, with the varying assumptions as listed above, show that the structure of the results (Table 2.4.1 and 2.4.2) are not affected by these assumptions. Therefore, we saw no need to generate further *Consequence Tables* (2.4.1) for other combinations of assumptions.

Table 2.4.2 ***Advantages/disadvantages for Scenarios fulfilling the Objectives***

Scenario	**Methane harvest** [(1)]	**Advantages**	**Disadvantages**	**Preference**
PR1	92 % of maximum	o simple concept of extraction and release o high CH_4 harvesting and energy production rate	o stability decreased to 81% of natural after 100 yr (still very stable) o most plants close together (at end of extraction process) near deepest location o reinjected CH_4 is lost	medium
RZ1	90 % of maximum	o simple concept of extraction and release	o most plants close together (at end of extraction process) near deepest location o CO_2 in lake reduced by only ~15% of today o reinjected CH_4 is partly lost	medium
RZ2	96 % of maximum	o no loss of CH_4 by incomplete extraction (reinjected CH_4 is reused)	o more complex extraction and release; potential short-circuiting between extraction and reinjection o CH_4 conc. and CH_4/CO_2 ratio decrease continuously with time o CO_2 in lake reduced by only 10 % of today	low
RZ3	96 % of maximum	o no loss of CH_4 by incomplete extraction (reinjected CH_4 is reused) o CO_2 in lake reduced by 30 % of today	o more complex extraction and release; potential short-circuiting between extraction and reinjection o CH_4 conc. and CH_4/CO_2 ratio at extraction depth decrease continuously with time	low
RZ4 (2)	88 % of maximum	o no loss of CH_4 by incomplete extraction (reinjected CH_4 is partly reused)	o more complex extraction and release o CH_4 conc. and CH_4/CO_2 ratio at extraction depth decreasing drastically with time	not a *Scenario* (with RZ5 only)
RZ5	89 % of maximum	o simple concept of extraction and release o reinjected CH_4 is only partly lost o high energy production rate o CO_2 in lake reduced by 40% of today	o most plants close together (at end of extraction process) near deepest location o CH_4 conc. and CH_4/CO_2 ratio decrease abruptly with time	medium
RZ6	88 % of maximum	o no loss of CH_4 by incomplete extraction (reinjected CH_4 is reused) o high energy production rate o CO_2 in lake reduced by 35% of today	o more complex extraction and release o most plants close together (at end of ext process) near deepest location o CH_4 conc. and CH_4/CO_2 ratio decrease continuously with time	high

(1) *Methane harvest = CH_4 harvested plus CH_4 harvestable (Table 2.2.2) relative to maximum of Scenario IZ4 (100%, Table 2.4.1).*

2.6 Conclusions and optimal extraction Scenario

(i) Trade-offs - Table 2.4.2 summarizes the advantages and disadvantages of the *Scenarios* which fulfil the three *Guiding Principles*. We argue that the optimal *Scenario* should not only fulfil the *Attribute*s towards the *Objectives*, and robustly resist against (i.e. not sensitively depend on) uncertainties in the model assumptions, but the optimal *Scenario* should also have technological and managerial advantages.

PR1 and RZ1 - The advantages of PR1 and RZ1 are the simple concept and the high ***CH_4 harvest***. The main disadvantages for PR1 are (i) the high density at the reinjection depth which leads to forming a thick layer above the main gradient with a relatively low CH_4 concentration (Figure 7.6.5) and (ii) the loss of CH_4 in the re-inject-water (re-inject-water will not be drawn-down in the next century). This loss is somewhat reduced for RZ1, especially if after a few years (decades) the CH_4 in the re-inject-water will hopefully be completely eliminated. The performance of RZ1 can be improved relative to the modelled *Scenario*, if the density adjustment of the re-inject-water is optimized by the fraction of CO_2 removed. The control of CO_2 removal in an extraction process depends on being able to control or vary the pressure of separation. This can in turn vary the CO_2 extraction from below 20% to above 80%. Hence the re-inject water density can be varied enough to control its density in order to match lake water density at its preferred reinjection depth. This separation pressure also affects the CH_4 extraction efficiency and the energy production rates.

RZ2 and RZ3 - The difference between RZ2 and RZ3 is only the fraction of the gases removed, which may be of interest for an optimized extraction operation. The main advantage of these *Scenarios* is the entrainment of the re-injected CH_4 into the *Resource Zone*, implying that this recycled CH_4 is not lost for future extraction. These *Scenarios* have two major disadvantages: (i) The extraction and reinjection is distributed over the entire RZ, which could lead to short-circuiting between release and intake flow. In principle this risk could be avoided, by a more elaborate vertical structuring of the intake and reinjection. (ii) The CH_4 concentration in the extracted water is continuously decreasing (if CH_4 extraction is higher than the formation of new CH_4) and will eventually reach a level of non-viable low CH_4 concentrations. To avoid the large loss of the remaining CH_4, the extraction needs to switch to a *Scenario* of the RZ1 type.

The implications are twofold: (1) These RZ2/RZ3 *Scenarios* would be an opportunity to create a long-term steady-state CH_4 extraction, in balance with the new formation rate, and retaining a long-term gas content at all levels in the lake. However, such a goal conflicts with the objective to harvest most of the CH_4 in the near future and to reduce the overall gas concentrations for improved safety. (2) If CH_4 will substantially be used in the near future, then RZ2/RZ3 would would only be a short-term (a few years) option in order not to decrease the concentration below a critical level. For these two reasons, we can not recommend these two *Scenarios* as an extraction option.

RZ6 - The goal of RZ6 is to minimize the disadvantages of all the RZ injection *Scenarios*. By extracting the Upper and Lower RZ separately (RZ4), the density difference within the RZ is maintained and potential CH_4 loss by the reinject-water in the first few years (decades) is avoided. The density stratification will reduce the risk of short-circuiting. During the second part of the extraction (RZ5) it is necessary to adjust the density of the reinject-water carefully (by removing increasingly more CO_2) such that the reinjected water restratifies at the top of the RZ and does not cause a large mixed layer with low CH_4-content (as in RZ1), which would be lost for further extraction. As for RZ1, the performance of RZ6 can be improved relative to the modelled *Scenario*, if the density adjustment of the reinject-water is optimized during the second part of the extraction operation. However, retaining reasonably high CO_2 levels is also a goal (in order to facilitate siphoning for future extraction). Therefore it is imperative that the extraction plants are designed in such a way to allow for the flexible removal of CO_2 for full control of the reinject-water density.

(ii) Conclusions - Several important conclusions from the overall comparison (summary in Table 7.13 and *Consequence Table* 2.4.1) as well as from Table 2.4.2 can be drawn:

(a) It is possible to extract the CH_4 in a responsible manner complying with safety precautions and maintaining lake ecological integrity. Concerning safety and lake ecological integrity, the impacts of deep-reinjection *Scenario*s (PR1, RZ1 to RZ6) are very similar.

(b) Using dilution-water shows no advantages over *Scenarios* which operate without dilution-water. As dilution-water increases nutrient upward fluxes and as dilution-water can - under unfavourable conditions - dilute CH_4 resources, there is no compelling or acceptable reason for using dilution-water.

(c) If the CH_4 extraction efficiency is lower than planned (i.e the CH_4 content in the reinject-water is too high), it becomes a significant advantage to release the reinject-water into the *Resource Zone*. Returned CH_4 remains then a (potential) resource and can be harvested later. However, CH_4 released into the *Intermediate Zone* can not be extracted in the future and is therefore lost (*Scenarios* IZ1 to IZ5).

(d) Compared to the most economic *Scenario* (IZ4), the RZ reinjection *Scenarios* reduce the ***available*** $\boldsymbol{CH_4}$ by only ~2%. The differences of ***available*** $\boldsymbol{CH_4}$ among the *Scenarios* are particularly small (~1% only).

(e) However, there is substantial difference concerning the $\boldsymbol{CH_4}$ ***harvest***, which reflects the different vertical distribution of CH_4 left behind in the lake after 100 yr of extraction. For the definition of $\boldsymbol{CH_4}$ ***harvest*** we have chosen a realistic, but arbitrary CH_4 threshold concentration of 5 mol m^{-3}. Although, we can assume that improved technology and experience will lower the threshold for economic CH_4 harvesting below 5 mol m^{-3}, the lowest economically extractable CH_4 concentration expected in the future remains uncertain. Therefore it is sensible to remain conservative and opt for a *Scenario* that maintains a favourable vertical distribution of CH_4 to the very end of the extraction process.

Compared to the most economic *Scenario* (IZ4), the ***CH_4 harvest*** is reduced in the worst case by up to ~12% (PR1, RZ1 and RZ6). However, with an optimized density management (by flexible removal of CO_2) in the second half of the extraction, the ***CH_4 harvest*** can be increased. If the density gradient above the *Resource Zone* (at 260 m depth) is maintained during the extraction, the *Potential Resource Zone* will most probably become harvestable in a few decades. Under those two optimal conditions, the loss of ***CH_4 harvest*** (relative to IZ4) will be significantly less than 10%.

From these considerations and the comparison of the advantages and disadvantages in Table 2.4.2, we concluded the following ranking of the *Scenarios*:

- Best - and recommended - *Scenario*:	RZ6
- Second - but still acceptable - *Scenario*s:	PR1 or RZ1

- the other *Scenario*s are not recommended.

The best and recommended *Scenario* corresponds to Plan A1/A2 and Plan B in MP (2009). We, however, recommend studying the details of a flexible removal of CO_2 and optimized vertical stacking of the reinjection water in more detail.

PART II: Technical Documentation

3. Lake data used for model simulations

3.1 CTD Profiles

In 2004 a set of 13 vertical profiles of temperature and conductivity (CTD) were acquired in the northern half of Lake Kivu with a Sea-Bird SBE-19 which was equipped with a Sea-Bird SBE-22B combined pH and oxygen sensor. With the exception of some cool intrusions observed at 180 and 250 m depth (see below; Schmid 2010), temperature and salinity were horizontally homogeneous in the deep-water. The four deepest reaching profiles were averaged to produce the temperature and salinity profiles used in the model. These temperature and salinity profiles are listed in Table 8.8 of the Appendix.

3.2 Water chemistry

Water samples were analyzed with standard methods for alkalinity (Alk), nutrient contents and main ionic composition. Salinity (S) was calculated from conductivity and ionic composition, according to Wüest et al (1996), and agreed within 2% with the values calculated by adding the measured ionic content. Historic conductivity and salinity values are inconsistent; the levels measured by Tietze (1978) in the deep-water are about 10% higher than our values, whereas those of Degens et al (1973) are lower by almost a factor of two. However, recalculating conductivity from the ionic composition given by Degens et al (1973) yields values comparable to ours which indicates that their salinity calculations were incorrect. CO_2 was calculated from pH and alkalinity including the effects of temperature and salinity and the first dissociation constant of H_2CO_3 (Cai and Wang 1998). The uncertainty in this calculation is mainly due to pH, since an error in pH of ±0.05 units produces an error in the CO_2 concentrations of approximately ±10%. The equations used in the model are listed in Appendix 8.3.

CH_4 was measured with a Capsum Mets CH_4 sensor, which was calibrated for the high concentrations in Lake Kivu. The standard deviation observed by the manufacturer in the calibration was 0.4 mol m^{-3}. In the deep-water of Lake Kivu this corresponds to an error of 2 to 5%. The sensor recorded the CH_4 concentration every 0.5 s. In the field, it exhibited an unexpectedly slow response time of 46 min. The measured concentrations were extrapolated by fitting time series of 200 to 600 consecutive samples to an exponential curve. The error due to the fitting procedure was 0.5% (below the main density gradient at 260 m depth), 2 to 3% (within the main density gradient), and up to 10% above 230 m depth. It was larger at lower concentrations due to the higher relative noise of the instrument. However, we lack a proper error analysis for the sensor and applied method.

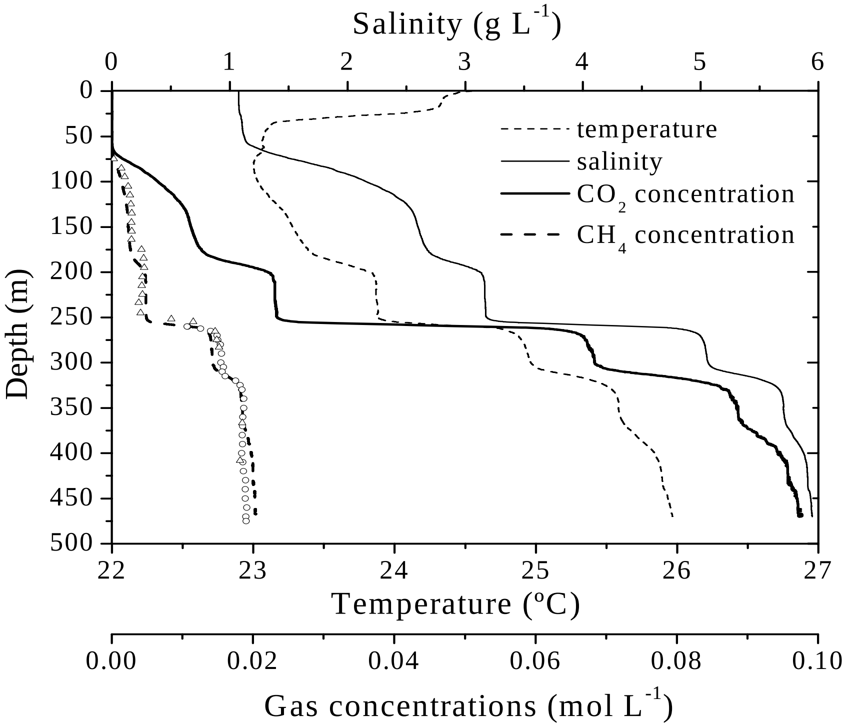


Figure 3.2 *Vertical profiles of temperature (T), salinity (S), CH_4 and CO_2, as observed in February 2004 (Schmid et al 2005a,b). The CH_4 profile used in this study (dashed, set proportional to the CO_2 concentration) slightly deviates from the observed data (open circles and triangles). Data in Table 8.8 (Appendix).*

In November 2003, CH_4 and CO_2 concentrations were measured by Michel Halbwachs by transferring water through a polyethylene tube to the lake surface, separating the gas and the water phases, measuring their flow rates, and determining the CH_4 and CO_2 concentrations in the gas phase with a portable GA2000 infrared gas analyzer. The gas analyzer was verified by measuring lake gas samples with another identical instrument before and after the expedition with a standard of 40% CH_4 and 60% CO_2. Errors were in the range of ±0.2% (volume), i.e., less than 2% of CH_4 concentrations observed in the lake. The measurement error for the Schlumberger gas flowmeter is about ±2%, while the error of the water flow can be neglected. Consequently, a total error of ±4% is assumed. Measured ratios of CH_4 to CO_2 concentrations ranged between 0.196 and 0.224. A continuous vertical CH_4 profile (Figure 1.1) was constructed from the data by assuming that CH_4 concentrations were 20.9% of CO_2 concentrations everywhere in the water column. M. Halbwachs (pers comm) remeasured the concentrations in 2009 with this “tube-method” and found values consistent within a few %.

Compared to previous measurements in the 1970s (Tietze 1978), the measured CH_4 concentrations in the deep-water have increased by 15 to 20% and CO_2 concentrations by about 10%. The increase in the CH_4 concentrations is clearly significant if we exclude a systematic error of much more than 5% relative to the measurements of Tietze (1978), while the observed 10% increase in CO_2 is hardly significant. Profiles of CO_2 and CH_4 are listed in Table 8.8 (Appendix).

The concentrations of the two most abundant nutrients, phosphate (PO_4) and ammonium (NH_4), were measured by means of a photometric analysis of water samples taken at 20 m vertical intervals with a Niskin bottle (Pasche 2009). Profiles of phosphate and ammonium are listed in Table 8.8 (Appendix).

4. Model description and model assumptions

4.1 Introduction

The goal of the modelling is to describe the development of the Lake Kivu stratification under the effects of the extraction operation for a period of 100 yr. The model provides the development of all variables relevant for the density stratification (T,S, gases), the gas content (CO_2 and CH_4) and the nutrient fluxes (PO_4 and NH_4). For any point in time, the eight *Attributes* (Table 2.2.2) can be calculated and these *Attributes* allow determining to which degree the *Guiding Principles* (Table 2.2.2) are fulfilled. The outcome of all 12 *Scenarios* (Table 2.3.2) can then be compared (Table 2.4.1) and assessed relative to the formulated *Objectives* of the extraction project.

A one-dimensional reactive-diffusive-advective model was set up with the lake module of the software AQUASIM 2.1 (Reichert 1994, http://www.aquasim.eawag.ch/). Simulations were performed with a 1-m vertical grid and with variable time stepping chosen by the integration algorithm. In this Section 4 the processes included in the model are explained and formulated. All equations used in the model are listed in Sections 8.3 to 8.5 (Appendix). The model parameters are given in Appendix 8.2. The model contains the following natural processes:

- surface inflow, upwelling (caused by the subaquatic sources inflow), and outflow
- turbulent and molecular diffusion (vertical mixing of water masses)
- gas exchange for CH_4 and CO_2 between lake surface and atmosphere
- CH_4 new formation and CO_2 release at the lake sediment
- CH_4 oxidation in the oxygen-containing *Biozone*
- algae growth in the *Biozone:* assimilation of nutrients (PO_4, NH_4)
- Sediment area-proportional release of nutrients by mineralisation of settling organic matter.

In addition, the model includes the processes induced by the extraction operation, such as lake-internal water dislocation (upwelling, dowelling and changes of concentrations at the reinjection depth). This modelling approach includes all the processes relevant for the evaluation of the *Scenario* simulations (Section 5) and we are convinced that no relevant process is neglected. Despite this comprehensive approach, the model has obviously uncertainties and limitations, comprising:

- uncertain CH_4 new formation
- uncertain discharges and varying concentrations of deep-water sources
- uncertain feedback between changing stratification and input depth of deep-water sources
- assumption of long-term steady state, although lake is not at steady-state
- one-dimensional model (not considering local effects at reinjection points)

- no feedback (model coupling) between nutrient input, primary production and CH_4 new formation
- dilution-factors are not continuously adjusted for the changing density
- uncertain feedback between changed stratification and diffusivity
- potential feedback between decreasing CH_4 concentrations due to extraction and CH_4 release from the sediments is neglected
- nitrogen fixation by cyanobacteria from the atmosphere is ignored
- removal of NH_4 by nitrification and denitrification is not included.

4.2 Surface inflow

The surface inflow to Lake Kivu consists of river flow from 127 small rivers, contributing 2.4 km^3 yr^{-1} (75 m^3 s^{-1}), and precipitation (1400 mm yr^{-1}) onto the 2370 km^2 large surface, yielding 3.3 km^3 yr^{-1} (Table 4.4; Muvundja et al 2009). In the model, the net surface inflow is considered, which reduces the above water flow by the evaporation from the lake surface, which is about 3.4 km^3 yr^{-1}.

For the model simulations, the input of phosphate (PO_4), ammonium (NH_4) and salinity (S) by the rivers and the atmospheric deposition is considered (Table 4.4). The inclusion of these dynamic variables in the model is described in the following Sections below.

4.3 Subaquatic inflow

The net surface inflow to Lake Kivu, estimated to ~2.3 km^3 yr^{-1} in the previous Section, is smaller than the Ruzizi River outflow of ~3.6 km^3 yr^{-1} (Degens et al 1973; Muvundja et al 2009), calling for an additional source of inflow into the lake of ~1.3 km^3 yr^{-1}. Also the fact that the salt loss by the Ruzizi outflow (Table 4.4) is larger than the salt inflow by the 127 rivers indicates a more salty additional input. From the previous model calculations (Schmid et al 2005a) we can conclude that several subaquatic sources, at several depth levels, contribute to this inflow. The water input by this subaquatic source displaces the lake water layers causing a slow upwelling flow.

Also the vertical structure of various water constituents calls for subaquatic source at several depth ranges. For example, the persistent strong temperature gradient at 260 m depth (Figure 4.7.2) with a step of 0.7 °C within 7 m, calls for an active process to sustain this sharp interface. Otherwise it would be destroyed by molecular heat diffusion within a few years. Also horizontal structures in that depth range provide evidence of such sources. A distinct negative temperature signal (and a weak salinity structure) was observed at 250 m depth which was strongest in the profiles measured in the North-Eastern part of the lake. Similar weaker signals were also observed at 180 m depth. Such signals can be explained by inputs of cooler and less saline water. These inflows are most probably sustaining the steep density gradients observed at several depths in the profiles. Especially, the main gradient at 255 to 262 m depth is maintained by the inflow at ~250 m depth. Furthermore, the observed decrease in CH_4 is due to dilution by subaquatic sources, although some minor oxidation (by oxygen, sulphate or nitrate contained in the subaquatic inflows) can not be excluded.

The observation that the gradient at 260 m depth got stronger since the work of Tietze (1978) and Newman (1976), indicates that some subaquatic flows may have become stronger since the 1970s (Schmid et al 2010).

The flow rates, temperatures and salt concentrations of these inputs as well as the geothermal heat flux were fitted to reproduce the observed profiles in a time frame of 990 yr prior to 2004. Figure 4.3.3 shows the upwelling flow resulting from deep-water inputs and Figure 4.3.4 shows the corresponding upwelling velocity. The depth ranges and the discharges of the subaquatic sources, which fit best the model results, are listed in Table 8.2.2 (Appendix).

In the next step, concentrations of CH_4, CO_2, phosphate (PO_4), salinity (S) and ammonium (NH_4) in the deep inflows were estimated (Table 8.2.2, Appendix) such that their deep-water concentrations in the lake remained constant within 30 yr of simulation with the historic CH_4 new formation rate (see below) and initial conditions from 2004. The model assumptions are listed in Table 8.2.1 (Appendix).

The assumption is that Lake Kivu was close to steady-state until 1944 and gas concentrations increased since then. Setting the measured concentrations from 2004 as initial values (instead of unavailable data from 1944 with lower values) probably leads to a slight overestimation of the concentrations in the sources. This effect is of minor importance for the comparison of different *Scenario*s but for the *Scenario* O, without gas extraction, the total amount of CH_4, CO_2, PO_4 and NH_4 may be overestimated in the long term. It is presently impossible to measure the estimated properties of the subaquatic water inputs mentioned above.

It is well possible that the intrusion depths of the subaquatic sources will alter if the vertical density stratification changes in the future. In the model those depths are kept constant, since the AQUASIM code does not allow programming the inflows as a function of the vertical density profile. Furthermore, we do not really know whether and how these depths would change. Therefore all *Scenario*s which lead to a major change of the density stratification contain an uncertainty of the effective intrusion depth of the subaquatic sources.

4.4 Surface outflow

The Ruzizi River is the only surface outflow from Lake Kivu with an average flow of ~3.6 $km^3\ yr^{-1}$ (114 $m^3\ s^{-1}$; Muvundja et al 2009). Together with the evaporation of ~3.4 $km^3\ yr^{-1}$, the total water input and output balances at ±7.0 $km^3\ yr^{-1}$.

For water constituents affected by a surface exchange process with the atmosphere (such as temperature and gases) the Ruzizi outflow is not relevant. Therefore the outflow of heat, CH_4 and CO_2 can be neglected.

Although nutrients leave the lake via Ruzizi, their outflow is small compared to sedimentation (Pasche et al 2009; Muvundja et al 2009) and therefore nutrient outflow - although included - is not relevant for the model output. As salinity has only a small sedimentation component the Ruzizi River outflow is the main sink for salinity.

The outflow of salt (salinity), nutrients (P and N components) and CO_2 are listed in Table 4.4.

Table 4.4 ***Mass inflows (surface and subaquatic) and outflows (Ruzizi River)***

Depth	**Water flow [m^3 s^{-1}] (1)**	**Salt flux (2) [10^6 t yr^{-1}]**	**Phosphate flux (3) [t-P yr^{-1}]**	**Nitrogen flux (4) [t-N yr^{-1}]**	**$CO_{2,total}$ (5) [kt-C yr^{-1}]**
Inputs					
at surface	75	0.24	230 (1)	5400 (1)	~60
at 180 m depth	22	1.46	370	5100	15.3
at 250 m depth	15	1.28	450	4300	22.0
at 310 m depth	1	0.11	0	620	2.2
at 365 m depth	1.5	0.26	20	930	12.5
at 425 m depth	0.8	0.15	0	0	7.6
at 465 m depth	1.25	0.24	150	1660	15.0
Degradation sed					284 (7)
Output					
Ruzizi River	-114	-3.89	-70 (6)	-300 (6)	-505
Net sediment	-	?	-280	1900	?
To atmosphere	-3	-	-	not included	

(1) Water balance according Muvundja et al (2009): rivers = 2.4 km^3 yr^{-1}; Ruzizi outflow = 3.6 km^3 yr^{-1}

(2) Salinity values of inflows are: 0.1, 2.1, 2.7, 3.4, 5.5, 5.8 and 6, respectively (see Table 8.2.2 Appendix)

(3) Phosphate values of inflows are: 0.003, 0.017, 0.032, 0, 0.012, 0, 0.12 mol m^{-3}

(4) Dissolved nitrogen values of inflows are: 0.043, 0.52, 0.65, 1.4, 1.4, 0, 3.0 mol m^{-3}

(5) $CO_{2,total}$ (definition in Section 4.10) enters as any of the carbonate components (Table 8.2.2, Appendix). In the lake water, this $CO_{2,total}$ forms carbonate species according to the pH and alkalinity in the lake.

(5) Assumption on the $CO_{2,total}$ release by organic matter degradation: 705 mol s^{-1} .

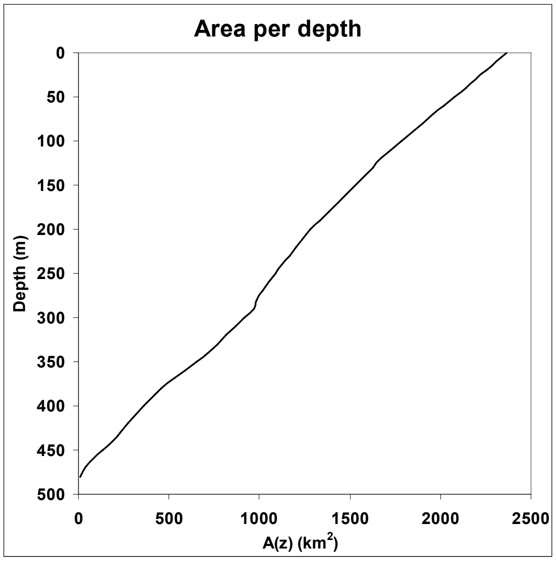


Figure 4.3.1 *Cross sectional area A(z) of the lake as a function of depth z.*

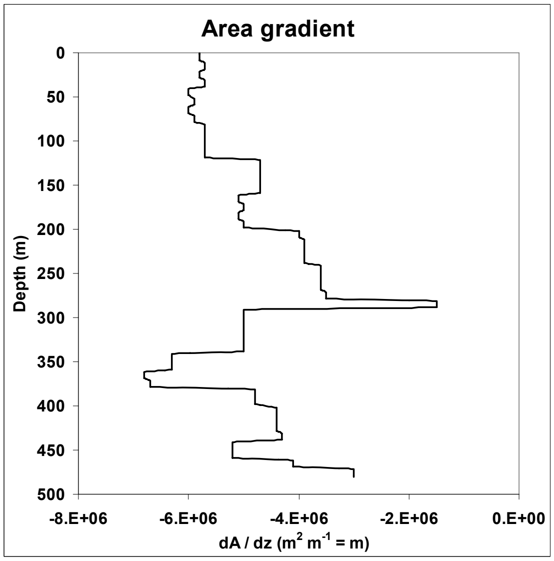


Figure 4.3.2 *Area change per depth dA/dz(z) (negative scale, as area decreases with z).*

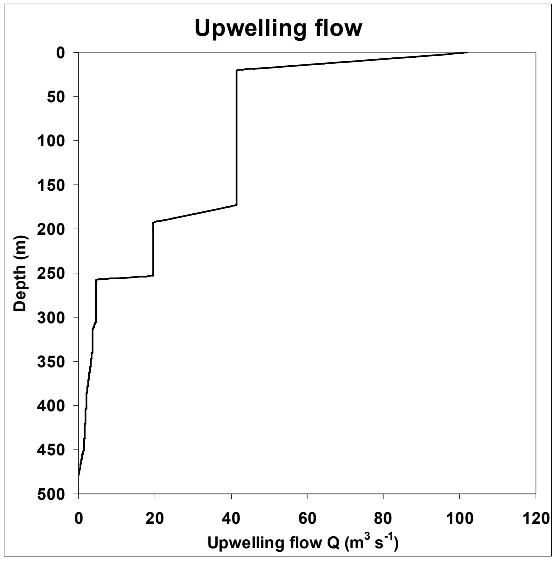


Figure 4.3.3 *The upwelling flow Q (z) at depth z is the sum of all subaquatic water inflows below depth z.*

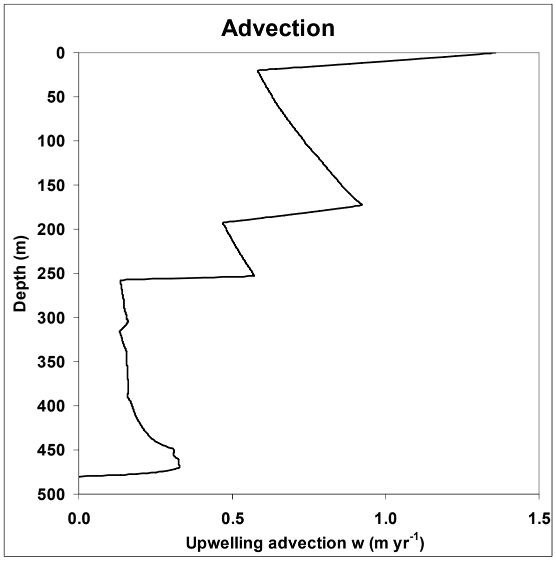


Figure 4.3.4 *The upwelling velocity w(z) is the upwelling flow Q(z) divided by the area A(z) at depth z; w(z) = Q(z)/A(z).*

4.5 Turbulent Diffusion

Below 120 m depth (down to maximum depth) double-diffusive staircases (a sequence of sharp interfaces and homogeneous layers) can be observed over almost the entire water column (Schmid et al 2010). Above 120 m depth none have been found so far. Therefore, below 120 m depth, turbulent vertical diffusivity was set equal to $0.15*\varepsilon/N^2$ (Osborn 1980; Wüest et al 2000) for heat and - based on our analysis of the fluxes through the double diffusive layers - a factor 10 lower for salt and gases (Schmid et al 2010). Here, $N^2 = (-g/\rho)*(d\rho/dz)$ is the stability of the density stratification (Figures 4.5.3/4), which is continuously calculated during the simulations according to Chen and Millero (1986) and Schmid et al (2004) (equations in Appendix 8.3). The energy dissipation ε below 120 m depth is on the order of 1.0×10^{-10} W kg^{-1}, which was confirmed by three independent methods (Schmid et al 2005a).

The continuous calculation of density stratification generates a numerical problem due to the following positive feedback: Turbulent diffusion causes a weakening of the density stratification which leads to increased diffusion, weakening the stratification further. Therefore vertical heat diffusivity was limited to a maximum value of 10^{-4} m^2 s^{-1} (Figures 4.5.1/2). The effect of this damping is that convective mixing caused by unstable stratification, which would require a value of about 10^{-3} m^2 s^{-1} or even more for turbulent vertical diffusion, can not be simulated correctly. This deficiency is not critical, as the mass balances (most important) remains correct.

The natural diffusive transport in the deep-water is weak compared to the dominant upward flux by upwelling and a maximum value of 10^{-4} m^2 s^{-1} for turbulent vertical heat diffusion is rather too high for the basic simulation *Scenario* O (no extraction). Since vertical transport is dominated by upwelling in this depth range, it is not critical how the diffusivity is parameterized, as long as the results of the simulations are not unstable.

Above 120 m depth no double-diffusive layers were observed (Schmid et al 2010) and the temperature minimum at 68 m indicates occasional seasonal convective mixing of the *Biozone* to this depth. As there is no seasonality implemented in the model, turbulent vertical diffusion was kept constant above 120 m depth and the values were adapted to reproduce the observed salinity profile. The top 50 m of the lake are mixed annually and the top 18 m of the *Biozone* are almost completely mixed (scale of about a week).

4.6 Temperature

Heat input (geothermal heat flux) - The temperature gradient in Lake Kivu is simulated with a homogeneous geothermal heat flux of 0.02 W m^{-2} at the sediment surface. This value agrees well with the independent estimates of small-scale double-diffusive heat fluxes (Schmid et al 2010). The temperatures of the subaquatic sources were fitted to reproduce the observed temperature profile in a time frame of 990 yr. A comparison of the temperature measurements from 1973

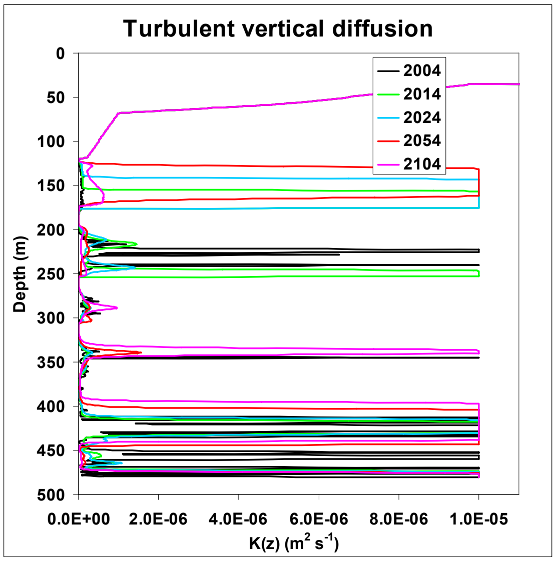


Figure 4.5.1 *Vertical heat diffusivity K(z) below 120 m depth (Scenario O, no extraction).*

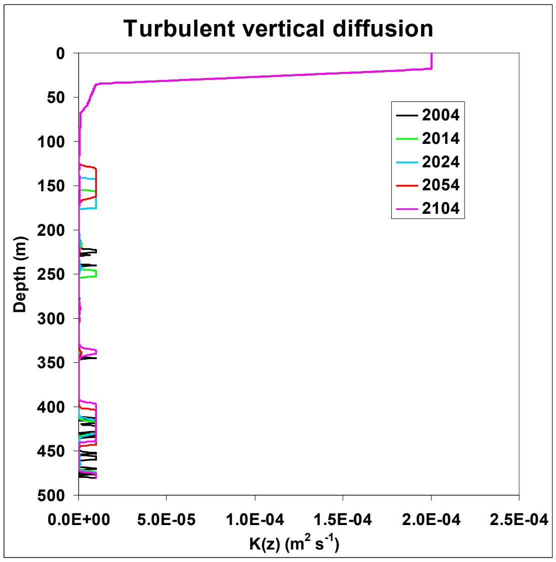


Figure 4.5.2 *Vertical heat diffusivity K(z) above 120 m depth (Scenario O, no extraction).*

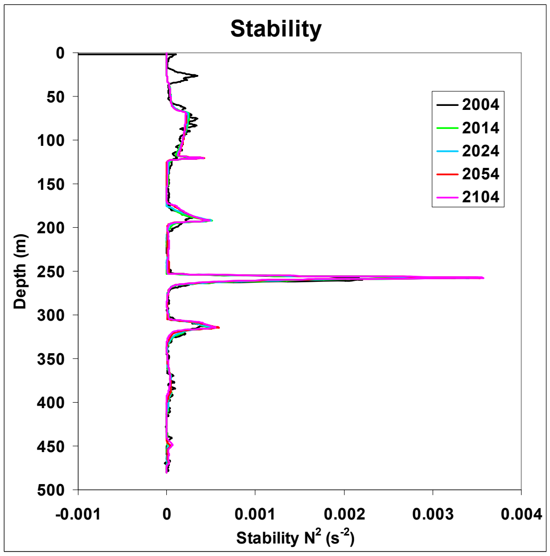


Figure 4.5.3 *Observed (2004) and simulated stability N^2 profiles (Scenario O, no extraction; linear scale).*

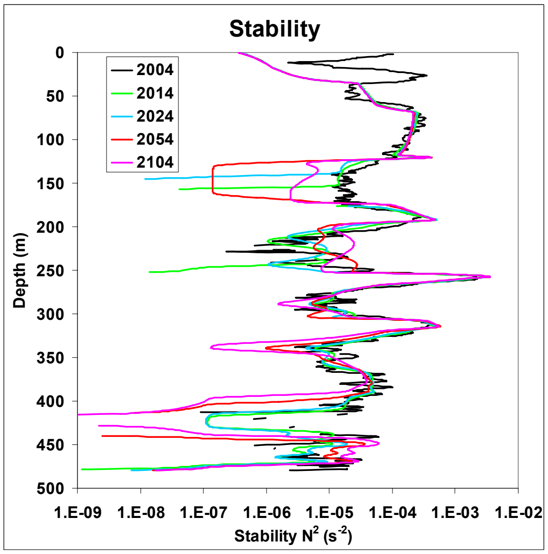


Figure 4.5.4 *Observed (2004) and simulated stability N^2 profiles (Scenario O, no extraction; log scale).*

and 2004 shows a slow warming of the upper part of the lake. The temperature of the subaquatic source at 180 m depth was fitted again to reproduce this observed warming in a time frame of 30 yr.

Heat output at the lake surface - The model does not include the seasonal variation of temperature due to atmospheric heat exchange. The temperature at the lake surface was set to 23.06 °C, which was the minimum temperature found in 2004 at 60 m depth. This temperature minimum is assumed to be a relict from the last cooling-induced convective mixing.

4.7 Salinity

The vertical structure of the salinity can be understood solely by the interplay of the input via subaquatic sources (defining the high deep-water concentrations), the upwelling of the salts to the lake surface and the surface flushing by the low-salinity river inflow and precipitation. Basically the subaquatic salt input balances the sink via the Ruzizi River plus some negligible sedimentation within the lake.

Salinity input (surface and subaquatic inflow) - In the model, six subaquatic sources sustain and shape the strong vertical salinity structure in the water column (Table 4.4). The flow rates and the salinities of these water inputs have been fitted to reproduce the observed profiles over a time scale of 990 yr (Table 4.4). The discharges of all the subaquatic inflows as well as their different concentrations of the water constituents are listed in Table 8.2.2 (Appendix).

Salinity output (surface outflow) - The Ruzizi outflow (~114 $m^3 s^{-1}$; Muvundja et al 2009) transports about 3.9×10^6 t yr^{-1} of salt from the surface of Lake Kivu to Lake Tanganyika (Table 4.4).

4.8 Density

In this report and in the model simulations, the density of Lake Kivu water has been calculated by the following approximation:

$$\rho(S, T, CH_4, CO_2) = \rho(T) * (1 + 0.75\times10^{-3}\ m^3\ kg^{-1} * S + 0.284\times10^{-6}\ m^3\ g^{-1} * 44.0099\ g\ mol^{-1} * CO_2 - 1.25\times10^{-6}\ m^3\ g^{-1} * 16.04\ g\ mol^{-1} * CH_4) \qquad [kg\ L^{-1}]$$

$$\rho(T) = 0.999839 + 6.7914\times10^{-5} * T - 9.0894\times10^{-6} * T^2 + 1.0171\times10^{-7} * T^3 - 1.2846\times10^{-9} * T^4 + 1.1592\times10^{-11} * T^5 - 5.0125\times10^{-14} * T^6 \qquad [kg\ L^{-1}]$$

CH_4 and CO_2 are the gas concentrations [mol m^{-3}]. T = temperature [°C], and S = salinity [kg m^{-3}]. The equations for calculating CO_2 (the gaseous CO_2 concentrations) from $CO_{2,total}$, are given in Appendix 8.3.

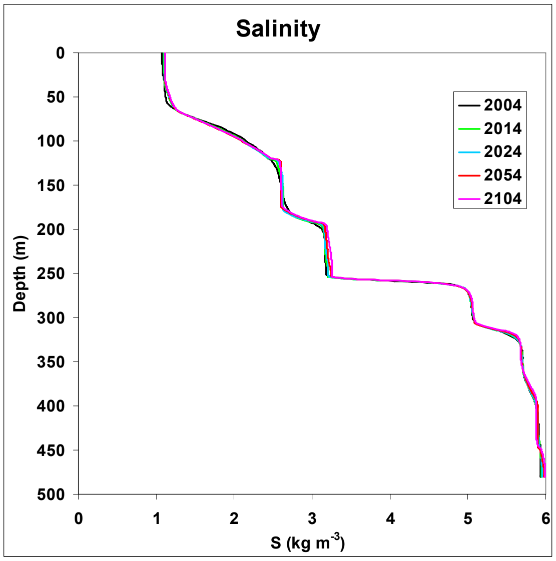


Figure 4.7.1 *Observed (2004) and simulated salinity S profiles (Scenario O, no extraction).*

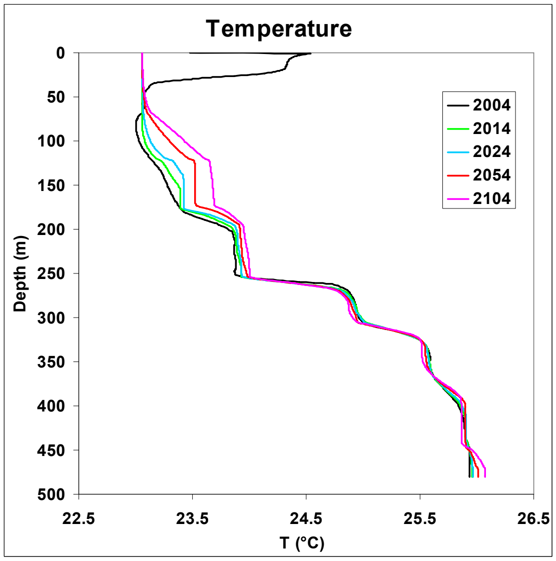


Figure 4.7.2 Observed (2004) and simulated temperature T profiles (*Scenario* O, no extraction).

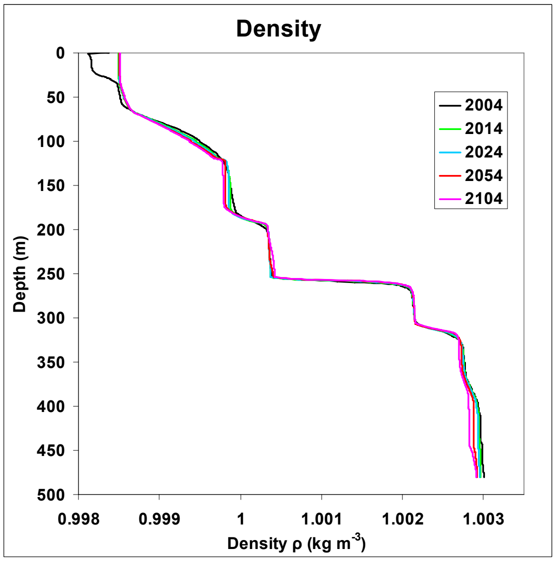


Figure 4.8.1 *Observed (2004) and simulated density profiles (Scenario O, no extraction).*

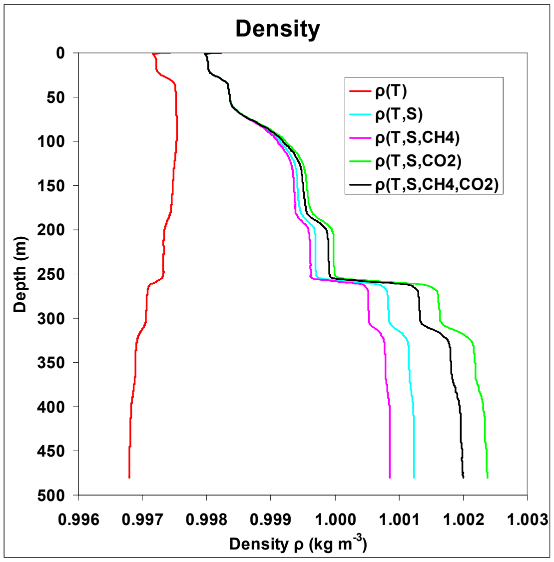


Figure 4.8.2 *Effects of temperature, salinity, CH_4 and CO_2 on the lake water density for profiles in 2004.*

4.9 Methane

Methane new formation in the lake - CH_4 formation was assumed to be homogeneous at the sediment surface; i.e., the CH_4 input into the lake is proportional to the sediment area at each depth of the lake. Formation within the water column (open lake water) was considered to be negligible. It was further assumed that the historic value of CH_4 new formation, 30 g-C m^{-2} yr^{-1}, had been constant for a sufficiently long time to approach steady-state (in the model we arbitrarily used 990 yr). We further assumed that the CH_4 formation increased from 1944 to 1974 to 70 g-C m^{-2} yr^{-1} and then to 120 g-C m^{-2} yr^{-1} between 1974 and 2004 (Figure 4.9.1). The three values of CH_4 formation (historic, 1974 and 2004) were determined by fitting to the CH_4 profiles observed in 1974 (Tietze 1978) and 2004 (Schmid et al 2005a,b). Of course, the chosen temporal development is one of several realistic possibilities, but using another time frame would not alter the average CH_4 new formation needed to produce the observed increase in concentrations between 1974 and 2004 (Schmid et al 2005a). The future development of the CH_4 new formation is not well predicted and therefore the fitted value for 2004 was used for the simulation of gas extraction. The CH_4 new formation is one of the major uncertainties in the model. Potential effects of different new formation rates have been tested (Section 2.5). However no changes, relevant for the *Consequence Table* 2.4.1 have been observed.

The most probable CH_4 new formation rate of today is somewhere between 30 and 120 g-C m^{-2} yr^{-1}. According to Pasche et al (submit) the most plausible estimate is ~60 g-C m^{-2} yr^{-1}, but includes a large error of ~30 g-C m^{-2} yr^{-1}.

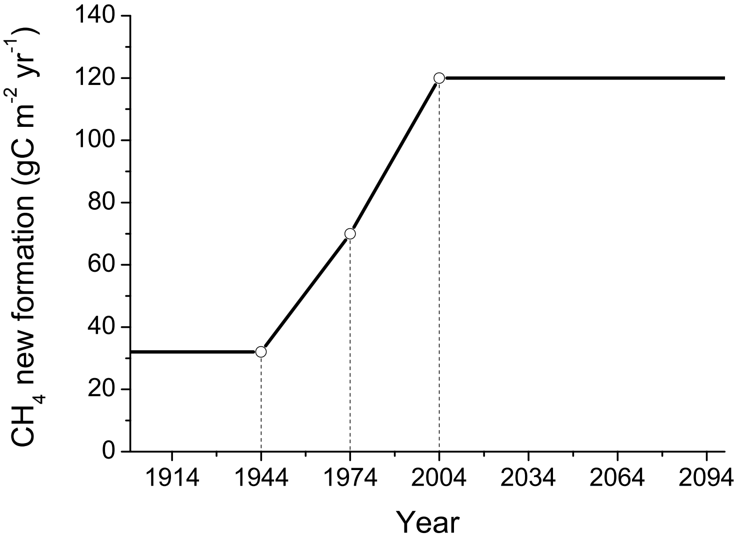


Figure 4.9.1 *CH_4 formation rate (g-C m^{-2} yr^{-1}) as implemented in the model, based on best fit to the measured profiles in 1974 and 2004.*

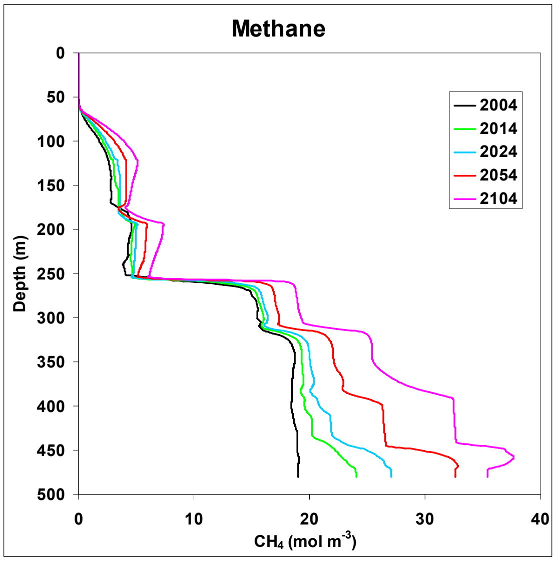


Figure 4.9.1 *Observed (2004) and simulated CH$_4$ profiles (Scenario O, no extraction).*

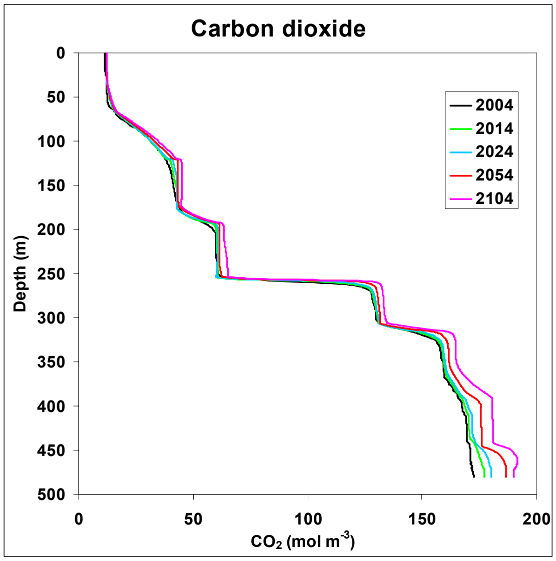


Figure 4.9.2 *Observed (2004) and simulated CO$_2$ profiles (Scenario O, no extraction).*

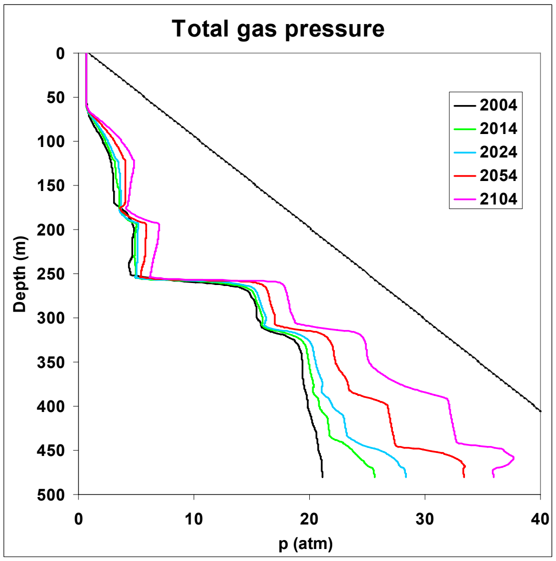


Figure 4.9.3 *Total gas pressure and hydrostatic pressure (Scenario O, no extraction).*

Methane loss (sink) - The CH_4 in the lake is transported towards the *Biozone* by the upwelling flow and by turbulent diffusion. CH_4 is consumed by oxidation once it reaches the shallower water layers, which contain oxygen (most important) as well as sulphate and nitrate (less important, Section 2.1). Therefore a self-limiting process transforming CH_4 to CO_2 by oxidation above 60 m depth with a rate of 10^{-6} s^{-1} was implemented in the model. The sum of oxidized (and thus lost) CH_4 for *Scenario* O (no extraction) is 6.4 km^3 in the first 50 yr and 15.4 km^3 in the total 100 yr (calculated from the CH_4-flux in 70 m depth). With regard to the estimated CH_4 new formation below 60 m depth, ~45 km^3 during 100 yr (Table 1.1), the CH_4 concentrations in Lake Kivu are not in a steady-state and will continue to grow, if not extracted.

4.10 Carbon dioxide

Modelling of CO_2 - Modelling carbon dioxide (CO_2) in the lake water bears some complexity, as the CO_2 dissociates into different dissolved carbonate components in water: H_2CO_3 (dissolved, covalently bound), HCO_3^- (bicarbonate), and CO_3^{2-} (carbonate). We have chosen to simulate in the model the "total CO_2", defined by the sum:

$$CO_{2,total} = \Sigma CO_2 = H_2CO_3 + HCO_3^- + CO_3^{2-}$$

and to estimate the various carbonate components from this $CO_{2,total}$ and from pH. The three carbonate species equilibria are calculated from the dissociation constants pK_1 and pK_2 and pH, which depend on salinity and temperature by:

$$pK_1 = f(T, S)$$
$$pK_2 = f(T, S).$$

The three carbonate components are then calculated by

$$H_2CO_3 = f(CO_{2,total}, pH, pK_1, pK_2)$$
$$HCO_3^- = f(H_2CO_3, pH, pK_1)$$
$$CO_3^{2-} = f(HCO_3^-, pH, pK_2).$$

All five equations are detailed in Appendix 8.3. In this report, the term CO_2 relates only to the dissolved gas component (H_2CO_3), as this component is responsible for the partial gas pressure and the potentially dangerous release of CO_2 gas. The ionic forms of $CO_{2,total}$ (i.e. HCO_3^- and CO_3^{2-}) are included in the salinity.

Sources of CO_2 - CO_2 is assumed to be produced proportional to the sediment area at a rate of 120 g-C m^{-2} yr^{-1} (1:1 with CH_4, 750 mol s^{-1}) and additional $CO_{2,total}$, enters by the subaquatic sources (200 mol s^{-1}, Table 8.2.2). It is assumed that the decomposition of organic matter leads to the production of the same amount of CO_2 as of CH_4. The total CO_2 input is then 950 mol s^{-1} (Table 4.4).

For a layer at depth z, the accumulation of CO_2 is therefore practically proportional to the sediment area per unit depth, -dA/dz(z), which increases as a function of depth (Figures 4.3.1/2). The lake water contains approximately 10-times more $CO_{2,total}$ than CH_4. Based on the estimated concentrations in the subaquatic springs and the CH_4 new formation rate, we expect that ~90% of the CO_2 in the lake is of magmatic origin, whereas the rest stems from the decomposition of organic material.

The oxidation of CH_4 above 60 m depth represents only a minor source of CO_2 (Section 4.9).

Loss (sinks) of CO_2 - CO_2 is leaving the lake water by the Ruzizi River outflow (minor contribution) and by degassing into the atmosphere (Table 4.4). These two CO_2 fluxes are parameterized in the model as follows:

(i) Ruzizi River outflow = water discharge (m^3 s^{-1}) * lake surface concentration (mol m^{-3}),
(ii) Gas exchange with the atmosphere: $v_{\text{gas exchange}}$ * ($CO_{2\text{ surface eq.}}$ - CO_2)* surface area. The parameterizations used in this equation, are detailed in Appendix 8.3.

4.11 Phosphate and ammonium

Sources of nutrients - The external inputs of PO_4 and NH_4 have been estimated based on field measurements in 2006 to 2008 (Muvundja et al 2009). The comparison with the lake internal nutrient cycling shows (Pasche et al 2009) that the input of phosphate (PO_4) and ammonium (NH_4) into the *Biozone* is largely dominated by the lake internal loading. Therefore, in this model, the major and only important source for nutrients for the *Biozone* is the upwelling of nutrient-rich deep-water. The reason for the high deep-water nutrient concentrations is the mineralization (degradation) of the lake internal organic material (plankton) at the sediment surface in combination with the long residence time of the deep water.

Mineralization is assumed proportional to CH_4 with the stoichiometric coefficients of the organic material found in the sediment traps in 2007 (molar ratios C:P = 216 and N:P = 13.9 (Pasche et al submit; Appendix 8.4). Degradation of organic matter in anaerobic water transforms carbons in equal parts to CH_4 and CO_2.

Although, direct nitrogen fixation by algae or bacteria from the atmosphere may be an additional nutrient source, this process is not included in the model.

Sinks of nutrients - To account for the primary production (algae growth at the lake surface), a fast self-limiting process (limiting in PO_4 and NH_4), removing PO_4 with a rate of 10^{-6} s^{-1} in the *Biozone*, was implemented. It was observed that PO_4 is the limiting factor for most of the time, but occasionally NH_4 appears to be limiting (Pasche et al 2009; Muvundja et al 2009). This sink of PO_4 implies that any

PO_4 entering the *Biozone* is consumed on average within 12 days. NH_4 is removed in parallel with the ratio of the corresponding stoichiometric coefficients (Appendix 8.4). Removal of NH_4 by nitrification and denitrification is not included in the model, implying that NH_4 surface concentrations are overestimated.

The Ruzizi outflow transports ~50 t-P yr^{-1} as PO_4 and an additional ~20 t-P yr^{-1} as plankton from Lake Kivu to Lake Tanganyika (Table 4.4; Muvundja et al 2009). This small phosphorus export has no influence on this model as the nutrient cycle is not closed. Simulated PO_4 release by algae degradation (mineralization) is constant and does not depend on PO_4 consumption (i.e. primary production). Consequently, a potential positive feedback between enhanced nutrient upwelling, higher primary production and therefore increased mineralization cannot be reproduced by the model.

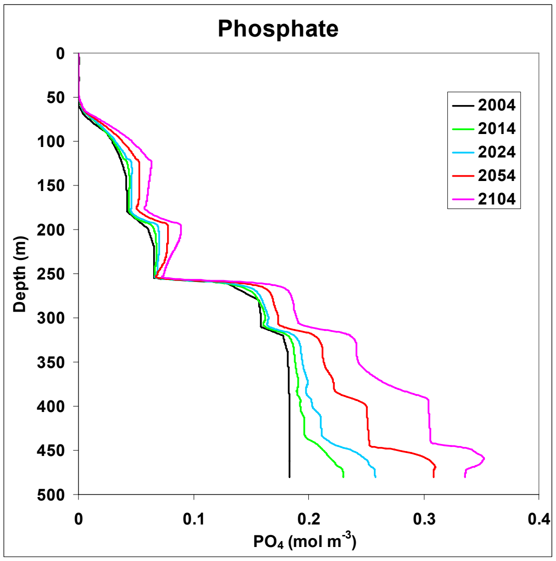


Figure 4.11.1 *Observed (2004) and simulated PO_4 profiles (Scenario O, no extraction).*

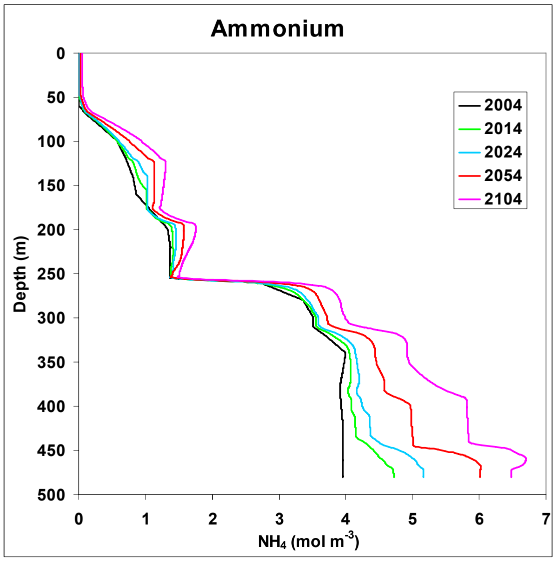


Figure 4.11.2 *Observed (2004) and simulated NH_4 profiles (Scenario O, no extraction).*

4.12 Lake development without extraction - Scenario O

With these assumptions, detailed in the above Sections 4.1 to 4.11, we performed model simulations for 100 yr duration without CH_4 extraction (*Scenario* O, natural development). We used these results from *Scenario* O in the following

Scenario simulations (Section 7) as a reference. The “no extraction” simulations reveal the following (see various figures in this Section 4):

Salinity (Figure 4.7.1) and temperature (Figure 4.7.2) are, according to the assumptions, in a quasi-steady state. For this reason, salinity (Figure 4.7.1) and temperature (Figure 4.7.2) change only slightly over the 100 yr of simulation. Although we know from various other evidence that the lake is not exactly in steady state, we consider this assumption as reasonable, as changes to salinity and temperature may occur in “both directions”.

As salinity and temperature are the main components defining the density (Figure 4.8.1), also the density profile is not much affected over 100 yr of simulation. Therefore the simulated stability N^2 of the density stratification (Figures 4.5.3, 4.5.4) and the *Attribute* “Schmidt Stability” (Table 7.1) also remain almost constant.

The major changes over 100 yr of simulation are related to the gases and the nutrients. CH_4 (Figure 4.9.1) would increase to almost double the current concentration in the *Resource Zone*, whereas CO_2 (Figure 4.9.2) would increase only slightly. As an effect of both, the total gas pressure (Figure 4.9.3) is expected to become very critical below 250 m depth (*Resource Zone*) within the next century.

Also the nutrient concentrations of PO_4 (Figure 4.11.1) and NH_4 (Figure 4.11.2) would rise by up to 50% in the deep-water (below *Biozone*) and therefore also the nutrient fluxes to the Biozone would increase by about ~55 % (Table 7.1).

The simulations without extraction also show the effect of the interaction of the assumptions. If for example the water discharge of the subaquatic sources would weaken, then the accumulation of CH_4 in the deep-water would intensify (and the risk would increase even faster), because the “dilution” effect of the inflowing source water would be reduced. Therefore it is important to monitor the development of the vertical stratification of all relevant lake water properties (gases, temperature and salinity, nutrients) to detect potential changes in due time.

5. Definition of the extraction *Scenario*s

5.1 Design Parameters

The extraction *Scenarios*, tested in the following simulations, are characterized by five plant-defining *"Design Parameters"*. Here we focus only on plants which are qualitatively similar to the currently projected plants, i.e., water is taken to the surface in a vertical pipe, degassed, and reinjected again, by a vertical pipe into the lake (Figure 1.2). These five *Design Parameters* (Table 2.3.1), comprise:

(1) withdrawal depth and withdrawal depth range
(2) reinjection depth (of the depleted deep-water) and reinjection depth range
(3) dilution-water flow (% of extraction flow) and dilution-water intake depth
(4) removal (%) of CH_4, and
(5) removal (%) of CO_2.

Withdrawal depth and withdrawal depth range - The withdrawal of the to-be-extracted water is located in the Resource Zone (Figure 1.2), as the concentration in the *PRZ* and the *IZ* are currently too low for viable extraction.

The flow towards the holes of the intake pipe is not horizontal close to the intake (Figure 5.1). The vertical width of the "selective withdrawal" depends on the flow Q [$m^3\ s^{-1}$] as well as the local stability $N^2(z)$ [s^{-2}] of the stratification at depth z (Kataoka et al 2000; Woods 2001). The withdrawal width can be approximated by

$$D \approx 1.8 * (Q/N)^{1/3} \qquad [m]$$

where the factor of 1.8 can vary from 1.6 to 2.0 according to Table 2 in Fan (2008). For example, an extraction flow Q of 1 $m^3\ s^{-1}$ taken from the deepest reaches (460 to 480 m depth; N^2 in Figures 4.5.3, 4.5.4), would cause a vertical withdrawal range of ~16 m. In the Upper RZ (stronger stratification) the corresponding withdrawal range would be narrower.

Although, the selective withdrawal appears not to cause concerns, it may be important to maintain a smooth and gentle flow with only small vertical distortion of the horizontal layers by spreading the flow over a certain vertical range and by adding holes to the intake pipe. The values listed in Table 5.5 indicate the withdrawal depth (centre of such a withdrawal range) and the (full) vertical range. For the model simulations, a minimum withdrawal range of 10 m is used (Table 5.5). If the withdrawal pipe is not reaching the deepest location, the model assumptions imply that the lake volume below the intake is only affected by the turbulent diffusion and the natural upwelling. Therefore the simulation results occasionally show much higher concentrations in the very lowest reach of the lake

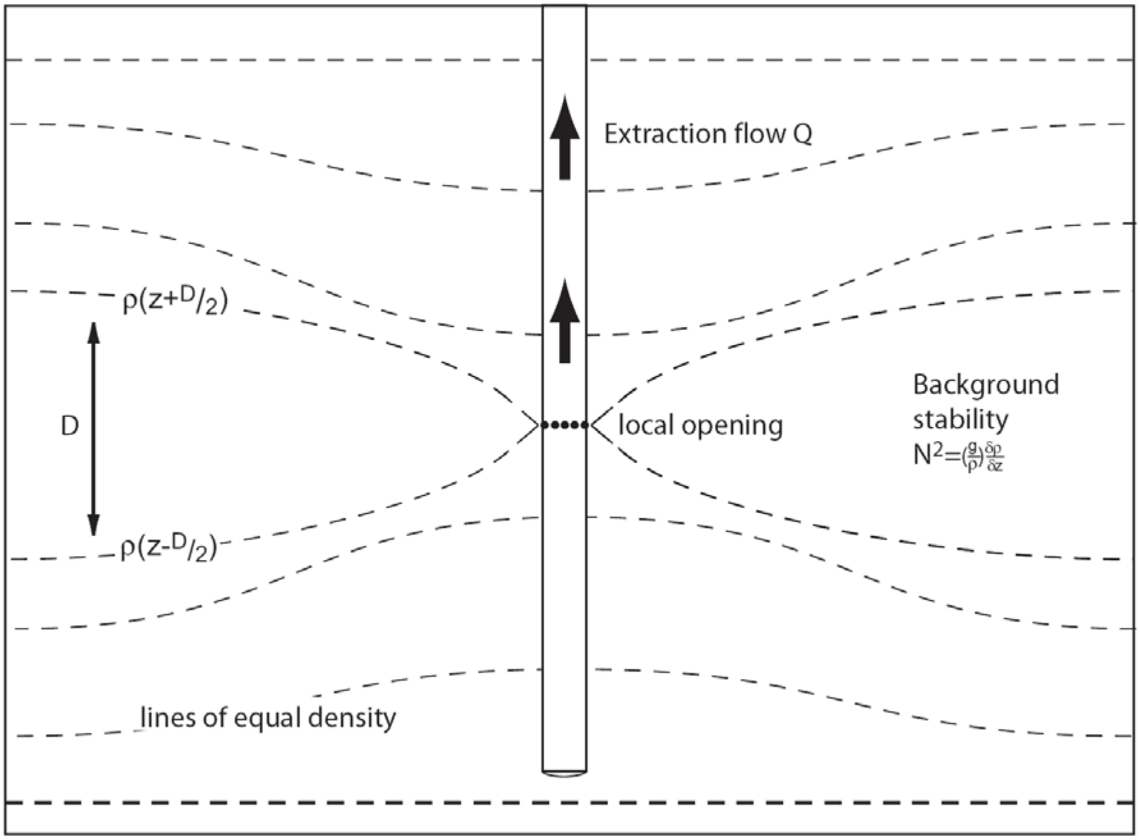


Figure 5.1 *Schematic diagram defining the thickness D of the withdrawal layer (depth range from where water is entering the pipe, point sink) for the flow Q in the ambient lake stratification N^2. Details in Fan (2008).*

Reinjection depth and reinjection depth range - The depth of the reinjection is a key parameter for this study, as its level affects strongly the future development of the stratification and the vertical distribution of the gases and density in particular. The pros and cons of the different reinjection depths - the key outcome of this study - are discussed throughout but specifically in the Sections 2.4 to 2.6.

Two different concepts have intensively been discussed: the “Density Gradient Lowering Method” and the “Density Structure Maintaining Method“ (MP 2009). The idea of the first approach is to stack the (lighter) CH_4-depleted reinject-water on top of the RZ (or on top of the PRZ) while “Lowering” the RZ to the deepest point and completely emptying the RZ from CH_4. The second approach conserves the vertical structure of the lake density stratification, as the CH_4-depleted deep-water is reinjected into the RZ. However, in order to avoid dilution of the RZ, which would decrease the efficiency of the extraction as well as the energy production (at least below the “non-economic” threshold concentration of CH_4), it is still necessary to stack the CH_4-depleted reinject water on top of the high-concentration RZ water. This can only be achieved by carefully controlling the density of the reinject water via adjusting the CO_2 removal (MP 2009).

Same as the withdrawal, also the reinject-water should be spread over a certain vertical range (Figure 5.1). The advantages are lower release velocity, less turbulence and more efficient mixing of the reinject-water with ambient lake water, as the reinjection entrains into a larger layer while enhancing the mixing. Density differences between reinject-water and ambient lake water are quickly reduced and as a result the reinject-water plumes sink or rise only short vertical distances. For example, the reinjection plume from the KP1 pilot plant has been observed to stratify only about 10 m below the reinjection depth at 90 m, while the natural restratification depth would have been located around 180 m (Nzayisenga et al 2009).

Dilution - The CH_4-depleted deep-water is usually denser than the ambient lake water at the chosen reinjection depth (the opposite is theoretically possible if almost all CO_2 is removed). Reasons for the higher density are the higher salinity (Figure 4.7.1) and CO_2 content (Figure 4.9.2) at greater depth. In addition the extrusion of gas cools the deep-water by up to ~0.5 ^oC. Usually the reinject-water is also lighter than the originally extracted deep-water (again the contrary is possible under special circumstances when almost all CO_2 is retained).

To ensure that the released water re-stratifies within the chosen reinjection depth range (no sinking or rising of the plumes) two measures can be taken: (i) The reinject-water can be diluted with near-surface water to adjust its density to the density of lake water near the reinjection depth, or (ii) the reinject-water can be spread (horizontally or vertically) with multiple outlets to efficiently mix it with ambient lake water.

The simulations (Section 7) demonstrate two major disadvantages by using dilution-water and therefore we recommend refraining from its use (Section 2.4). If no dilution-water is used (what we encourage), enough mixing of the reinject-water (usually heavier) with the ambient lake water is needed to avoid sinking or rising plume within the lake.

Removal efficiency for CH_4 - An ideal plant would have 100% removal efficiency for CH_4. Not extracted CH_4 is returned to the lake with the reinject-water. If the reinject-water is released at shallow depth, the upwelling will remove this remaining CH_4 from the lake (details below) and hence the non-extracted CH_4 is lost. However, when reinjecting into the RZ, non-extracted CH_4 remains within the RZ and is not lost for future extraction. If a plant operation, for whatever reasons, performs inefficient removal of CH_4, it does not cause a loss of CH_4.

Removal efficiency for CO_2 - The fraction of CO_2 removed is relevant for two reasons: (i) the remaining CO_2 concentration affects the density of the reinject-water and (ii) the CO_2 content in the extracted gas mixture affects the efficiency of the power production. As CO_2 has a much higher solubility compared to CH_4, the CO_2 removal is not critical for the safety of the lake (see below), but its removal is still a welcomed safety advantage. Plants with the possibility to adjust the CO_2 removal, can adjust the density of the reinject-water within a certain range.

Plant size - This study does not consider the pros and cons of the size of individual plants, as for the development of the lake stratification in a one-dimensional model only the water flows of the overall extraction operation are relevant. If large plant modules would be located in close proximity to each other, flow interactions could become relevant and therefore 3-dimensional modelling could become necessary. However, as the lake currents are not well known, a conservative planning is required. To make the different extraction simulations comparable the water flow was set to 70 m^3 s^{-1} for all *Scenario*s. This flow is probably in the lower range of the expected future CH_4 extraction rate, as this flow corresponds to a typical electrical energy production of 100 to 200 MW.

Energy production - The plant efficiency defines the electric power output per flow of CH_4 led to the power production unit. Investigating these conversions is not the subject of this study, and we used a constant value of 2.6 kWh m^{-3} (Morkel pers comm) to convert CH_4 to electrical energy. Note that the estimated energy output may decrease with time, as the conversion may decrease due to lower CH_4 concentrations as a function of time. In our simulations, the comparison of the extraction is done based on CH_4 only, but we list the electrical energy for practical reasons.

5.2 Intermediate Zone reinjection - Scenarios IZ1 to IZ5

Because the early reasoning on the most economic way of CH_4 harvesting asked for reinjection in the upper part of the *Intermediate Zone*, reinjections at 90, 150 and 190 m depth have been tested (Table 5.5). The idea of the *Intermediate Zone* reinjection is to keep the CH_4-containing *Resource Zone* and the layer of reinjection as far as possible apart, so that no dilution of the *Resource Zone* can occur. The main disadvantage of this option is the large additional nutrient input into the *Intermediate Zone* which ends up - due to upwelling - in the *Biozone* after a few years / decades (Table 2.3.2). This disadvantage is especially important for the *Scenarios* IZ1, IZ2 and IZ3, where dilution-water is used to adjust the density of the reinject-water. Together with the nutrients, also the upwards flux of dissolved CH_4 to the surface layer is increased, where it is oxidized and therefore lost for a potential future extraction. No dilution-water is used for IZ4 and IZ5 (Table 5.5) and therefore the induced upward fluxes of nutrients and CH_4 are reduced. In terms of CH_4 harvest, *Scenario* IZ4 provides most output.

The details of the *Scenario*s IZ1 to IZ5 are provided in Table 5.5. The different extraction *Scenarios* are described in Table 2.3.2.

5.3 Potential Resource Zone reinjection - Scenarios PR1

The idea of the *Potential Resource Zone* reinjection (*Scenario* PR1) is (i) to profit from the advantage of the vertical separation of the CH_4 resources (deep) and the reinjection (above the *Resource Zone*) and (ii) to reduce the disadvantage of the nutrient upflux compared to the IZ scenarios by reinjection into the medium-depth of 240 m. The details of *Scenario* PR1 are provided in Tables 5.5 and 2.3.2.

5.4 Resource Zone reinjection - Scenarios RZ1 to RZ6

The *Intermediate Zone* reinjection has the disadvantage of increasing nutrient fluxes to the lake surface and of weakening the density stratification (Section 2.4). To avoid these negative effects, it has been suggested to reinject the depleted deep-water back into the Resource Zone. This approach has the great advantage that the lake stratification is almost undisturbed, except for the changes within the RZ, which is, however, far away form the *Biozone*. The main disadvantage of these options is the danger that, due to the weak stratification within the Resource Zone, the CH_4-depleted reinject water may mix with the high-CH_4 concentration water and thereby the CH_4 resource may become diluted. Besides the CH_4 concentration also the CH_4/CO_2 ratio is decreasing, because the reinject-water contains more of the original CO_2 than CH_4.

Six different Resource Zone reinjection *Scenario*s (RZ1 to RZ6) have been simulated to test the subtle differences in search for an optimal *Scenario*. The idea of RZ1 is to keep the withdrawal and reinjection depth vertically separated as far as possible within the RZ. Some of the *Scenarios* (RZ2 to RZ4) have two withdrawal and two reinjection layers with the aim to manage the Upper RZ and the Lower RZ separately. *Scenario* RZ6 is a combination of two (first RZ4 and later RZ5).

The *Design Parameters* of *Scenario*s RZ1 to RZ6 are detailed in Table 5.5 and the *Scenarios* are described relative to each other in Table 2.3.2. The so-called "**Plan A1/A2 and Plan B**" in the ***Management Prescriptions*** (MP 2009) corresponds in this report appoximately to *Scenario* RZ6. The scenario RZ4 (corresponding to A1/A2) can only be run until the Upper RZ is used up (a few years/ decades). It is not a stand-alone *Scenario* and not examined in the evaluation procedure.

5.5 Summary of the simulated extraction Scenarios

In Section 7 the results of the simulated extraction *Scenarios* are presented and the evaluation criteria (Section 6) are quantified. The following Table 5.5 summarizes the *Design Parameters* for all extraction *Scenarios* as used in the simulations.

Table 5.5 *Summary of the Design Parameters used for Scenario definitions*

Scenario		0	IZ1	IZ2	IZ3	IZ4	IZ5	PR1	RZ1	RZ2	RZ3	RZ4	RZ5	RZ6
Design Parameters														
CH$_4$ re-injected	%		5.9	30	15	5.9	30	5.9	5	5	3.4	6	3.4	RZ4->5
CO$_2$ re-injected	%		60	60	90	60	60	60	78	78	46	60 (1) 55 (2)	50	RZ4->5
Dilution water withdrawal depth	m		40	10	50									
Dilution factor	-		2	1.1	1									
Withdrawal (1)	$m^3 s^{-1}$		70	70	70	70	70	70	70	52.5	52.5	23	70	RZ4->5
Withdrawal depth (1)	m		475	320	350	475	320	475	475	400	400	410	400	RZ4->5
Withdrawal range (1)	m		10	10	20	10	10	10	10	160	160	60	160	RZ4->5
Re-injection depth (1)	m		150	90	90	150	190	240	290	400	400	325	270	RZ4->5
Re-injection range (1)	m		100	40	20	100	10	60	30	160	160	5	10	RZ4->5
Withdrawal (2)										17.5	17.5	47		RZ4->5
Withdrawal depth (2)	m									290	290	310		RZ4->5
Withdrawal range (2)	m									30	30	10		RZ4->5
Re-injection depth (2)	m									290	290	270		RZ4->5
Re-injection range (2)	m									30	30	10		RZ4->5
Scenario		**0**	**IZ1**	**IZ2**	**IZ3**	**IZ4**	**IZ5**	**PR1**	**RZ1**	**RZ2**	**RZ3**	**RZ4**	**RZ5**	**RZ6**

6. Scenario evaluation criteria

6.1 Extraction Objectives and quantification by Attributes

As laid out in Section 2, the CH_4 extraction concept and implementation has to live up to the following *Guiding Principles* (order of priority):

(i) Reduce the probability of a catastrophic gas release from the lake
(ii) Conserve the ecological integrity of the lake
(iii) Maximize the benefit from the CH_4 resources in the lake.

In order to make these principles operational, we define seven "concrete *Objectives*, which can be used to evaluate different extraction *Scenarios*, defined in Section 5. These seven *Objectives* are:

(a) Keep lake stratification as stable as possible, at least at 50% of natural
(b) Reduce gases content in lake, at least by 25% over the next century
(c) Increase required activation energy for (and thereby reduce chance of) initiation of bubble formation
(d) Minimize additional nutrient input to Biozone, at maximum 25% increase
(e) Minimize losses of CH_4 (i) to Biozone and (ii) by the extraction operation
(f) Allow new formation of deep-water CH_4
(g) Avoid dilution of CH_4 resources.

With the model simulations we want to quantify how well these seven *Objectives* are fulfilled. Therefore, we assign quantifiable *Attributes* to those *Objectives* (Table 2.2.1). The simulations allow for any given time and for any *Scenario* to calculate those *Attributes.* This procedure allows quantifying how well the *Objectives* are fulfilled for any moment, and also - more important - it allows the different *Scenario*s to be compared over several decades of extraction. We have used the following eight *Attributes*, which are well-defined physical quantities to measure the *Objectives*:

- **Schmidt stability** = required energy for complete mixing of the lake
- **Safety margin** = minimal energy required to initiate bubbles
- **Phosphorus upward flux** = upward flux of P into the Biozone
- **Nitrogen upward flux** = upward flux of N into the Biozone
- **CO_2 content** = CO_2 content in the lake
- **CH_4 content** = CH_4 content in the lake
- **CH_4 harvested** = amount of CH_4 led to power production
- **CH_4 harvestable** = amount of economically harvestable CH_4 in the lake.

Although the eight *Attributes* have a value at any point in time, we listed them only for 2004 (0 yr), 2054 (50 yr) and 2104 (100 yr). Definitions are provided in the following Section 6.2 and values of the *Attributes* are summarized in Table 7.13.

6.2 Definitions of the Attributes

Schmidt stability - The Schmidt stability is an overall measure of how strong a water body is density-stratified. Numerically, the Schmidt stability indicates the amount of energy [J] needed to completely homogenize a particular water body. An alternative unit of the Schmidt stability SS [J m^{-2}] provides the energy needed per lake surface area A_o. It is calculated as the vertical integral over the lake volume of the density difference between the actual stratification and the homogenised density times the dislocation from the centre of mass (Schmidt 1928):

$$SS = g \int_0^{\max depth} (z - z_*)(\rho_z - \langle \rho \rangle) A_z dz \qquad \text{[J]}$$

(g = gravitational acceleration, A_o = lake surface area). The Schmidt stability allows assessing the changes in the strength of the stratification (large SS = higher stability).

The effects of the extraction operation are mainly (1) to remove CO_2 and thereby to lower the density of the deep-water and (2) to move denser (more saline) water to higher levels in the lake. Both effects lower the Schmidt stability of the stratification. As shown in the Tables 7.1 to 7.12, all *Scenarios* lower the stability. However the differences among the *Scenarios* are very large: whereas the IZ reinjections change the Schmidt stability massively, the RZ reinjections have almost no effect on the Schmidt stability (comparison in Table 7.13).

It may be interesting to realize that Lake Kivu is among the lakes with the highest Schmidt stability (> 300,000 J m^{-2}). Compared to this potential energy, the kinetic energy in the lake (currents and waves due to wind energy input) is only a few 100 J m^{-2} (Schmid et al 2005a) and therefore the interior turbulence is very weak. Without extraction, the Schmidt stability would remain almost constant, even while the gas concentrations rise to dangerous levels, since the density in the lake is mainly determined by salinity and temperature.

Safety margin - As shown above, the Schmidt stability is an excellent measure to quantify the overall density stratification of a lake. However, it gives no information on how close a gas-saturated water body is from eruption. For this reason, we also introduced the *Attribute* “safety margin”, which expresses how much energy is needed [J m^{-3}] to bring the most critical water layer (in the lake) to spontaneous degassing which could potentially trigger a catastrophic eruption.

The safety margin is calculated in two steps. First we evaluated for each depth z1 to which level z2 a (virtual) water parcel would need to be lifted until its total gas pressure reaches the hydrostatic pressure. At the level z2 this water parcel would become 100% saturated (and bubbles could be created without any further energy input). In a second step, the mechanical energy SM [J m^{-3}] to lift this water parcel (from z1) to this estimated level z2 was calculated by:

$$SM = \int_{z1}^{z2} g(\rho(z1) - \rho(z)) dz \qquad \text{[J m}^{-3}\text{]}$$

In the Figure 7.2.1 to 7.2.12 SM is plotted as function of depth.

This definition of the safety margin does not include the volume or amount of gases available in the critical depth range. In practice, the amount of gases available to initiate and to fuel a chain reaction is highly relevant for eruptive degassing. Close to the surface, the safety margin becomes undefined, as there the total gas pressure is too low and also the required energy SM decreases towards zero. However, within the Biozone and the *Intermediate Zone*, the safety margin is irrelevant, since gas concentrations are not sufficient to cause any risk (no self-sustaining degassing). For this reason, we consider in this particular case of Lake Kivu the safety margin only below 200 m depth (Potential Resource Zone and deeper), where the gas concentrations are relevant for the safety.

The *Scenario* O (no extraction) shows that after 100 yr the most dangerous layer for degassing is not found at 260 m depth (Figure 6.2.1) but near the deepest reaches. Although, the total gas pressure is closest to saturation near 260 m depth, the strong density gradient above 260 m depth suppresses vertical movement of water parcels. The highest risk will be located below 400 m depth (Figure 6.2.1). Although water parcels in this deepest layer would have to be lifted further to reach saturation compared to 260 m depth, the density gradient in the deepest reach is weaker and therefore less energy is required to move water vertically. The values discussed in Section 7 represent the lowest energy required for the most critical layer below a depth of 200 m.

Phosphorus and nitrogen upward fluxes - The nutrient fluxes at z = 80 m depth are calculated from the local nutrient concentration gradients dC/dz (z) times the local vertical diffusivity K(z), as well as from the local concentration C(z) times the local upwelling velocity w(z). Taking into account the lake area A(z) at the given depth leads to upward transports of:

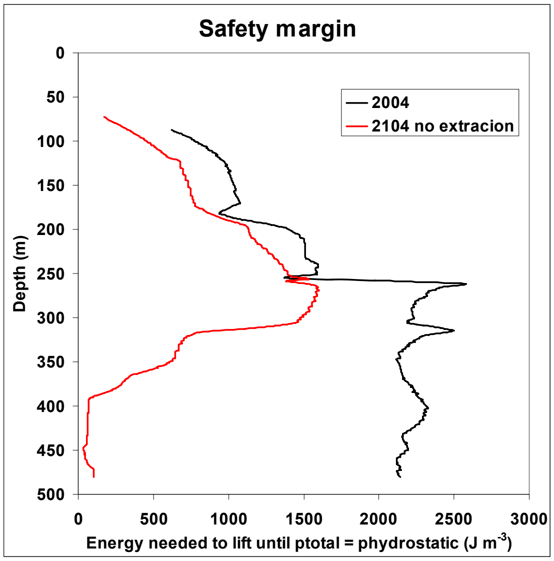


Figure 6.2.1 *Safety margin for Scenario O (no extraction). In the year 2104 the gas concentrations are estimated to approach saturation in the deepest part of the lake, and the safety margin is therefore very low (~30 J m^{-3}).*

$$F_{advective} = A(z)\,C(z)\,w(z) \qquad [\text{mol s}^{-1}]$$
$$F_{diffusive} = -\,A(z)\,K\,dC/dz \qquad [\text{mol s}^{-1}]$$

$$F_{total} = F_{advective} + F_{diffusive} \qquad [\text{mol s}^{-1}]$$

The evaluation of the model simulations showed that the upwelling (advective transport) is more important than the diffusive transport for most of the deeper water body, but in 80 m depth, where turbulent diffusion is already higher, both fluxes contribute to similar parts. Any changes to the lake which enhance the water upward flow or the entrainment into the *Biozone*, also enhance the nutrient transport into the *Biozone* and are therefore considered as critical for the *Guiding Principle* of the “lake ecological integrity”. The simulated future nutrient upward transport is therefore compared to the current nutrient fluxes (2004) and to the fluxes for the “no extraction” *Scenario* O (Tables 7.1 to 7.12).

According to the *Management Prescriptions (MP 2009)*, the upwards nutrient fluxes should not be increased by the extraction operation by more than 25% compared to the *Scenario* O (no extraction).

Gas content in the lake - The amount (M_{Lake}) of CH_4 or of CO_2 present in the lake at any point in time is calculated by vertically integrating the gas concentrations C(z) times the lake area A(z):

$$M_{Lake} = \int_0^{\max depth} A(z)\;C(z)\;dz\,. \qquad [\text{km}^3]$$

The CO_2 in the lake is relevant in a threefold way: (i) as the gas adds to the partial pressure and therefore to the risk, parts of the CO_2 should be removed during extraction; (ii) the CO_2 supports the self-siphoning in the pipe and is therefore a welcomed source of buoyancy and finally (iii) the CO_2 reduces the efficiency of power production (such as by turbines). The ideal management of the CO_2 is therefore an optimization issue.

CH_4 harvested (to power production) - The total amounts of “effectively” harvested CH_4 is the time-integrated instantaneous flow of CH_4 supplied to the power production (turbines). The instantaneous CH_4 flow is calculated as the product of the water withdrawal rate Q(t), the gas concentration C(t) at withdrawal depth and the fraction f_{turb} of CH_4 led to power production relative to the CH_4 in the withdrawal water:

$$M_{Turbine} = \int_0^{t_{end}} Q(t)\;C(t)\;\;f_{turb}\;\;dt \qquad [\text{km}^3]$$

CH_4 harvestable (still in the lake) - The vertical distribution of the remaining CH_4 in the lake varies for the different *Scenario*s and with time. As CH_4 at higher concentrations is easier extractable, and since below some threshold concentration (depending on the technology used) CH_4 extraction will not be economically viable, the value of the CH_4 remaining in the lake will depend on the vertical distribution of CH_4. We express this “dilution” phenomenon by the so-called “CH_4 harvestable”, defined by

$$M_{harvestable} = \int_0^{z_m} A(z)\ CH_{4\ harvestable}(z)\ dz \qquad [\mathrm{km}^3]$$

which accounts only for CH_4 exceeding a defined threshold $CH_{4,\text{limit}}$. In the definition above, $CH_{4,\text{harvestable}}$ is counted only if $CH_4 > CH_{4,\text{limit}}$ and set equal to 0 otherwise. The threshold value $CH_{4,\text{limit}}$ was set to 5 mol m^{-3} for the evaluation of model simulations.

7. Simulation results of all *Scenarios*

In this Section the simulations of all 12 *Scenarios* (Table 5.5) are documented. They comprise five *Scenarios* with reinjection into the *Intermediate Zone* (IZ1 to IZ5), one with reinjection into the *Potential Resource Zone* (PR1) and six with reinjection into the *Resource Zone* (RZ1 to RZ6).

The simulation results serve as input for the evaluation of the effects on the lake (Section 6) and for comparison between the *Scenarios*. The major model output are shown graphically for the years 2004 (simulation start), 2014, 2024, 2054, and 2104 (simulation end). These figures (7.1.1 to 7.12.8), containing much technical details, can be consulted for planning purposes. The outcome of the simulations is briefly discussed concerning the three *Guiding Principles* (here listed as “stability and safety”, “nutrients”, and “methane and energy”). Numerical values of the *Attributes* (evaluation criteria, Tables 7.1 to 7.12) are briefly discussed for all 12 simulations and summarized numerically in Table 7.13.

7.1 Scenario IZ1: Reinjection into Intermediate Zone with dilution

***Scenario* IZ1**	
Extraction flow	70 $m^3 s^{-1}$
CH_4 reinjected	5.9 %
CO_2 reinjected	60 %
Withdrawal depth	475 m
Withdrawal range	10 m
Dilution factor	2
Dilution withdrawal depth	40 m
Dilution withdrawal range	10 m
Reinjection depth	150 m
Reinjection range	100 m

Design parameters - For *Scenario* IZ1 the withdrawal depth is 475 ± 5 m and the reinjection is from 100 to 200 m. With this setting the entire RZ and part of the PRZ would be drawn down and could be emptied. The drawdown volume in the lake (downwelling below 183 m depth) is 212 km^3. This volume is withdrawn 1.04 times during the 100 yr of simulation (221 km^3). In the past, this *Scenario* has been considered as the obvious option for the CH_4 extraction.

For this *Scenario* IZ1 dilution-water is used to adjust the density to approximately 150 m depth of the ambient lake water (dilution factor of ~2). The depth of dilution-water intake was set to 40 m. As dilution-water, taken from the *Biozone*, is released below the *Biozone* (in 150 m depth) an additional upwelling flow (equal to dilution-water flow) is caused in the lake (Figure 7.1.1: upwelling between 150 and 40 m). As a consequence the nutrient fluxes to the surface layer are strongly enhanced compared to *Scenario* O (no extraction).

Stability and safety - The deep-water volume between the withdrawal depth and the reinjection depth is moving downward (Figure 7.1.1), towards the deepest reaches of the lake (= withdrawal level). The layer at the reinjection depth widens

Table 7.1 Evaluation of Scenario IZ1

	No Extraction			***Scenario* IZ1**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	4.0	11.7	8.1	10^3 tyr^{-1}
NH_4 upflux 80 m depth	15.9	21.0	26.0	34.3	113.9	82.1	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	3.2	1.7	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	28.7	18.2	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	14.2	3.3	km^3
CH_4 harvested (iii)					47.3	71.4	km^3
Average energy output					281	212	MW
CO_2 in lake	290	315	336	290	164	86	km^3
CO_2 removed from lake					86	119	km^3

downward (Figure 7.1.3), with the downwelling flow below ~170 m (Figure 7.1.1). As a result of this water volume replacement, the density stratification “flattens” and the density difference between IZ and RZ shrinks drastically (Figure 7.1.3). Therefore, the Schmidt stability decreases by more than 80% (compared to *Scenario* O, undisturbed) after 100 yr of simulation (Table 7.1). After 100 yr, the surface water is twice as salty as today.

Due to increasing density at the dilution-water intake (as a result of the reinjection into the IZ) the required dilution factor needs to be increased with time which would increase the upflow (upwelling more salts and nutrients into the *Biozone*). This positive feedback is not included in the model, but in reality this would further reduce the density stratification and lower the stability.

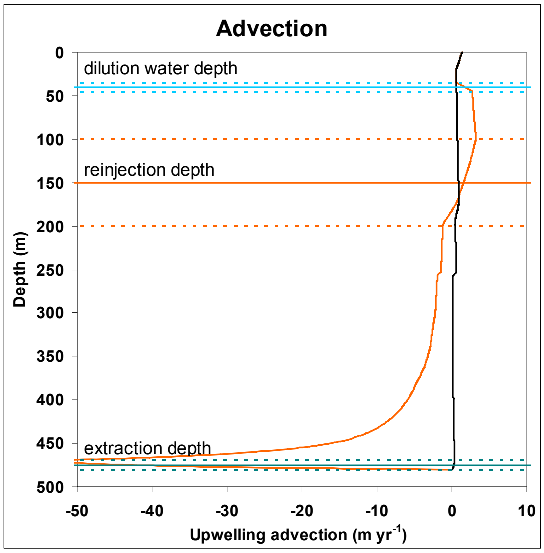
The safety margin shows that the minimal energy needed to lift any water parcel until the gas pressure reaches the hydrostatic pressure would be found in the *Intermediate Zone* above 200 m depth. The top 200 m we consider as not critical for the risk of an eruption (Section 6.2) and therefore we evaluate the safety margin only below 200 m depth. Even after 100 yr, the safety margin at 200 m depth is still comfortingly high (184 J m^{-3}) and the risk of an uncontrolled degassing remains low. Compared with *Scenario* O (no extraction), the safety margin improves massively below 330 m depth (Figure 7.1.2), where dissolved gas concentrations are highest (Figures 7.1.5 to 7.1.8). However above 330 m depth, IZ1 reduces the safety margin, as the stability is significantly weakened.

Nutrients - The nutrient transport to the surface layer strongly increases for IZ1. Right after the start of the extraction the PO_4 flux in 80 m depth would double and after 50 yr of simulation the flux is even 4.6 times as high as for *Scenario* O (Figure 7.1.4). This enhanced nutrient fluxes would lead to excessive algae growth. *Scenario* IZ 1, therefore, obviously fails on the *Objective* of maintaining the lake ecological integrity.

Methane and energy - The increased upwelling between the dilution-water intake and the reinjection (Figure 7.1.1) depth leads to an additional upward transport of CH_4 and therefore to an additional loss of CH_4 due to oxi-

dation of about ~7 km^3 during the first 50 yr and ~10 km^3 CH_4 (relative to IZ4) for the entire 100 yr (oxidation and gas exchange to the atmosphere are the only ways to loose CH_4). The CH_4 concentration in the intake water (Figure 7.1.7) would remain high for ~50 yr and then drop by a factor of ~2 within one decade from ~20 to ~10
mol m^{-3} (Figure 7.1.7).

The harvested amount of CH_4 during 100 yr is 71.4 km^3 and the corresponding average electrical energy production is ~212 MW (Table 7.1).



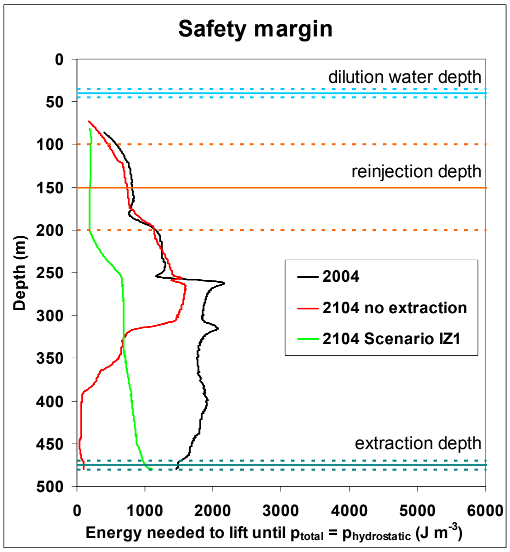
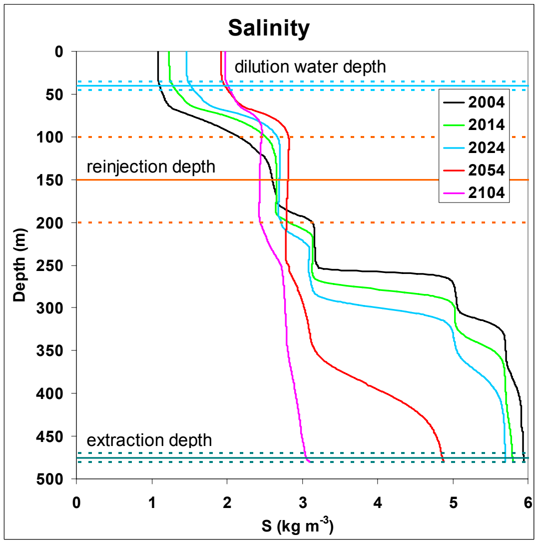


Figure 7.1.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario IZ1 (orange) compared to natural (black).*

Figure 7.1.2 *Safety margin for Scenario IZ1 compared to Scenario O.*



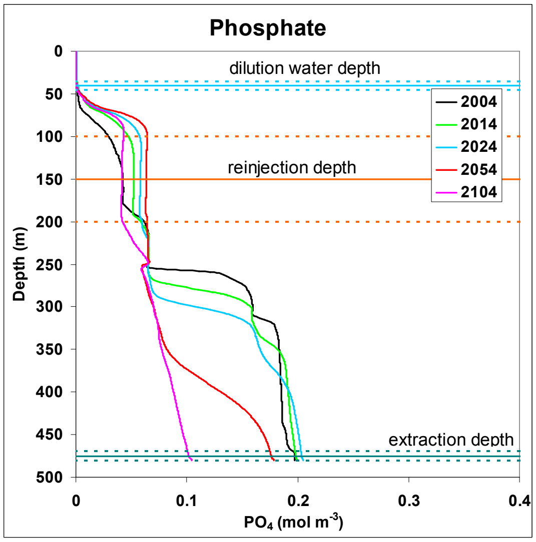


Figure 7.1.3 *Simulated salinity profiles for Scenario IZ1.*

Figure 7.1.4 *Simulated PO_4 profiles for Scenario IZ1.*

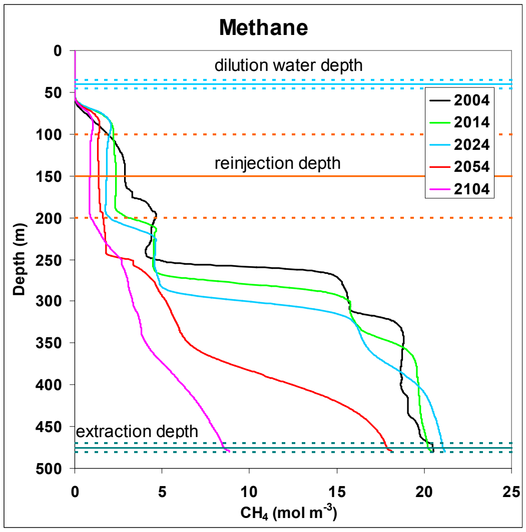


Figure 7.1.5 *Simulated CH_4 profiles for Scenario IZ1.*

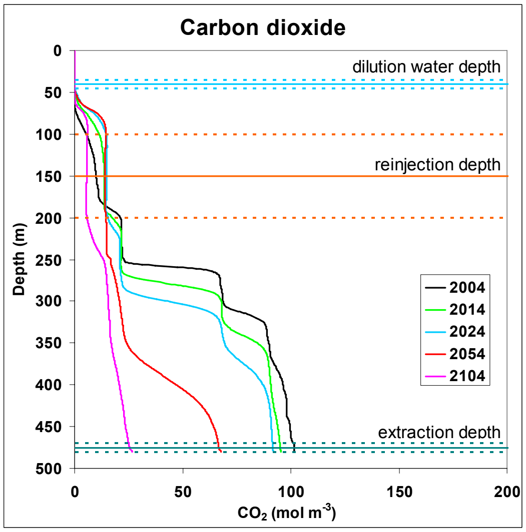


Figure 7.1.6 *Simulated CO_2 profiles for Scenario IZ1.*

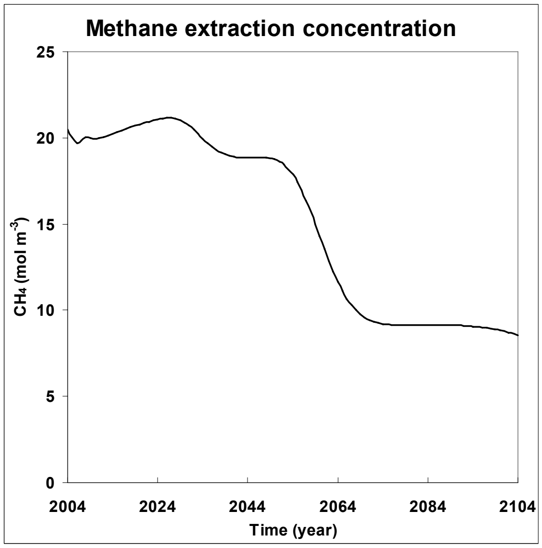


Figure 7.1.7 *Simulated CH_4 extraction concentration as a function of time for Scenario IZ1.*

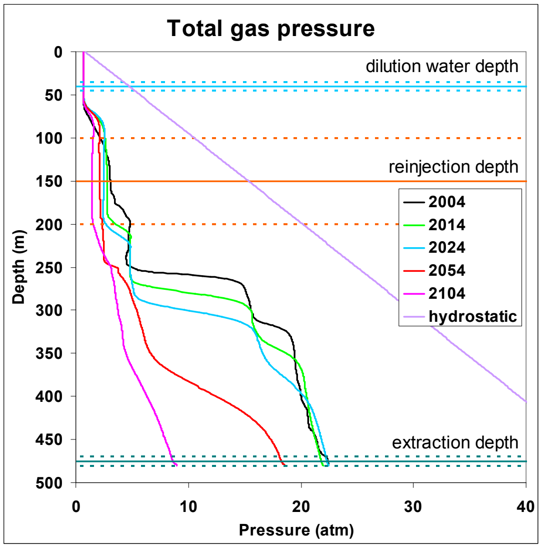


Figure 7.1.8 *Simulated total gas pressure profiles for Scenario IZ1.*

7.2 Scenario IZ2: Reinjection into Intermediate Zone with dilution

Design parameters - *Scenario* IZ2 is similar to IZ1, as CH_4-containing deep-water is withdrawn from the RZ (320 ± 5 m) and reinjected at the upper end of the IZ (90 ± 20 m depth). Dilution-water is also used, however, withdrawn in 10 m depth in order to minimize its flow (although seasonal variations of the density remains a challenge) and the dilution factor is therefore only 1.1. The water volume between 90 and 320 m depth (298 km^3) is drawn down (Figure 7.2.1) by the extraction volume of 221 km^3 during the simulated 100 yr (0.74 times recycling).

Scenario IZ2	
Extraction flow	70 $m^3 s^{-1}$
CH_4 reinjected	30 %
CO_2 reinjected	60 %
Withdrawal depth	320 m
Withdrawal range	10 m
Dilution factor	1.1
Dilution withdrawal depth	10 m
Reinjection depth	90 m
Reinjection range	40 m

Similarly as in IZ1, the dilution-water causes an additional upwelling flow between the reinjection depth (90 m) and the *Biozone*, which also increases the nutrient upward flux as in *Scenario* IZ1. In this *Scenario* IZ2, this aspect is even more critical (Table 7.2), as the nutrient-rich deep-water is injected directly below the *Biozone* (90 ± 20 m; not entirely accounted for by the upflux in 80 m depth).

Stability and safety - The water of the IZ and the PRZ between the withdrawal depth (320 m) and the reinjection depth (90 m) is moving downward, towards the withdrawal level. The layer at the reinjection depth widens vertically and descends with the downwelling flow in the lake. As a result, the density stratification "flattens" and the density difference between the surface and 320 m depth is drastically reduced (Figure 7.2.3), and the surface water becomes significantly saltier. The RZ below is not affected. The vertical density gradient shrinks substantially and the Schmidt stability decreases by up to 40% after 100 yr of simulation compared to (undisturbed) natural (Table 7.2).

Table 7.2 Evaluation of Scenario IZ2

	No Extraction			*Scenario* IZ2			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth (1)	1.9	2.4	2.9	2.5	3.9	3.0	10^3 tyr^{-1}
NH_4 upflux 80 m depth (1)	15.9	21.0	26.0	20.9	37.3	29.4	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	5.6	5.3	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	56.2	60.8	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	31.8	33.8	km^3
CH_4 harvested (iii)					20.8	30.5	km^3
Average energy output					123	90	MW
CO_2 in lake	290	315	336	290	213	193	km^3
CO_2 removed from lake					51	69	km^3

(1) Nutrient fluxes shown are slight underestimates, as some of the reinject water is released above 80 m depth.

The safety margin (Figure 7.2.2) shows that the minimal energy needed to lift any water parcel until the gas pressure reaches the hydrostatic pressure would be found in the deep RZ (~450 m depth: ~30 J m^{-3}) where the gas would also accumulate during the 100 yr period. Therefore, the safety margin in the deepest layers would shrink (almost as for *Scenario* O*)* to dangerous levels and the *Guiding Principle* of safety would not be fulfilled. This simulation makes obvious that CH_4-containing water from the deepest reaches need to be removed not later than in a few decades.

Nutrients - The transport of nutrients to the surface (PO_4, Figure 7.2.4) strongly increases. Right after the start of the extraction the upward flux in 80 m depth would be enhanced by ~40% and after 50 yr by ~60% compared to natural (Table 7.2). These numbers even don't show the full impact, since part of the nutrient-rich water is reinjected above 80 m depth. This *Scenario* IZ2 obviously fails on the *Guiding Principle* of maintaining the lake ecological integrity.

Methane and energy - The increased upwelling flow between the dilution-water intake and the reinjection depth leads to an additional loss (relative to IZ4) of CH_4 via oxidation of about ~8 km^3 during the 100 yr of simulation. The main loss of CH_4 for this *Scenario* IZ2 is however due to the inefficient extraction of CH_4 (definition above). The 30% of the CH_4 reinjected into the IZ is diluted and lost for future harvesting. Therefore, this *Scenario* also fails on the *Guiding Principle* of maximizing the economic benefit. This simulation shows drastically, that the fraction of reinjected CH_4 needs either to be minimized (if released into the IZ or the PRZ), or - if technically not possible - needs to be reinjected into the *Resource Zone*, such that the reinjected CH_4 remains "harvestable" for later.

The harvested amount of CH_4 during 100 yr is 30.5 km^3 and the corresponding average electrical energy production is ~90 MW (Table 7.2).

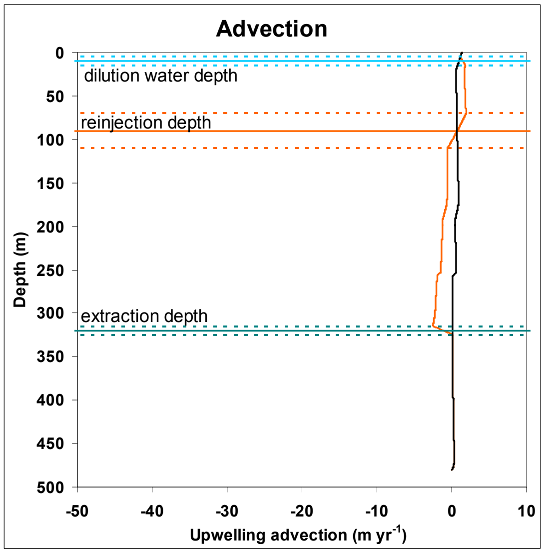


Figure 7.2.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario IZ2 (orange) compared to Scenario O (black).*

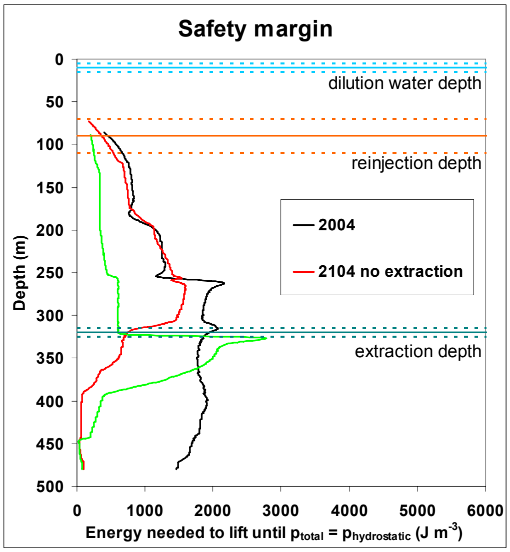


Figure 7.2.2 *Safety margin for Scenario IZ2 in 2104 (green) compared to Scenario O (red).*

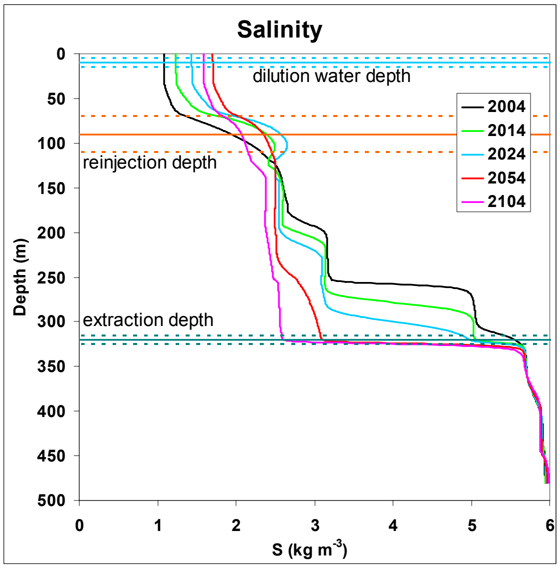


Figure 7.2.3 *Simulated salinity profiles for Scenario IZ2.*

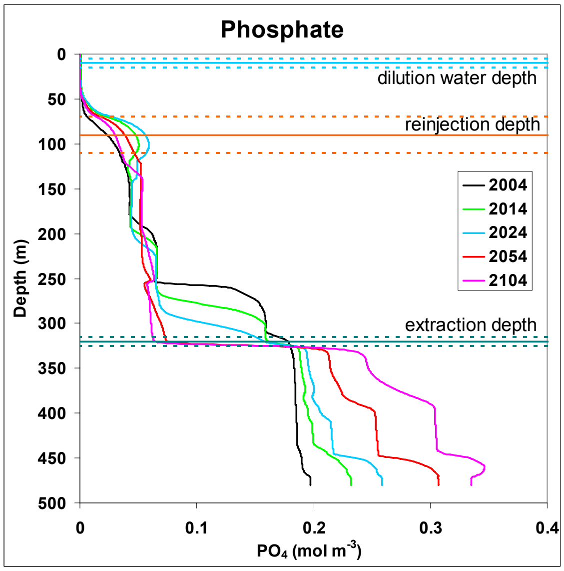


Figure 7.2.4 *Simulated PO_4 profiles for Scenario IZ2.*

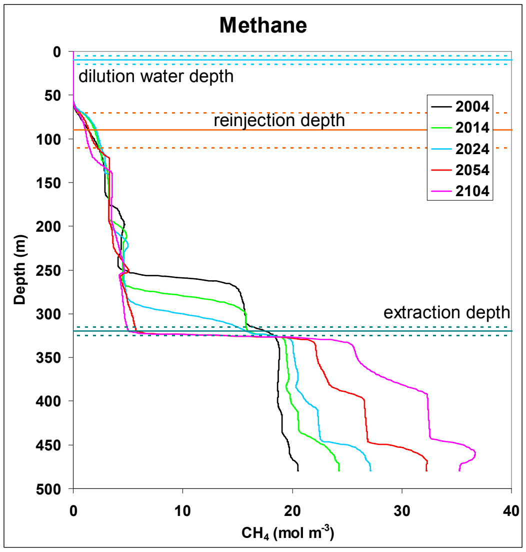


Figure 7.2.5 *Simulated CH_4 profiles for Scenario IZ2.*

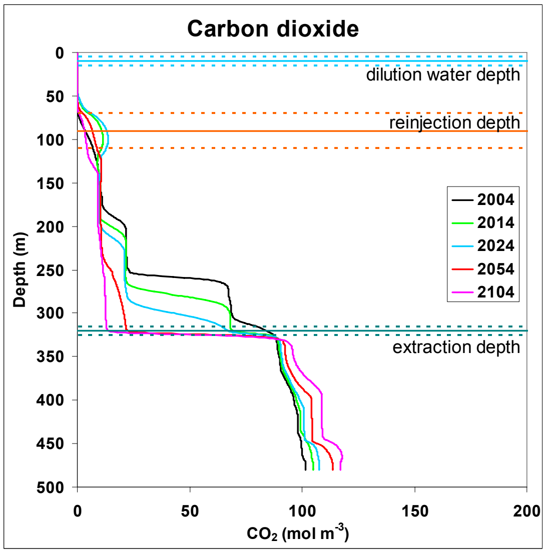


Figure 7.2.6 *Simulated CO_2 profiles for Scenario IZ2.*

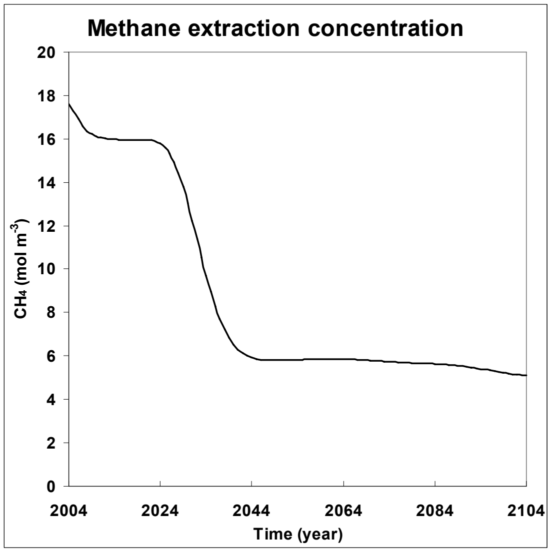


Figure 7.2.7 *Simulated CH_4 extraction concentration as a function of time for Scenario IZ2.*

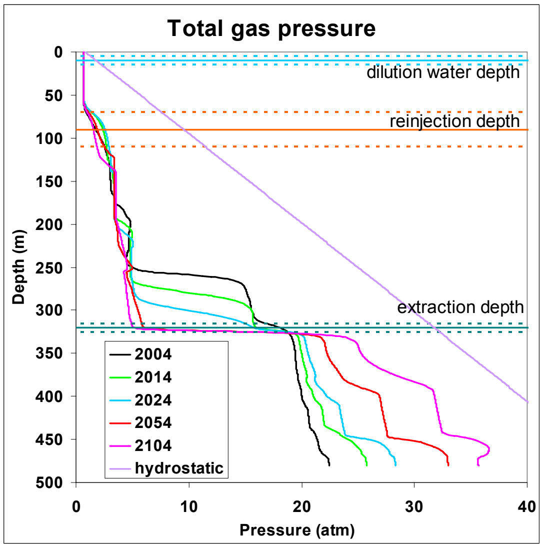


Figure 7.2.8 *Simulated total gas pressure profiles for Scenario IZ2.*

7.3 Scenario IZ3: Reinjection into Intermediate Zone with dilution

Scenario IZ3	
Extraction flow	70 m^3 s^{-1}
CH_4 reinjected	15 %
CO_2 reinjected	60 %
Withdrawal depth	350 m
Withdrawal range	20 m
Dilution factor	1.0
Dilution withdrawal depth	50 m
Reinjection depth	90 m
Reinjection range	20 m

Design parameters - The description of *Scenario* IZ3 is similar to IZ2, as the CH_4-containing deep-water is also extracted (slightly deeper) in 350 ± 20 m depth (RZ), dilution-water from 50 m depth (dilution factor = 1.0) is used, and the reinject-water is released in 90 ± 20 m depth.

The draw-down lake volume of 320 km^3, below 90 m depth, is withdrawn 0.69 times during the 100 yr of simulation (221 km^3).

Besides the vertical setting, the difference to IZ2 is that only half the amount of CH_4 is reinjected into the lake for IZ3. Therefore, we expect a better efficiency (less loss) concerning the CH_4 harvested.

Smaller differences are due to the slightly deeper withdrawal depth, causing slightly higher nutrient fluxes and causing slightly higher density. Therefore we expect slightly higher nutrient fluxes as well as slightly lower stability after 100 yr of simulation.

Stability and safety - The water volume between reinjection (90 m) and withdrawal (350 m) depth is entirely replaced after 100 yr (Figures 7.3.3 to 7.3.6) and as a result this layer is almost homogenised. The density structure remains strong only below 350 m (to 485 m depth; Figure 7.3.3). Therefore the Schmidt stability drops after 100 yr to only 48% of the natural stability. Exploiting the remaining deepest layers will additionally reduce the stability. Therefore this *Scenario* does not fulfil the *Guiding Principle* concerning safety.

Table 7.3 Evaluation of Scenario IZ3

		No Extraction				***Scenario* IZ3**			
		2004	**2054**	**2104**		**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth		1.9	2.4	2.9		2.9	6.3	4.6	10^3 tyr^{-1}
NH_4 upflux 80 m depth		15.9	21.0	26.0		24.6	61.8	44.7	10^3 tyr^{-1}
Schmidt stability		8.8	8.7	8.7		8.8	4.5	4.1	10^{14} J
CH_4 in lake (i)		64.6	81.7	96.3		64.6	47.4	49.3	km^3
CH_4 harvestable (ii)		42.3	58.9	69.0		42.3	24.4	22.4	km^3
CH_4 harvested (iii)							32.6	46.2	km^3
Average energy output							193	137	MW
CO_2 in lake		290	315	336		290	207	177	km^3
CO_2 removed from lake							16	22	km^3

The safety margin (Figure 7.3.2) shows that the minimal energy needed to lift any water parcel until the gas pressure reaches the hydrostatic pressure would be found in the deep RZ (~450 m depth: ~30 J m^{-3}) where the gas would accumulate during the 100 yr period. Therefore, the safety margin in the deepest layers would shrink (almost as for *Scenario* O*)* to dangerous levels and the *Guiding Principle* of safety would not be fulfilled. It is evident that CH_4-containing water from the deepest reaches needs to be removed not later than in a few decades.

Nutrients - This *Scenario* IZ3 would strongly increase the nutrient transport to the surface. After 50 yr, the flux would be enhanced by 160% (Table 7.3) relative to natural (*Scenario* O). Such an intensification of the nutrient cycling is in contradiction to the *Guiding Principle* of maintaining the lake ecological integrity.

Methane and energy - The increased upwelling flow between the dilution-water intake depth and the reinjection depth leads to an additional loss of CH_4 (relative to IZ4) due to the oxidation of ~4 km^3 during the 100 yr of simulation. Compared to *Scenario* IZ2 the loss to the *Biozone* is smaller, as for IZ3 the CH_4 content of the reinjected water (15%) is smaller than for IZ2 (30%). But still, as CH_4 in the reinject-water is high, the reinject-water forms a large column above 350 m depth with a not harvestable CH_4 concentration of ~3 mol m^3 (Figure 7.3.5). Relative to the most economic *Scenario* (IZ4, below), this *Scenario* IZ3 reveals that ~8.5 km^3 of CH_4 harvest would be lost (Table 7.13). Therefore, IZ3 also fails on the *Guiding Principle* of maximizing the economic benefit.

The harvested amount of CH_4 during 100 yr is 46.2 km^3 and the corresponding electrical energy production is ~137 MW (Table 7.3).

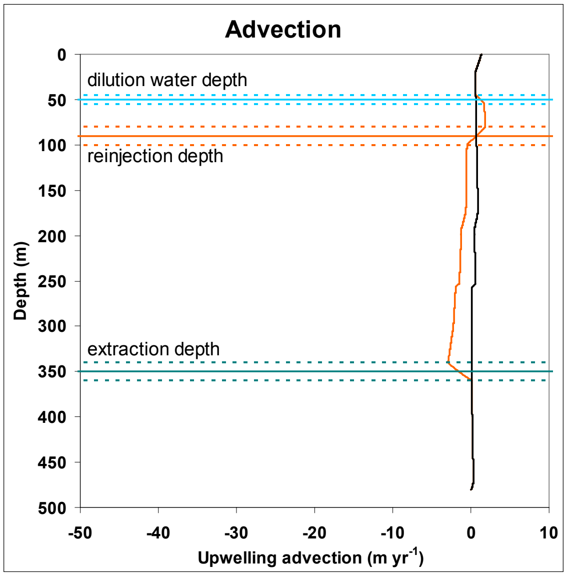


Figure 7.3.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario IZ3 (orange), compared with Scenario O (black).*

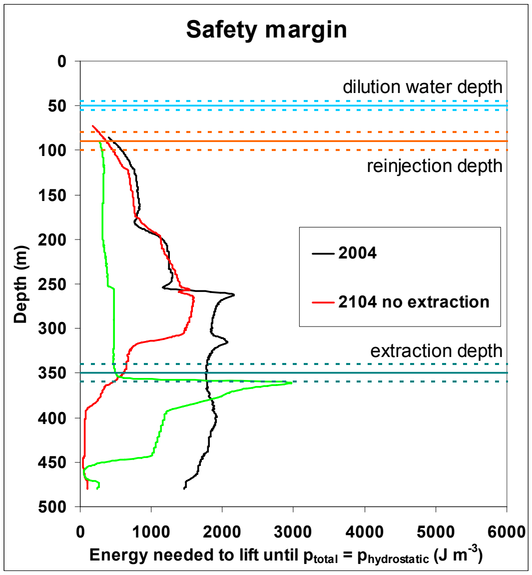


Figure 7.3.2 *Safety margin for Scenario IZ3 in 2104 (green) compared to Scenario O (red).*

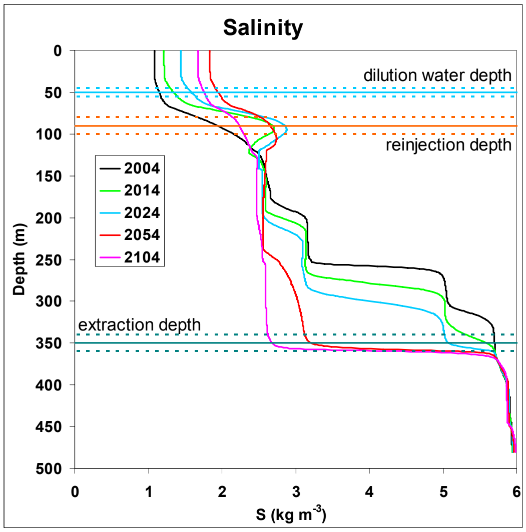


Figure 7.3.3 *Simulated salinity profiles for Scenario IZ3.*

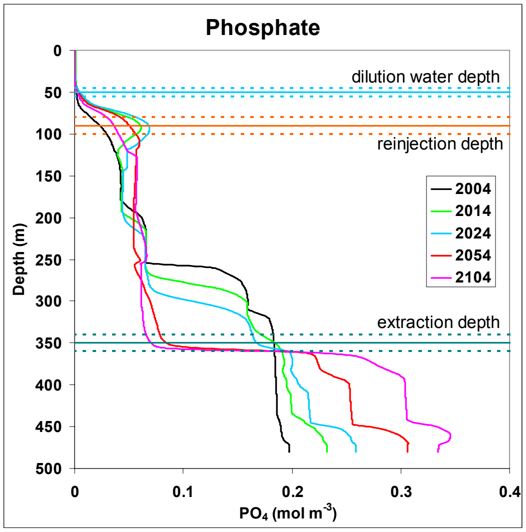


Figure 7.3.4 *Simulated PO_4 profiles for Scenario IZ3.*

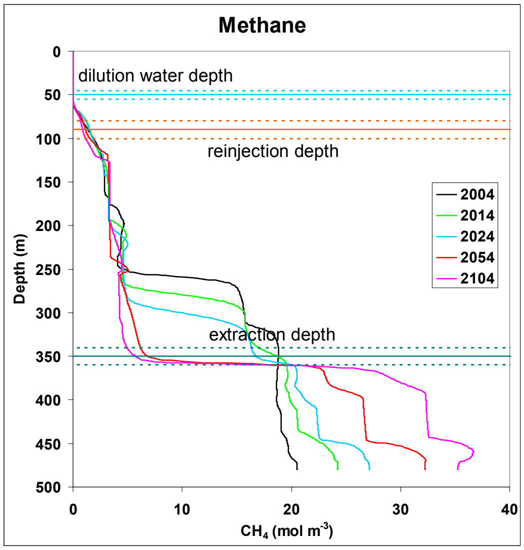


Figure 7.3.5 *Simulated CH_4 profiles for Scenario IZ3.*

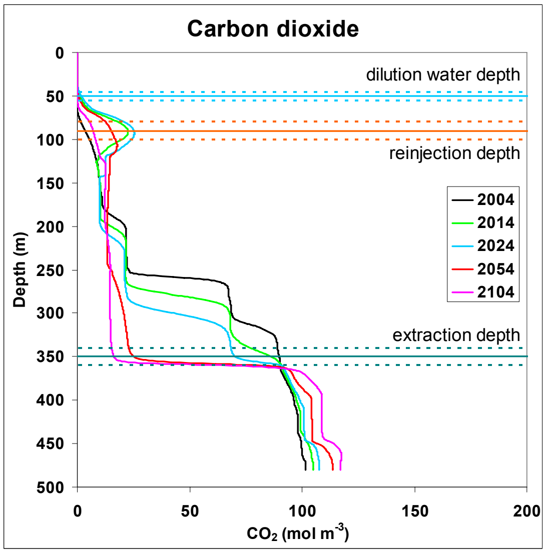


Figure 7.3.6 *Simulated CO_2 profiles for Scenario IZ3.*

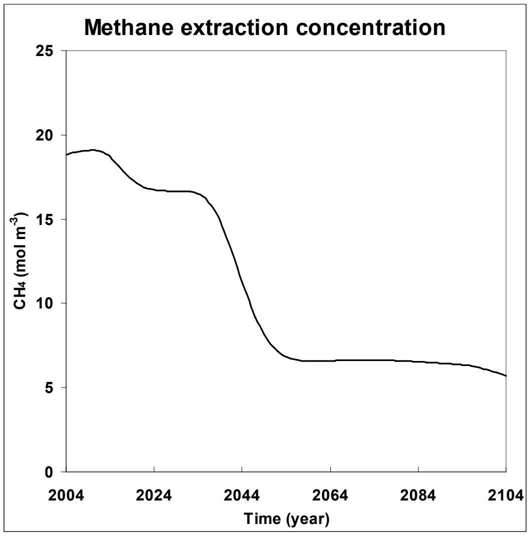


Figure 7.3.7 *Simulated CH_4 extraction concentration as a function of time for Scenario IZ3.*

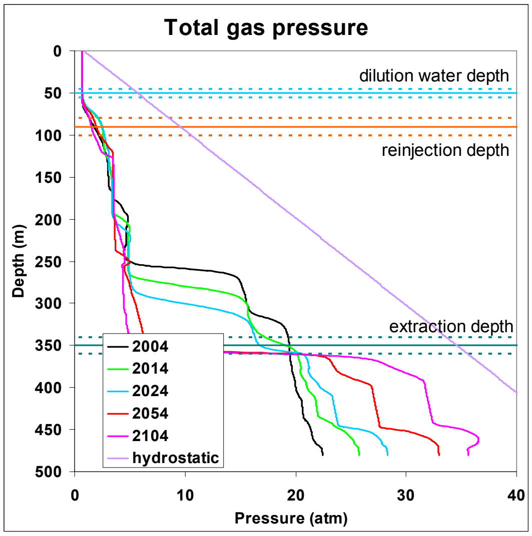


Figure 7.3.8 *Simulated total gas pressure profiles for Scenario IZ3.*

7.4 *Scenario IZ4: Reinjection into Intermediate Zone - no dilution*

Scenario IZ4	
Extraction flow	70 m^3 s^{-1}
CH_4 reinjected	5.9 %
CO_2 reinjected	60 %
Withdrawal depth	475 m
Withdrawal range	10 m
Dilution factor	0 (no dilution)
Reinjection depth	150 m
Reinjection range	100 m

Design parameters - This *Scenario* IZ4 is identical to IZ1 except that no dilution-water is used for density adjustment. It is assumed that the reinject-water is mixed efficiently into the ambient lake water by technological measures (multiple and spatial spreading of the outlets). In the model, this is achieved by homogenous distribution of the re-inject-water into the ±50 m thick reinjection layer.

The draw-down lake volume is 239 km^3 (downwelling below 164 m depth). This volume is withdrawn 0.92 times (221 km^3) during the 100 yr of simulation.

Note that the density of the lake water layer receiving the reinject-water (100 to 200 m depth) rises rapidly and reaches the density of the *Potential Resource Zone* in less than 20 yr (Figure 7.4.3). Thereafter, further density increase causes an expansion of the receiving layer which reaches down to ~360 m depth after 50 yr (Figures 7.4.3 to 7.4.6). The deep layers below (RZ) remain stratified and with higher CH_4 concentrations.

Stability and safety - The lake volume between the reinjection depth and the withdrawal depth is moving downwards to the deepest reaches (= withdrawal level). The IZ, particularly the layer at the reinjection depth, widens rapidly in the vertical direction (see above) and is descending with the draw-down. Similar as in *Scenario* IZ1, the density stratification flattens, and the density difference between surface and the down-moving front shrinks (Figure 7.4.3), however, at a much lower rate than for IZ1. The Schmidt stability decreases by about 50% after 100 yr of simulation, compared to natural (Table 7.4). The density gradient between the surface and the reinjection depth however remains much stronger than in *Scenario* IZ1.

Table 7.4 ***Evaluation of Scenario IZ4***

		No Extraction				***Scenario* IZ4**			
		2004	**2054**	**2104**		**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth		1.9	2.4	2.9		1.9	4.8	5.2	10^3 tyr^{-1}
NH_4 upflux 80 m depth		15.9	21.0	26.0		15.9	43.8	46.1	10^3 tyr^{-1}
Schmidt stability		8.8	8.7	8.7		8.8	5.1	4.2	10^{14} J
CH_4 in lake (i)		64.6	81.7	96.3		64.6	35.9	31.5	km^3
CH_4 harvestable (ii)		42.3	58.9	69.0		42.3	7.6	9.2	km^3
CH_4 harvested (iii)							47.2	67.8	km^3
Average energy output							280	201	MW
CO_2 in lake		290	315	336		290	220	182	km^3
CO_2 removed from lake							86	120	km^3

The analysis of the safety margin does not reveal much difference to IZ1. The safety margin increases with depth and therefore the lowest relevant value is taken in 200 m depth (170 J m^{-3}). As no dilution water is used, the overall stratification is less degraded than for IZ1. But still, the safety margin is not improved relative to *Scenario* O (natural, no extraction; Table 7.13). However the risk of degassing remains low due to the extraction of gases, which reduces the gas content massively (Table 7.4).

Nutrients -The nutrient transport to the surface layer doubles after ~50 yr of simulation compared to the natural development of the lake. This increase is due to the nutrient-rich deep-water, released below the *Biozone* and naturally lifted into the *Biozone* by the upwelling flow of the subaquatic sources (see IZ1). This *Scenario* IZ4 therefore fails on the *Guiding Principle* of maintaining the lake ecological integrity.

Methane and energy - It is not well-known, how much the turbulent vertical mixing would increase due to the weakening of the PRZ stratification. From Figure 7.4.4 it is obvious that the CH_4 loss to the *Biozone* increases with extraction time. However, compared to the natural development, the extraction and reinjection of the CH_4-depleetd water causes in fact a reduction of the CH_4-loss of ~3 km^3, mainly because the concentrations below the *Biozone* become lower.

The CH_4 concentration at the deep-water intake remains high and relatively constant for about 50 yr before it drops drastically by almost a factor of 4 during a ~20 yr period (Figure 7.4.7) from ~20 to ~5 mol m^{-3}.

The harvested amount of CH_4 during 100 yr is 68 km^3 and the corresponding electrical energy production is ~200 MW (Table 7.4). This *Scenario* is the one with the highest CH_4 harvest.

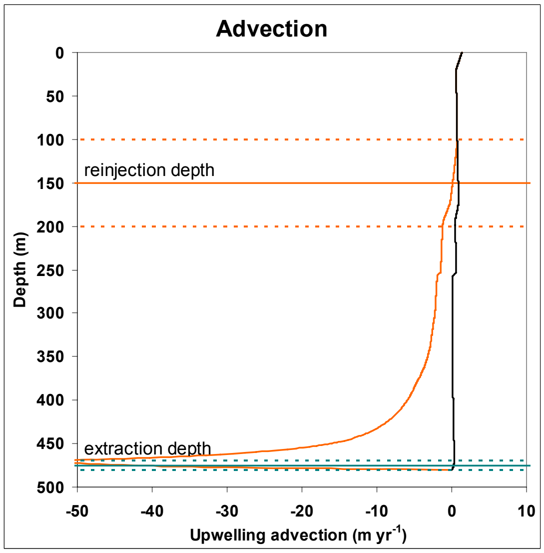


Figure 7.4.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario IZ4 (orange), compared with Scenario O (black).*

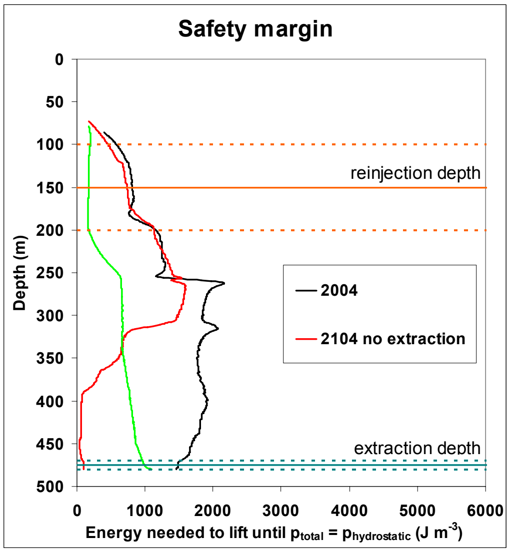


Figure 7.4.2 *Safety margin for Scenario IZ4 in 2104 (green) compared to Scenario O (red).*

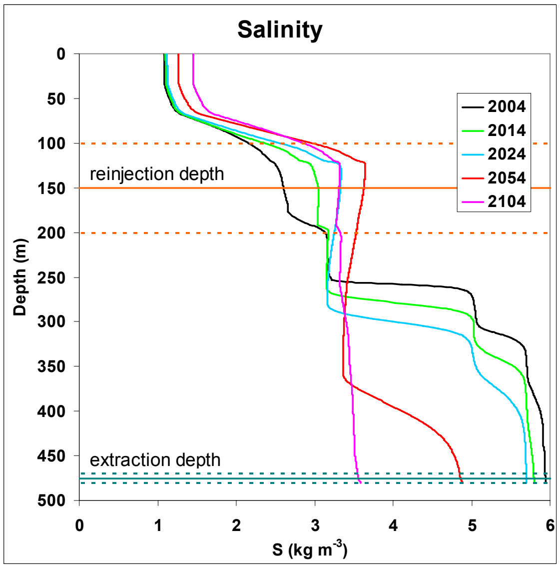


Figure 7.4.3 *Simulated salinity profiles for Scenario IZ4.*

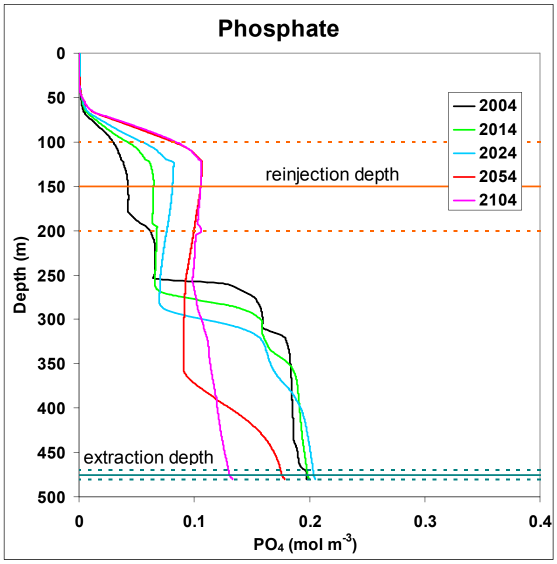


Figure 7.4.4 *Simulated PO_4 profiles for Scenario IZ4.*

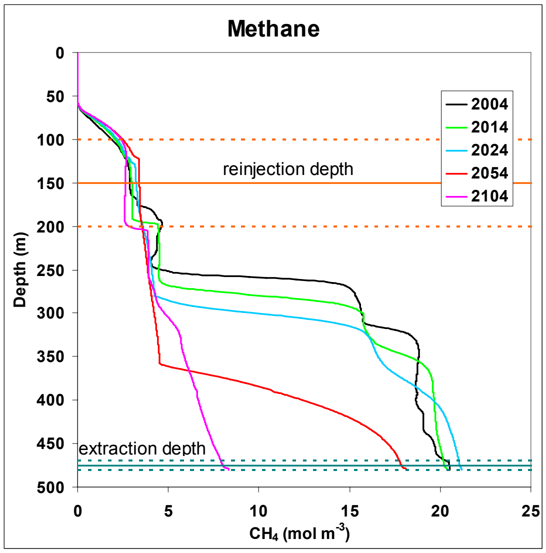


Figure 7.4.5 *Simulated CH_4 profiles for Scenario IZ4.*

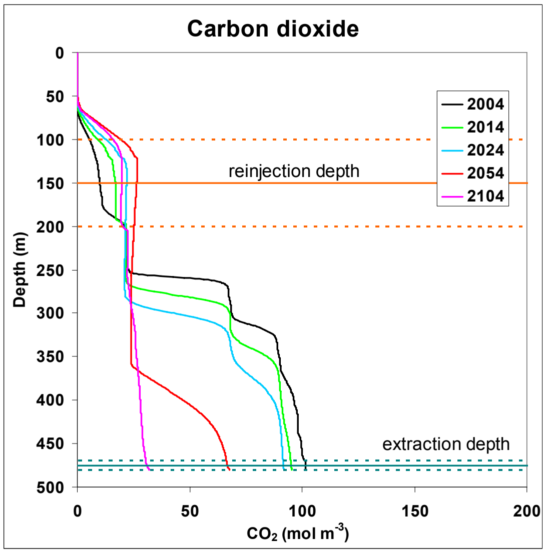


Figure 7.4.6 *Simulated CO_2 profiles for Scenario IZ4.*

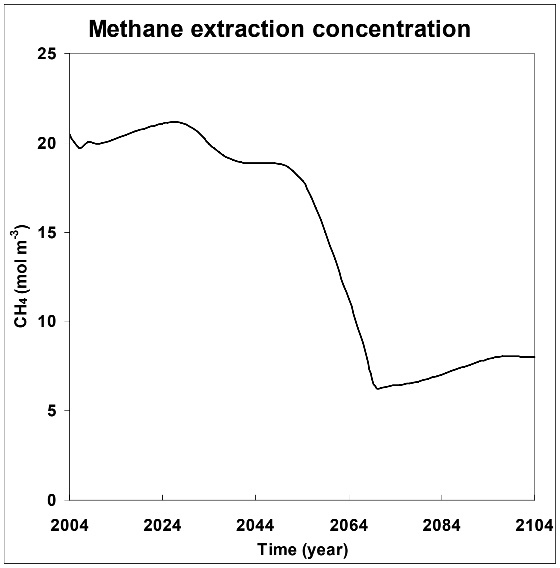


Figure 7.4.7 *Simulated CH_4 extraction concentration as a function of time for Scenario IZ4.*

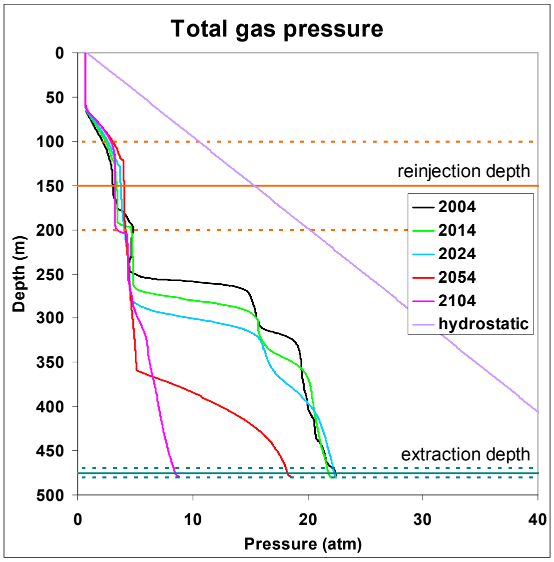


Figure 7.4.8 *Simulated total gas pressure profiles for Scenario IZ4.*

7.5 Scenario IZ5: Reinjection into Intermediate Zone - no dilution

Design parameters - *Scenario IZ5 is* similar to IZ2, as CH_4-containing deep-water is withdrawn from the RZ (320 ± 5 m) and reinjected at the lower end of the IZ (190 ± 5 m depth). However, dilution-water is avoided (compared to IZ2). It is again assumed that the reinjected water is mixed efficiently into the ambient lake water by technological measures (see IZ4).

The water volume between 190 and 320 m depth (158 km^3) is drawn down by the extraction volume (221 km^3) during the simulated 100 yr (1.4-times replaced).

Scenario IZ5	
Extraction flow	70 m^3 s^{-1}
CH_4 reinjected	30 %
CO_2 reinjected	60 %
Withdrawal depth	320 m
Withdrawal range	10 m
Dilution factor	no dilution
Reinjection depth	190 m
Reinjection range	10 m

Stability and safety - The water of the PRZ, which is between the withdrawal (320 m) and the reinjection depth (190 m) is moving downward to the withdrawal level. The layer at the reinjection depth widens vertically and descends following the downwelling in the lake (Figure 7.5.1). The layers above the reinjection depth (190 m) are only indirectly affected. Due to the natural upwelling (subaquatic sources) the receiving water layer is also moving upwards. Subsequently, a quite homogenous layer develops between 320 m and ~120 m depth with increasing concentrations of salinity, gases and nutrients at the upper end (~120 m) of this new layer. The lake waters above 100 m and below 320 m depth are only slightly modified.

As an effect, the overall stratification weakens much less (than for the previous *Scenarios*), and the Schmidt stability decreases by only ~18% after 100 yr of simulation compared to *Scenario* O (Table 7.5). For this *Scenario* IZ5, the reduction of the water column stability is not a concern.

The safety margin, remains on a natural level in the upper half of the lake. In the RZ the safety margin drops, due to the accumulation of gases, with time and

Table 7.5 Evaluation of Scenario IZ5

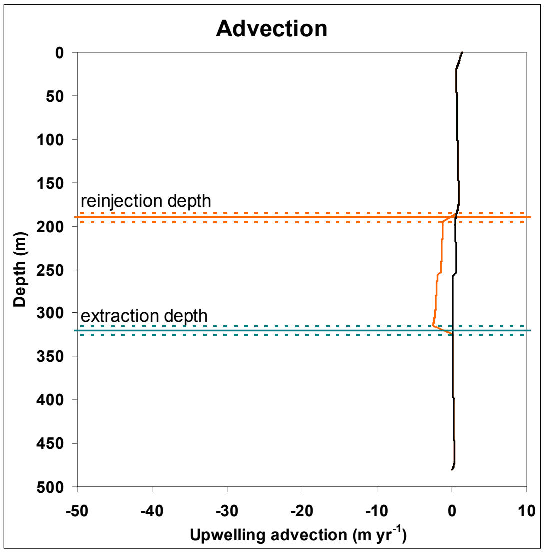
	No Extraction			***Scenario* IZ5**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	1.9	2.4	3.4	10^3 tyr^{-1}
NH_4 upflux 80 m depth	15.9	21.0	26.0	15.9	20.9	30.4	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	7.7	7.2	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	60.1	61.7	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	33.8	33.7	km^3
CH_4 harvested (iii)					20.2	30.5	km^3
Average energy output					120	90	MW
CO_2 in lake	290	315	336	290	257	241	km^3
CO_2 removed from lake					52	79	km^3

after 100 yr it reaches a level of only ~33 J m^{-3} in ~450 m depth. As there is no extraction of gases in the deepest part, the safety would be almost as critical as without extraction (*Scenario* O; Table 7.13). Therefore, also extraction of CH_4 from the deepest parts needs to start not later than in a few decades.

Nutrients - Due to the lower reinjection depth, and due to avoiding dilution-water, the upwelling as well as the nutrient concentration below the *Biozone* are lower. As a result, the upward transport of nutrients is significantly lower for this *Scenario*, then for IZ1 to IZ3 (with dilution-water), and is enhanced by only ~20% after 100 yr relative to *Scenario* O. The *Guiding Principle* of “lake ecological integrity” would just marginally be fulfilled.

Methane and energy - Despite the deep (190 m) reinjection and despite no dilution-water is used, the additional loss to the *Biozone* is about ~7 km^3 (relative to IZ4) during the 100 yr of extraction (Figure 7.5.5, Table 7.5). The main loss of CH_4 for this *Scenario* IZ5 is, however, due to the large volume of not harvestable CH_4 (~3 to 4 mol m^{-3}) in the lake water above 320 m depth (Figure 7.5.5). This “wasted” CH_4 of high concentration is due to the inefficient extraction of only 70% of CH_4 (see above). The 30% of the reinjected CH_4 is diluted into the IZ and PRZ and lost for future harvesting. Therefore, this *Scenario* fails the *Guiding Principle* of maximizing the economic benefit.

There is a drastic drop in the CH_4 concentration at the intake (320 m depth) between 2025 und 2035 from ~16 to ~6 mol m^{-3} (although this could be avoided by continuously moving the intake deeper). The harvested amount of CH_4 during 100 yr is 30.5 km^3 and the corresponding electrical energy production is ~90 MW (Table 7.5).



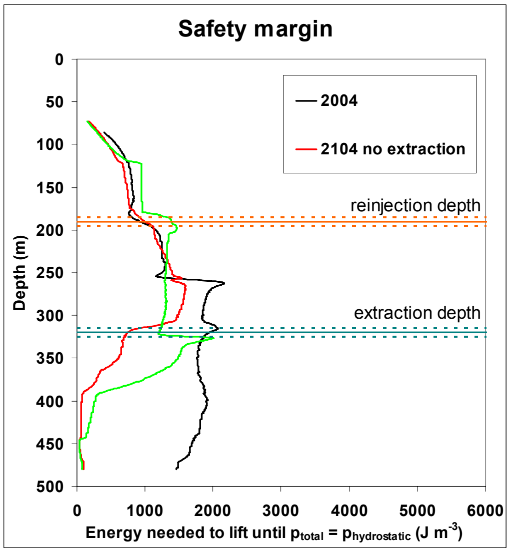
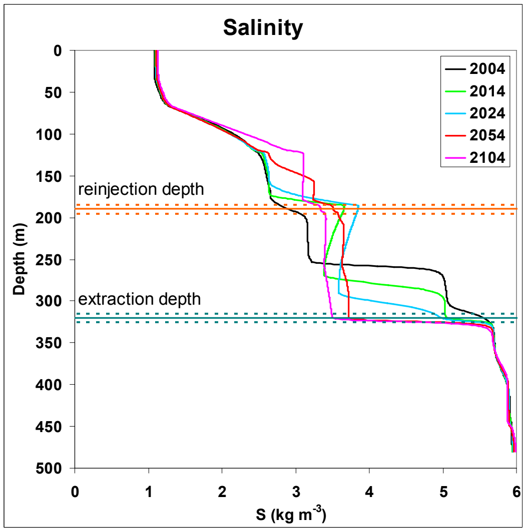


Figure 7.5.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario IZ5 (orange), compared with Scenario O (black).*

Figure 7.5.2 *Safety margin for Scenario IZ5 in 2104 (green) compared to Scenario O (red).*



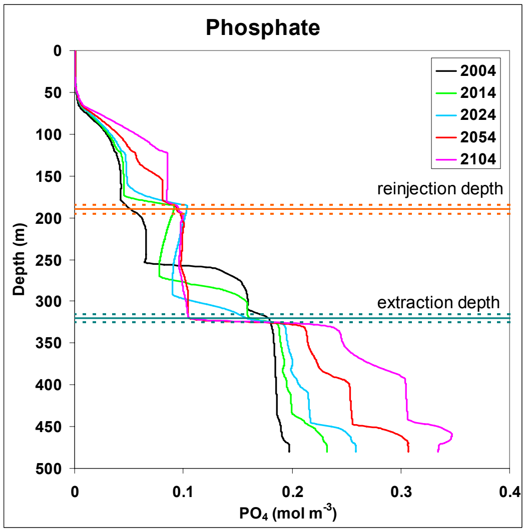


Figure 7.5.3 *Simulated salinity profiles for Scenario IZ5.*

Figure 7.5.4 *Simulated PO_4 profiles for Scenario IZ5.*

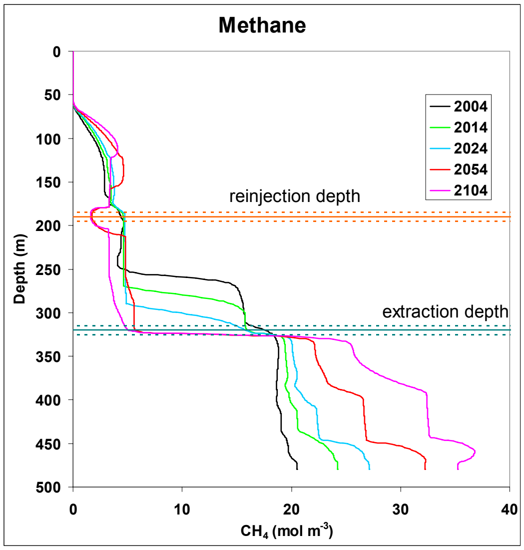


Figure 7.5.5 *Simulated CH_4 profiles for Scenario IZ5.*

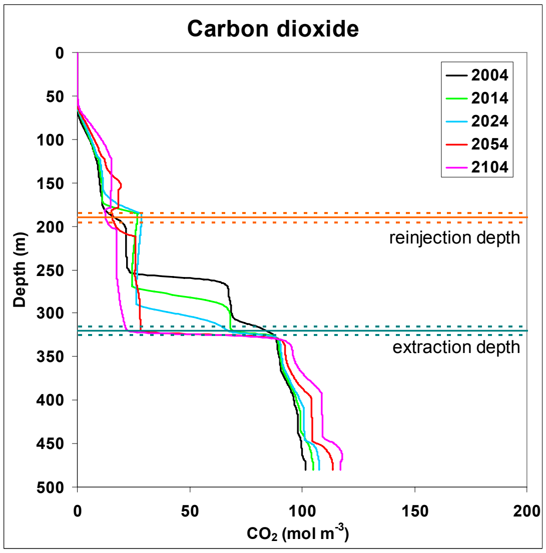


Figure 7.5.6 *Simulated CO_2 profiles for Scenario IZ5.*

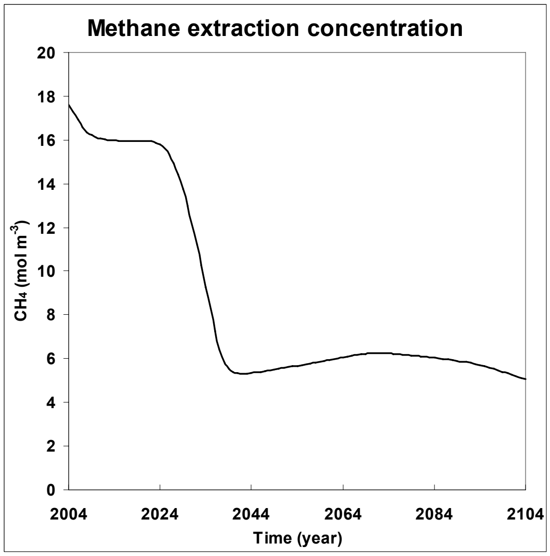


Figure 7.5.7 *Simulated CH_4 extraction concentration as a function of time for Scenario IZ5.*

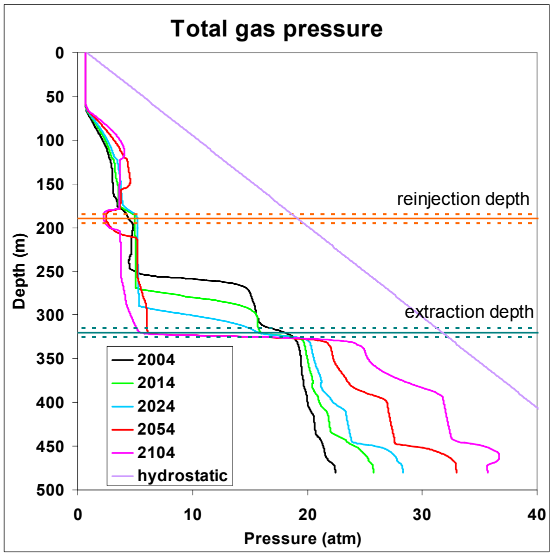


Figure 7.5.8 *Simulated total gas pressure profiles for Scenario IZ5.*

7.6 Scenario PR1: Reinjection into Potential Resource Zone

Scenario PR1	
Extraction flow	70 m^3 s^{-1}
Fraction of CH_4 reinjected	5.9 %
Fraction of CO_2 reinjected	60 %
Withdrawal depth	475 m
Withdrawal range	10 m
Reinjection depth	240 m
Reinjection range	60 m

Design parameters - The difference of PR1 to the IZ *Scenarios* is mainly the depth of the reinjection. The lower the reinjection, the smaller the density difference between the CH_4-depleted reinject-water and the ambient lake water. As an effect, the modification to the vertical structure of salinity, CO_2 and subsequently to density is smaller.

For PR1 the withdrawal (475 ± 5 m) and reinjection (210 to 270 m) depth is set deeper and the intention of PR1 is restratifying the reinject-water into the *Potential Resource Zone* (without dilution-water). The layer between withdrawal and reinjection (155 km^3 of downwelling water below 228 m depth) is 1.42-times replaced (221 km^3) during the 100 yr simulation time.

Stability and safety - As the volume between withdrawal and reinjection is relatively small, the concentrations of S, gases and nutrients are quite homogenous in the lower half of the lake (Figures 7.6.3 to 7.6.6) and the density stratification below the reinjection depth shrinks to a minimum. Above 100 m depth the modifications to salinity and CO_2 are minor and therefore the overall vertical density structure (density difference from top to max depth) remains intact to a large extent. The density gradient above the reinjection depth strengthens and becomes strongest in the lake after 50 yr of extraction. As a result, after 100 yr of extraction, the Schmidt stability is only reduced by ~20 % relative to natural.

The safety margin improves during the 100 yr of extraction over the entire water column and will be much less critical than today. Even in the relatively homo-

Table 7.6 ***Evaluation of Scenario PR1***

	No Extraction			***Scenario* PR1**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	1.9	2.4	2.9	10^3 tyr^{-1}
NH_4 upflux 80 m depth	15.9	21.0	26.0	15.9	21.0	26.2	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	7.6	7.0	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	35.5	30.4	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	5.1	4.5	km^3
CH_4 harvested (iii)					47.1	66.4	km^3
Average energy output					279	197	MW
CO_2 in lake	290	315	336	290	231	204	km^3
CO_2 removed from lake					86	133	km^3

geneous deep water the safety margin reaches very high (safe) values. They are lowest but still comfortably high at the deepest point with 1920 J m^{-3}. Compared to the IZ *Scenarios*, PR1 is on a much safer level after 100 yr of extraction, because the overall strong density stratification remains while the higher gas concentrations in the deepest reaches are removed.

Nutrients - The nutrient transport to the surface increases insignificantly, only ~1% after 100 yr of extraction. It is possible that it will be higher in the (long-term) steady state if the nutrient concentrations in the layer between 100 and 200 m depth increase due to the higher concentrations in the *Potential Resource Zone.*

Methane and energy - There is a benefit of reinjecting the extracted deep-water above the main density gradient: The high CH_4 concentrations of the *Resource Zone* are not diluted and the available CH_4 reserves can be depleted to a lower level. The efficiency of the power plants is most probably higher as the extracted CH_4 concentrations are higher.

The CH_4 flux to the surface should not increase noteworthily as the density gradient strengthened above the *Potential Resource Zone* replaces the function of the present main density gradient in ~180 m depth.

The harvested amount of CH_4 during 100 yr is ~66 km^3 and the corresponding electrical energy production is ~200 MW (Table 7.6).

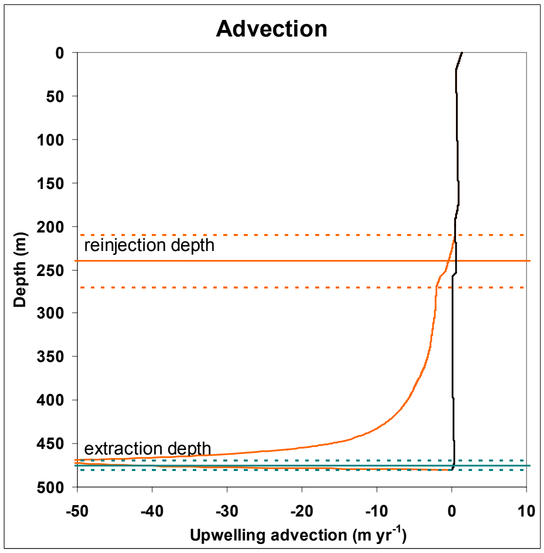


Figure 7.6.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario IZ5 (orange), compared with Scenario O (black).*

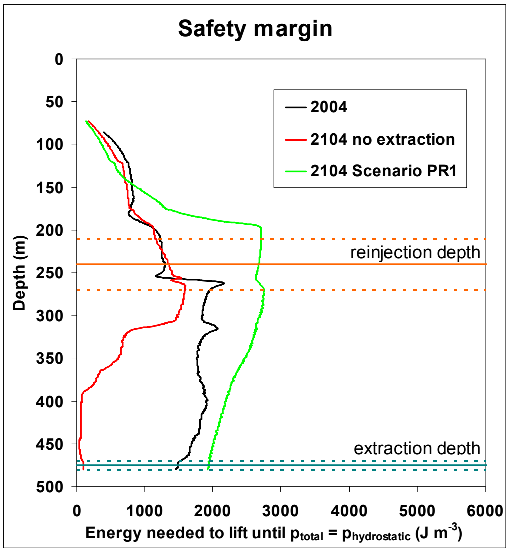


Figure 7.6.2 *Safety margin for Scenario PR1 in 2104 (green) compared to Scenario O (red).*

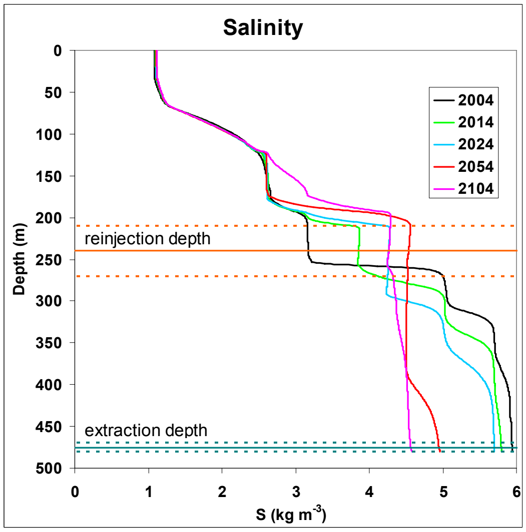


Figure 7.6.3 *Simulated salinity profiles for Scenario PR1.*

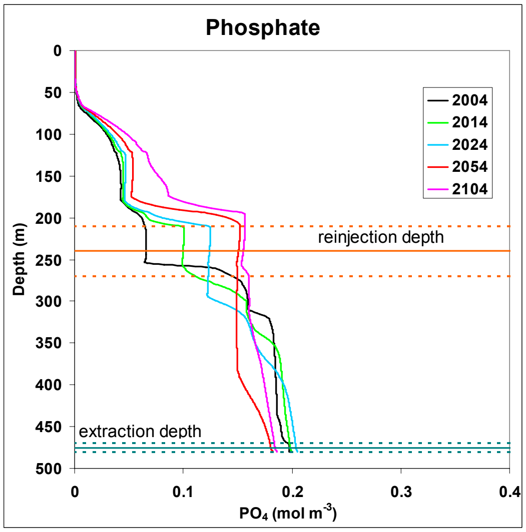


Figure 7.6.4 *Simulated PO_4 profiles for Scenario PR1.*

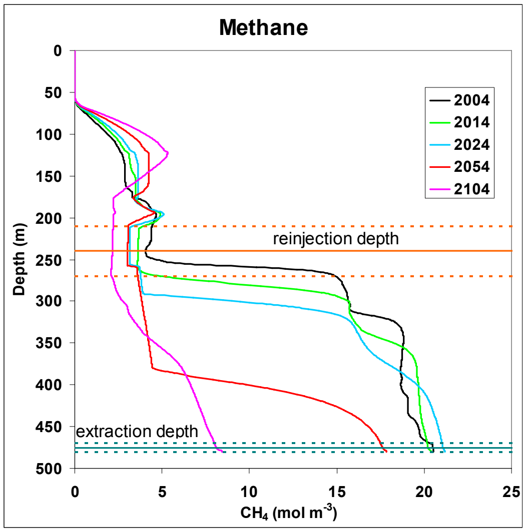


Figure 7.6.5 *Simulated CH_4 profiles for Scenario PR1.*

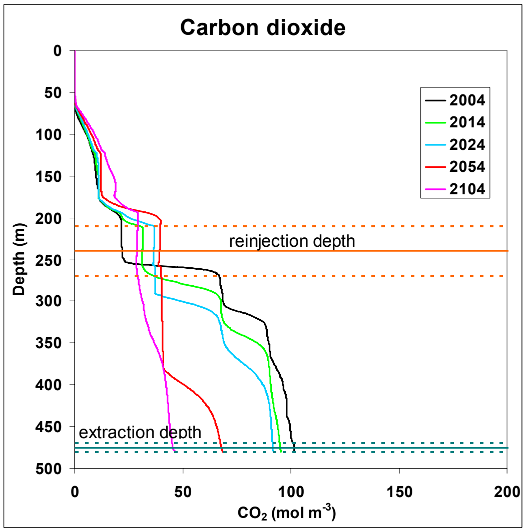


Figure 7.6.6 *Simulated CO_2 profiles for Scenario PR1.*

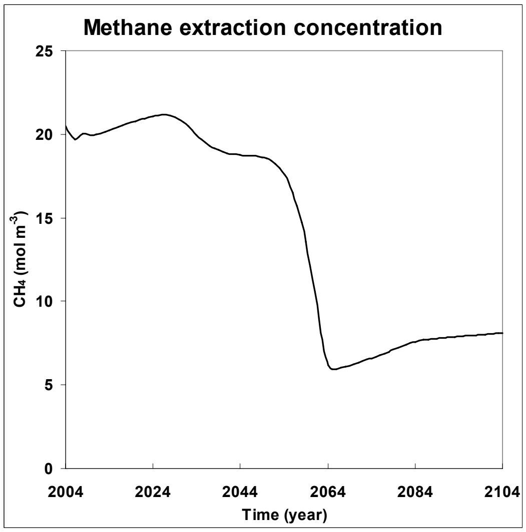


Figure 7.6.7 *Simulated CH_4 extraction concentration as a function of time for Scenario PR1.*

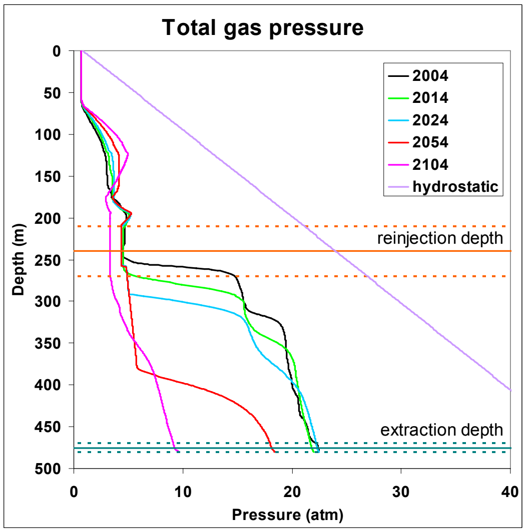


Figure 7.6.8 *Simulated total gas pressure profiles for Scenario PR1.*

7.7 Scenario RZ1: Single reinjection into Resource Zone

Design parameters - The intention of this *Scenario* RZ1 is to draw-down the entire Resource Zone to the deepest point - by reinjecting the water at the upper end of the RZ (290 ± 15 m depth) - and thereby not to affect the lake body above. The modifications to the vertical structure of salinity, CO_2, density and nutrients are small and much less than for the IZ *Scenarios*.

The layer between withdrawal (475 ± 5 m) and reinjection depth (112 km^3 of downwelling water below 275 m depth) is 2.0-times replaced (221 km^3) during the 100 yr simulation time.

***Scenario* RZ1**	
Extraction flow	70 $m^3 s^{-1}$
Fraction of CH_4 reinjected	5 %
Fraction of CO_2 reinjected	78 %
Withdrawal depth	475 m
Withdrawal range	10 m
Reinjection depth	290 m
Reinjection range	30 m

Stability and safety - As evident from the Figures 7.7.3 to 7.7.6, the major changes to the lake stratification occurs only in the lowest 200 m and the lake above is hardly affected. Within the *Resource Zone* the density stratification shrinks to a minimum (Figure 7.7.3). But the main density gradient above the RZ remains intact and steep. Therefore the overall stability is maintained and even after 100 yr of extraction, the Schmidt stability is still at the natural (undisturbed) level (Table 7.7).

The safety margin is minimal at 200 m depth but is comfortably high at 916 J m^{-3}. Below, and particularly in the RZ, the safety margin reaches high levels (Figure 7.7.2) - much higher than today - because the gases are extracted in the RZ.

Nutrients - The nutrient concentrations and the vertical nutrient gradients slightly increase with time (Figure 7.7.4). This increase is, however, related to the nutrient balance of the lake (Pasche et al 2009; Muvundja et al 2009) and is not related to the extraction process. Therefore, the nutrient transport to the surface does not increase during the 100 yr of simulation compared to natural (Table 7.7).

Table 7.7 ***Evaluation of Scenario RZ1***

		No Extraction				***Scenario* RZ1**			
		2004	**2054**	**2104**		**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth		1.9	2.4	2.9		1.9	2.4	2.9	10^3 tyr^{-1}
NH_4 upflux 80 m depth		15.9	21.0	26.0		15.9	21.0	26.0	10^3 tyr^{-1}
Schmidt stability		8.8	8.7	8.7		8.8	8.9	8.7	10^{14} J
CH_4 in lake (i)		64.6	81.7	96.3		64.6	44.1	39.3	km^3
CH_4 harvestable (ii)		42.3	58.9	69.0		42.3	20.9	12.1	km^3
CH_4 harvested (iii)							38.3	57.5	km^3
Average energy output							227	171	MW
CO_2 in lake		290	315	336		290	269	251	km^3
CO_2 removed from lake							47	85	km^3

We conclude that for all RZ *Scenarios* the nutrient transport to the *Biozone* will not change before reaching a steady-state. In a few hundred yr the nutrient flux to the *Biozone* will increase, however, independent of the extraction process.

Methane and energy - Oxidation and gas exchange to the atmosphere are the only ways to loose CH_4. As the IZ and the PRZ are only marginally affected by *Scenario* RZ1, we expect almost no additional losses due to the extraction operation. In fact the model simulations indicate even a slightly smaller loss, as a result of upwelling lower CH_4 concentrations after some decades of extraction. A potential disadvantage of *Scenario* RZ1 is evident from Figure 7.7.7 which shows that the CH_4 concentration at the intake collapses after ~25 yr within a very brief time span by a factor of 2 from ~20 to ~10 mol m^{-3}.

The *Potential Resource Zone* is not affected by this extraction method and can be treated separately as soon as its CH_4 concentration has grown to an extractable level.

The benefit of this deep zone extraction method is that the low CH_4 concentrations at the reinjection depth are being recharged with renewing CH_4 while they are moving downwards towards the withdrawal depth. The CH_4 gradient which evolves thereby allows an extraction of higher CH_4 concentrations and a depletion of the CH_4 stock to a lower level in comparison to the “completely mixed” *RZ2 and RZ3 (see below)*. The efficiency of the power plants will be larger due to higher CH_4 concentrations.

The harvested amount of CH_4 during 100 yr is ~58 km^3 and the corresponding electrical energy production is ~170 MW (Table 7.7).

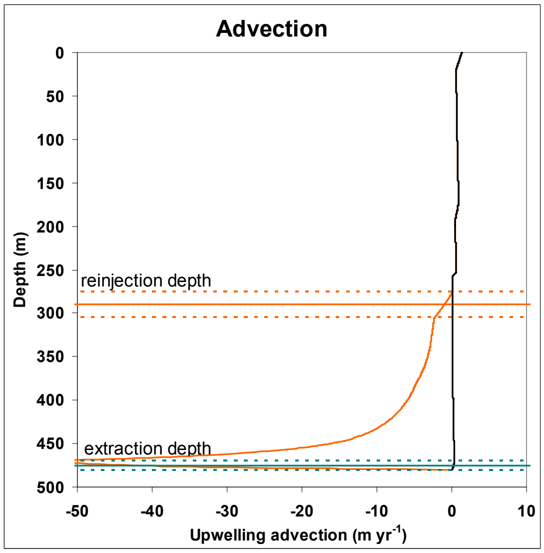


Figure 7.7.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario RZ1 (orange), compared with Scenario O (black).*

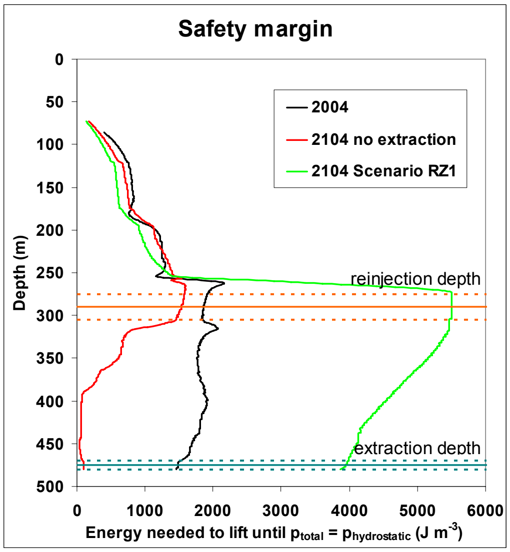


Figure 7.7.2 *Safety margin for Scenario RZ1 in 2104 (green) compared to Scenario O (red).*

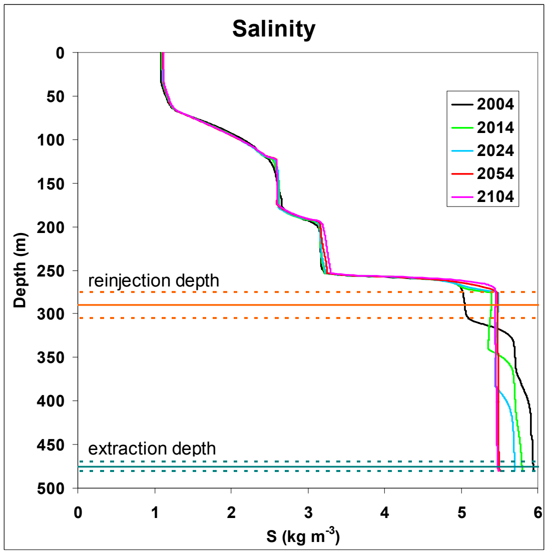


Figure 7.7.3 *Simulated salinity profiles for Scenario RZ1.*

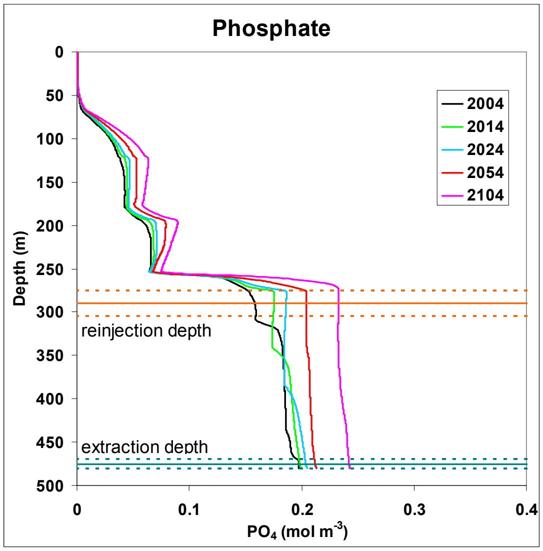


Figure 7.7.4 *Simulated PO_4 profiles for Scenario RZ1.*

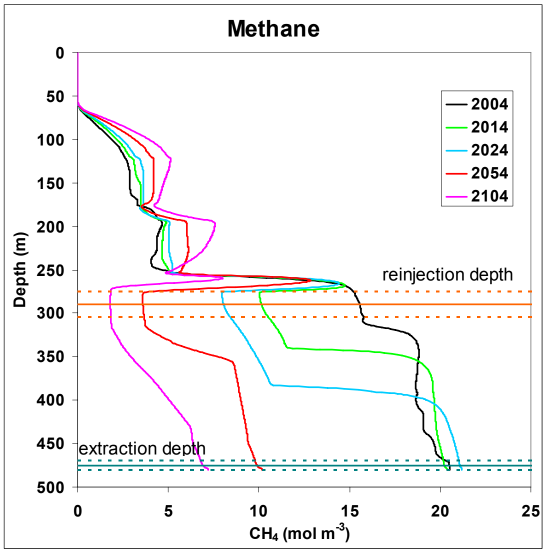


Figure 7.7.5 *Simulated CH_4 profiles for Scenario RZ1.*

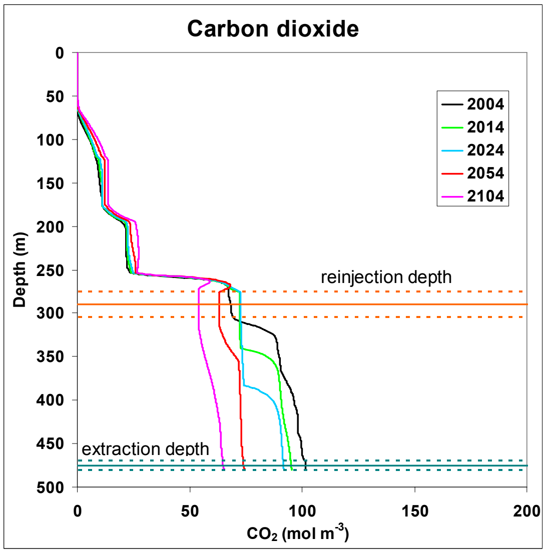


Figure 7.7.6 *Simulated CO_2 profiles for Scenario RZ1.*

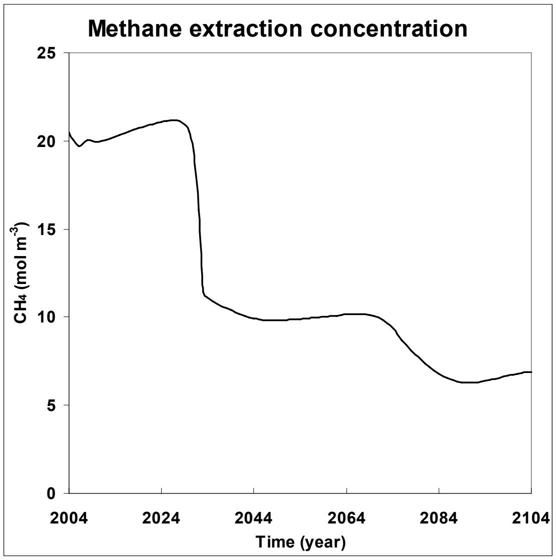


Figure 7.7.7 *Simulated CH_4 extraction concentration as a function of time for Scenario RZ1.*

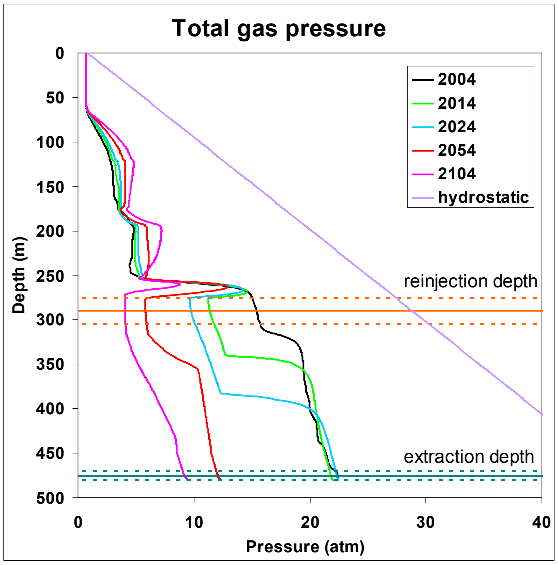


Figure 7.7.8 *Simulated total gas pressure profiles for Scenario RZ1.*

7.8 *Scenario RZ2: Double reinjection into Resource Zone*

Scenario RZ2	
Extraction flow	70 $m^3 s^{-1}$
Fraction of CH_4 reinjected	5 %
Fraction of CO_2 reinjected	78 %
1. Withdrawal depth	400 m
1. Withdrawal range	160 m
1. Reinjection depth	400 m
1. Reinjection range	160 m
2. Withdrawal depth	290 m
2. Withdrawal range	30 m
2. Reinjection depth	290 m
2. Reinjection range	30 m

Design parameters - The intention of *Scenario* RZ2 is to extract CH_4 over the entire RZ without causing any changes to the overall stratification of the lake. As lake water is extracted and reinjected in the same layers (from 275 m to 480 m depth) there is no additional (relative to natural) up- or down-welling induced by the extraction process (Figure 7.8.1). The extraction (two depth ranges) and reinjection (two depth ranges) is proposed to be realized by two sets of pipes to harvest the Upper RZ (275 to 305 m depth) and the Lower RZ (320 to 480 m depth) at the same pace. The water flow of 70 m^3 s^{-1} is split between the two zones to reach homogenous CH_4 concentrations in the two layers: 75% for the primary extraction and 25% for the secondary extraction (Table 5.5). The lake volume between extraction and reinjection depth (104 km^3) is 2.13 times flushed during the 100 yr of extraction (volume: 221 km^3).

The lake water body above the RZ is not affected by this extraction method and can be treated separately as soon as its CH_4 concentration has grown to extractable level. Therefore we do not expect any changes of the overall stratification or of the lake internal (nutrient) fluxes.

Stability and safety - As evident from Figures 7.8.3 to 7.8.6, the changes to the lake stratification occur only in the RZ (lowest 200 m) and the lake above 275 m depth is not affected (see explanations for RZ1). Therefore, the Schmidt stability

Table 7.8 ***Evaluation of Scenario RZ2***

	No Extraction			***Scenario* RZ2**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	1.9	2.4	2.9	10^3 tyr^{-1}
NH_4 upflux 80 m depth	15.9	21.0	26.0	15.9	21.0	26.0	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	8.8	8.7	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	54.2	51.2	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	33.9	28.1	km^3
CH_4 harvested (iii)					28.3	45.9	km^3
Average energy output					168	136	MW
CO_2 in lake	290	315	336	290	276	263	km^3
CO_2 removed from lake					44	79	km^3

remains at the natural (undisturbed) level (Table 7.8). The safety margin is at the minimum in 200 m depth at a high value of 926 J m^{-3} (see explanations for RZ1).

Nutrients - The nutrient transport to the *Biozone* (Table 7.8) does not increase during the 100 yr of simulation compared to the natural fluxes to the surface (see explanations for RZ1).

Methane and energy - As explained for RZ1, there is no additional loss of CH_4 due to the extraction operation. The effect of the RZ-wide withdrawal and reinjection is the continuous and steady decrease of the CH_4 concentrations at the intake (Figure 7.8.7). This continuous CH_4 decrease for RZ2 is in contrast to the IZ and the PR1 *Scenarios* which all showed some rather discontinuous decrease in concentration (see examples in Figures 7.2.7, 7.5.7).

If the extraction rate for RZ2 would be chosen low, such that it would not exceed the CH_4 new formation by much, then RZ2 could be run for very long, without causing any changes to the zones above. After many decades, some of the PRZ could become economically harvestable and could be extracted independently of the RZ.

It is important to realize that *Scenario* RZ2 leads to almost homogenous CH_4 concentrations which finally would approach the economic threshold (5 mol m^{-3} assumed in this report). Before this level is reached, the extraction *Scenario* needs to be changed, such that lake water is drawn-down (at higher CH_4) and the reinject-water is stacked back into the lake above the draw-down zone. *Scenarios* PR1 or RZ4 offer such options. This choice, which should also account for the PRZ CH_4 concentration, can be made in several decades in the future.

The harvested amount of CH_4 during 100 yr is ~46 km^3 and the corresponding electrical energy production is ~136 MW (Table 7.8).

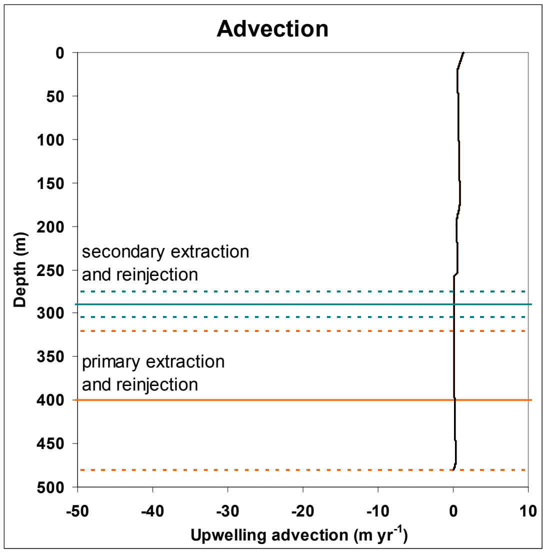


Figure 7.8.1 *Simulated profiles of vertical velocity for Scenario RZ2 is identical to Scenario O (no extraction), as the water is reinjected into the same volume as extracted.*

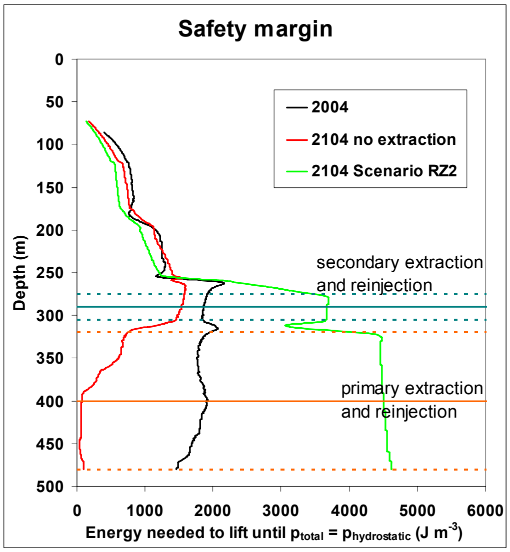


Figure 7.8.2 *Safety margin for Scenario RZ2 in 2104 (green) compared to Scenario O (red).*

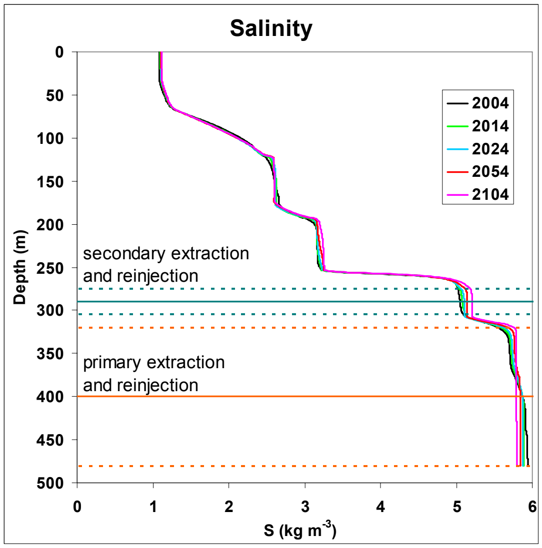


Figure 7.8.3 *Simulated salinity profiles for Scenario RZ2.*

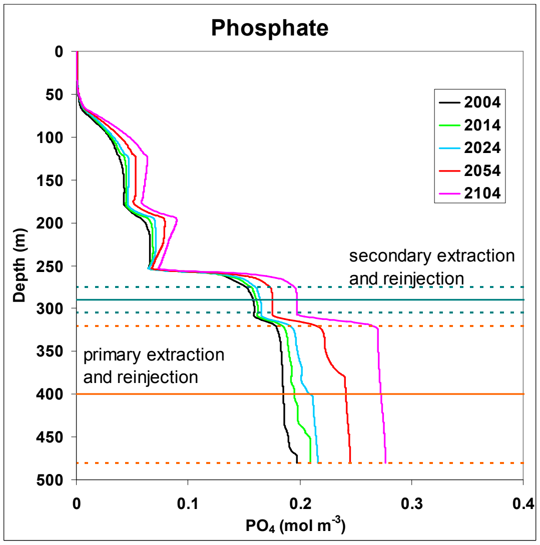


Figure 7.8.4 *Simulated PO_4 profiles for Scenario RZ2.*

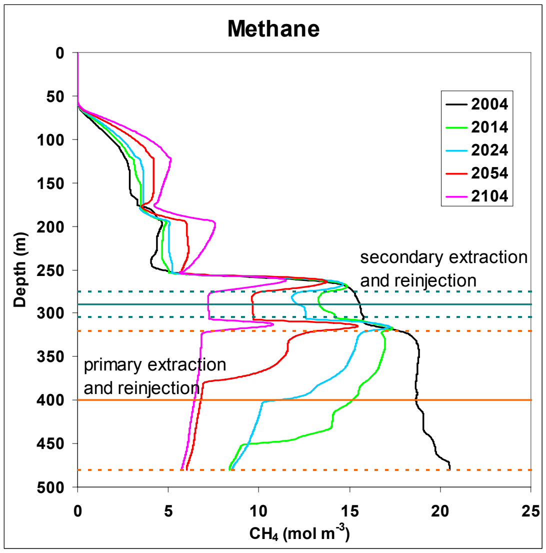


Figure 7.8.5 *Simulated CH_4 profiles for Scenario RZ2.*

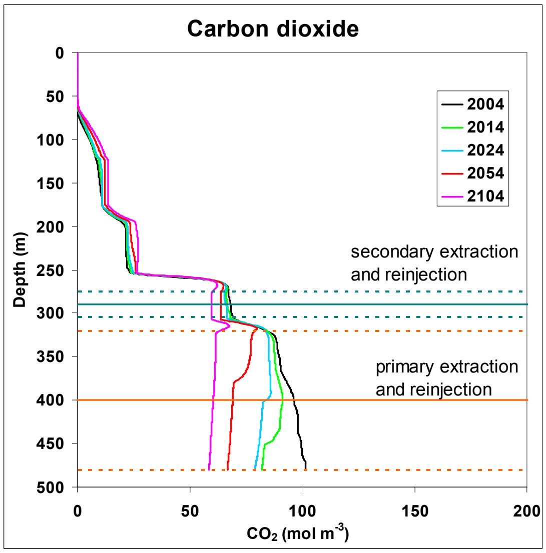


Figure 7.8.6 *Simulated CO_2 profiles for Scenario RZ2.*

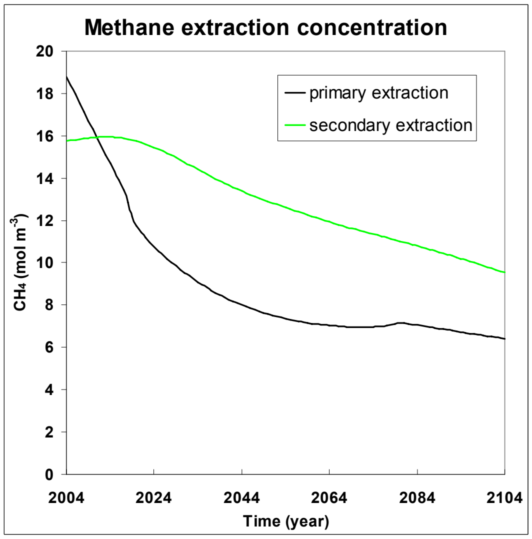


Figure 7.8.7 *Simulated CH_4 extraction concentrations as a function of time for both pipes of Scenario RZ2.*

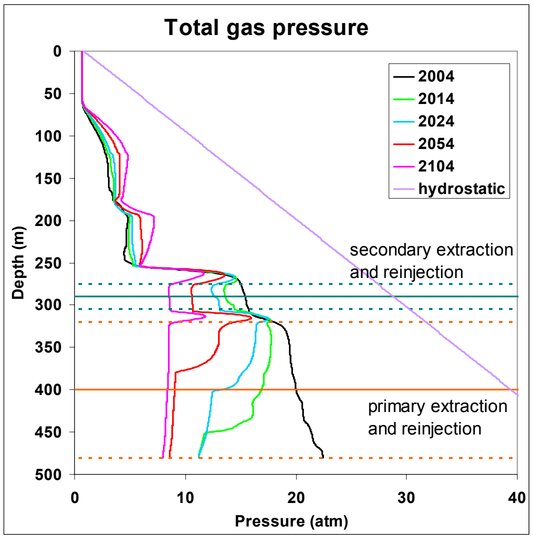


Figure 7.8.8 *Simulated total gas pressure profiles for Scenario RZ2.*

7.9 Scenario RZ3: Long-term effects of gas removal efficiency

Scenario **RZ3**	
Extraction flow	70 m^3 s^{-1}
Fraction of CH_4 reinjected	3.4 %
Fraction of CO_2 reinjected	46 %
1. Withdrawal depth	400 m
1. Withdrawal range	160 m
1. Reinjection depth	400 m
1. Reinjection range	160 m
2. Withdrawal depth	290 m
2. Withdrawal range	30 m
2. Reinjection depth	290 m
2. Reinjection range	30 m

Design parameters - This *Scenario* RZ3 is identical to RZ2 except that the fraction of reinjected gases is different: For RZ3 only 46% and 3.4 % of the extracted CO_2 and CH_4, respectively, remain in the reinject-water.

Stability and safety - As only 46% of the CO_2 is reinjected, the deep-water becomes lighter in the long-term, while CO_2 concentrations in the lake decrease. Although the stratification structure remains, the density difference between surface and deep-water is reduced and therefore the Schmidt stability is significantly (~13%) reduced (Table 7.9.1) but still very safe. The safety margin remains the same (929 J m^{-3}), as at the critical depth in 200 m the changes to the stratification by RZ2 or RZ3 are negligible.

CH_4/CO_2 ratio in the extraction water - If RZ *Scenarios* are chosen as extraction option, then the reinject-water evidently influences in the long-term the gas composition of the RZ water. This influence becomes stronger over time, as the fraction of recycled water is increasing, until the steady-state (long-term continuous extraction) would be achieved. For steady-state the CH_4/CO_2 ratio is solely determined by the *Design Parameters* of the extraction plant (*Scenario*) and by the rate of recharge of CO_2 and CH_4. Practically, the threshold concentration for extractable CH_4 (5 mol m^{-3}) would define how much water can be extracted in order to stay in steady-state balance with new formation, extraction and reinjection.

Table 7.9 ***Evaluation of Scenario RZ3***

	No Extraction			***Scenario* RZ3**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	1.9	2.4	2.9	10^3 tyr^{-1}
NH_4 upflux 80 m depth	15.9	21.0	26.0	15.9	21.0	26.0	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	8.0	7.5	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	53.2	49.8	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	33.1	26.9	km^3
CH_4 harvested (iii)					29.3	47.3	km^3
Average energy output					174	140	MW
CO_2 in lake	290	315	336	290	233	199	km^3
CO_2 removed from lake					93	151	km^3

However, we assume that at least for the next few decades the steady-state concept is not the envisaged harvesting option. But also for much shorter time scales it is important to realize that the CH_4/CO_2 ratios are decreasing during extraction (see Figures 7.9.1 to 7.9.6 for the Scenarios RZ1 to RZ6). Only for RZ3 (Figure 7.9.3) the CH_4/CO_2 ratio is maintained on a practically constant level of ~18 to ~22%. The reason for the CH_4/CO_2 ratio to be maintained and not to decrease is the low CO_2 reinjection percentage.

The estimation of the ideal CH_4/CO_2 ratio is a delicate issue: On the one hand, CO_2 helps to siphon the deep water, as the CO_2-containing bubbles in the tubes support the buoyancy. On the other hand a low CH_4/CO_2 ratio reduces the efficiency of the power production. Thus, the benefit of reinjecting less CO_2 in the lake is a higher long-term CH_4/CO_2 ratio and therefore better power plant efficiency. Finding the ideal ratio is obviously an engineering optimization

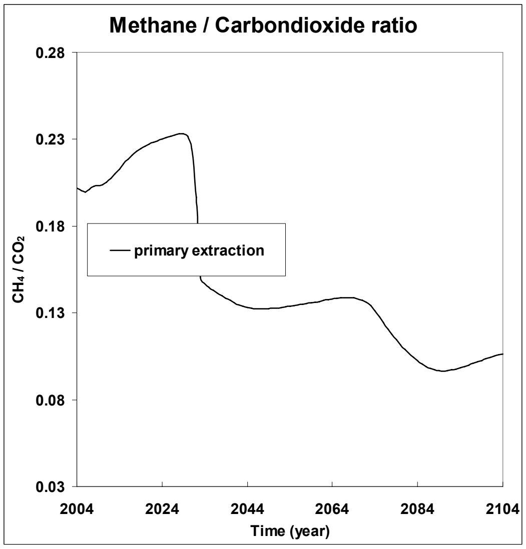


Figure 7.9.1 *Simulated CH_4/CO_2 ratio as a function of time for Scenario RZ1.*

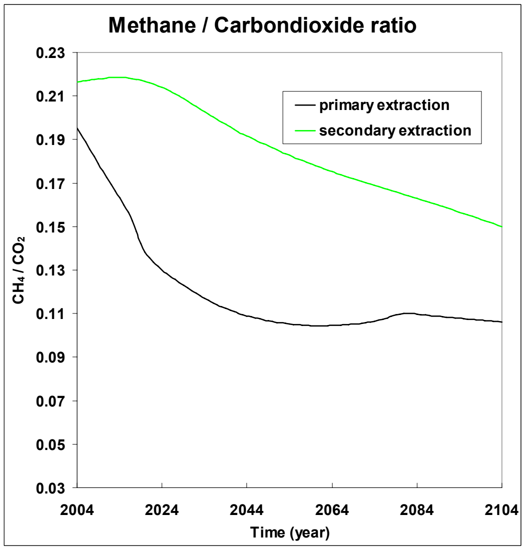


Figure 7.9.2 *Simulated CH_4/CO_2 ratio as a function of time for Scenario RZ2.*

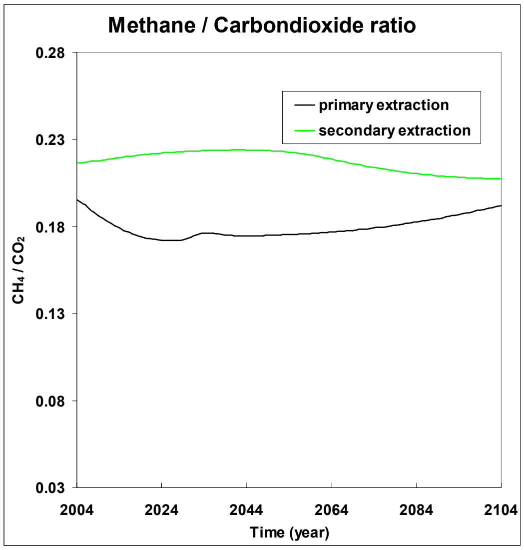


Figure 7.9.3 *Simulated CH_4/CO_2 ratio as a function of time for Scenario RZ3.*

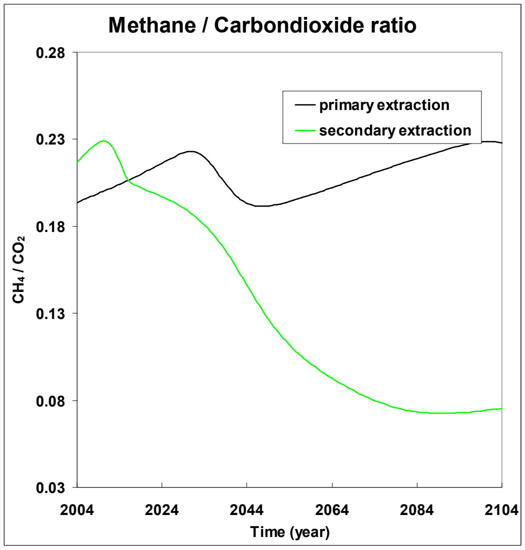


Figure 7.9.4 *Simulated CH_4/CO_2 ratio as a function of time for Scenario RZ4.*

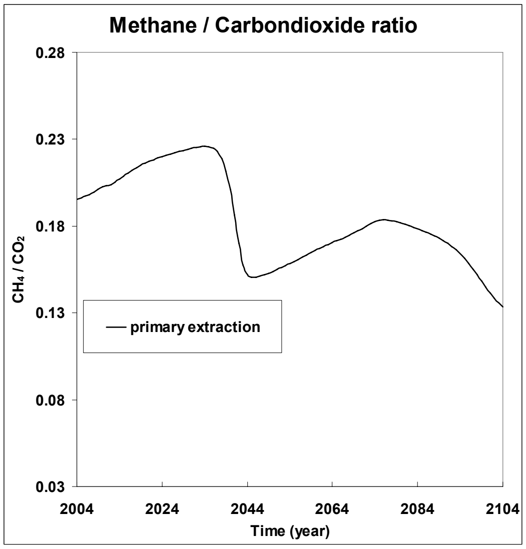


Figure 7.9.5 *Simulated CH_4/CO_2 ratio as a function of time for Scenario RZ5.*

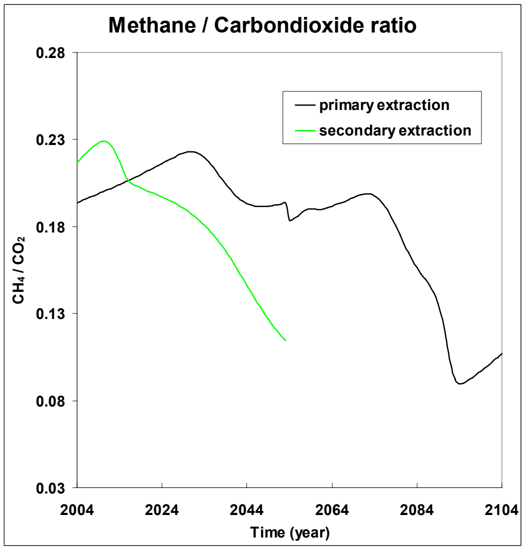


Figure 7.9.6 *Simulated CH_4/CO_2 ratio as a function of time for Scenario RZ6.*

7.10 *Scenario RZ4: Resource Zone Reinjection*

Scenario RZ4	
Extraction flow	70 $m^3 s^{-1}$
Fraction of CH_4 reinjected	6 %
Fraction of CO_2 reinjected	60/55 %
1. Withdrawal depth	410 m
1. Withdrawal range	60 m
1. Reinjection depth	325 m
1. Reinjection range	5 m
2. Withdrawal depth	310 m
2. Withdrawal range	10 m
2. Reinjection depth	270 m
2. Reinjection range	10 m

Design parameters - This *Scenario* RZ4 is not a “stand-alone” *Scenario*, but is considered as the first leg in combination with RZ5, which would cover the second part. The idea of RZ4 is to use CH_4 in the RZ (Upper and Lower RZ) as for *Scenario* RZ2, but to use the CH_4 in the Upper RZ (275 to 305 m depth) at a faster rate than in the Lower RZ (320 to 480 m depth) and basically remove the CH_4 in the Upper RZ in order to create a CH_4-free space (Figure 7.10.5), which the follow up RZ5 could use for disposing the reinject-water.

Another difference is that for RZ4 the ranges of withdrawal and reinjection are vertically separated, so that no recirculation can occur from the reinjection outlet to the intake pipe. The water flow of 70 $m^3 s^{-1}$ is split between the two zones (details in Table 5.5). The lake water volume (104 km^3) between extraction and reinjection depth is recycled 2.13-times for the extraction volume (221 km^3) for the 100 yr of simulation.

The Lower RZ is intentionally extracted with a larger CO_2 removal (55% rejected, see above) in order to reduce the density of the Lower RZ water. This preparation is advantageous for the stacking of the reinject-water while *Scenario* RZ5 is in operation.

Again, as for RZ2, there is no additional (relative to natural) up- or down-welling induced above the RZ (such as in the PRZ or the IZ) by the extraction process (Figure 7.10.1). Only within the two RZ layers, there is dowelling between reinjection and withdrawal (Figure 7.10.1). Therefore we do not expect significant changes of the overall stratification or of the lake internal (nutrient) fluxes.

Table 7.10 ***Evaluation of Scenario RZ4***

	No Extraction			***Scenario* RZ4**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	1.9	2.4	2.9	$10^3 tyr^{-1}$
NH_4 upflux 80 m depth	15.9	21.0	26.0	15.9	21.0	26.0	$10^3 tyr^{-1}$
Schmidt stability	8.8	8.7	8.7	8.8	8.4	7.9	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	48.9	44.1	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	24.3	15.1	km^3
CH_4 harvested (iii)					33.7	53.0	km^3
Average energy output					200	157	MW
CO_2 in lake	290	315	336	290	243	209	km^3
CO_2 removed from lake					74	125	km^3

Stability and safety - As evident from Figures 7.10.3 to 7.10.6, the changes to the lake stratification occur only in the RZ (lowest 200 m) and the lake above 275 m depth is not affected (see explanations for RZ1). Therefore, the Schmidt stability remains at the natural (undisturbed) level (Table 7.10).

After 100 yr, the safety margin would be minimal at 445 m depth at only 70 J m^{-3} (see explanations for Figure 7.10.2). However, this *Scenario* RZ4 is not intended to run for 100 yr, as after ~25 yr the latest, the operation has to switch to RZ5 (as otherwise the CH_4 concentration would become too low for extraction; Figure 7.10.7). Therefore, the safety- margin is not a concern and can only be judged in combination with RZ5 (realized as RZ6).

Nutrients - The nutrient transport to the *Biozone* (Table 7.10) does not increase during the 100 yr of simulation compared to the natural fluxes to the surface (see explanations for RZ1).

Methane and energy - As explained for RZ1, there is no additional loss of CH_4 due to the extraction operation. Compared to RZ2/RZ3, the CH_4 concentrations are not homogenised, as the separation of extraction and withdrawal generates vertical gradients (differences; Figure 7.10.5) and keeps the CH_4 on a higher concentration at the intakes (Figure 7.10.7). Well before (~25 yr) the Upper RZ withdrawal reaches uneconomically low CH_4 levels (~5 mol m^{-3}, Figure 7.10.7), the operation has to switch to RZ5 such that lake water is drawn-down (at higher CH_4-level) and the reinject-water is stacked back into the lake above the draw-down zone.

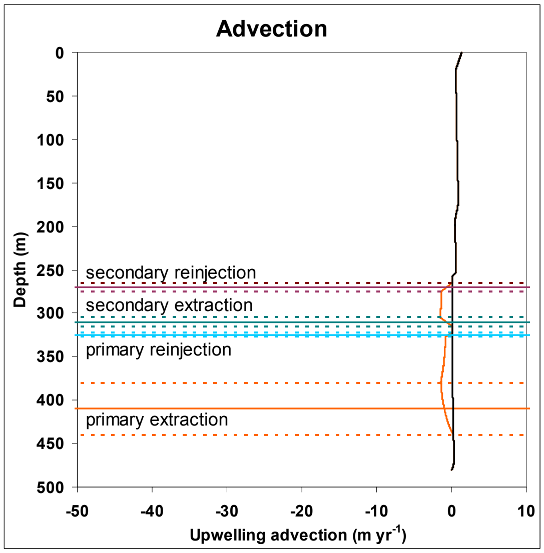


Figure 7.10.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario RZ4 (orange), compared with Scenario O (black).*

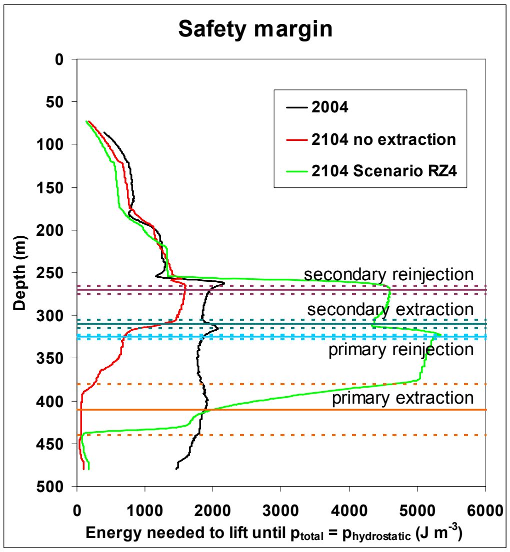


Figure 7.10.2 *Safety margin for Scenario RZ4 in 2104 (green), compared to Scenario O (red).*

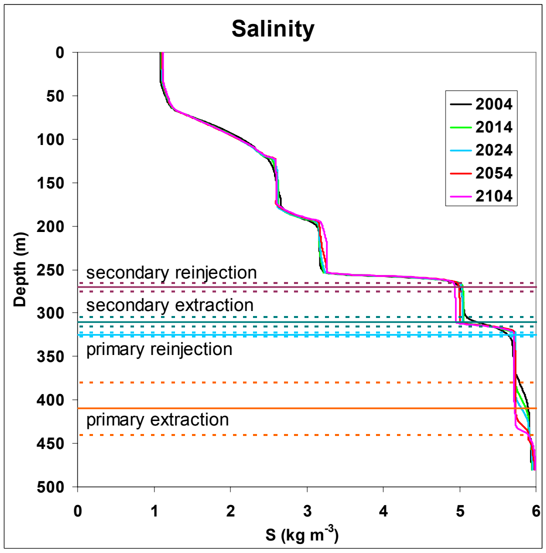


Figure 7.10.3 *Simulated salinity profiles for Scenario RZ4.*

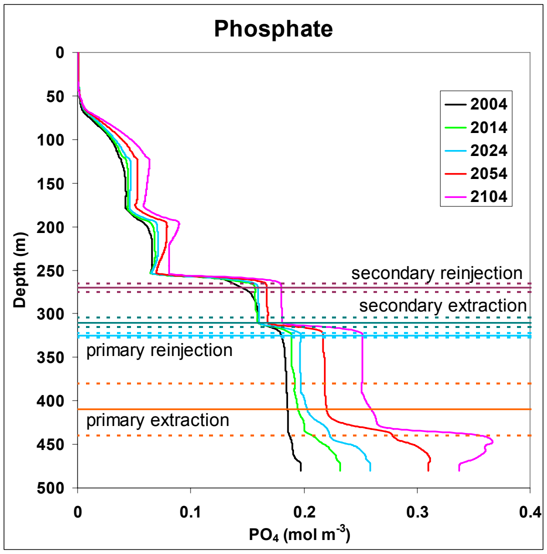


Figure 7.10.4 *Simulated PO_4 profiles for Scenario RZ4.*

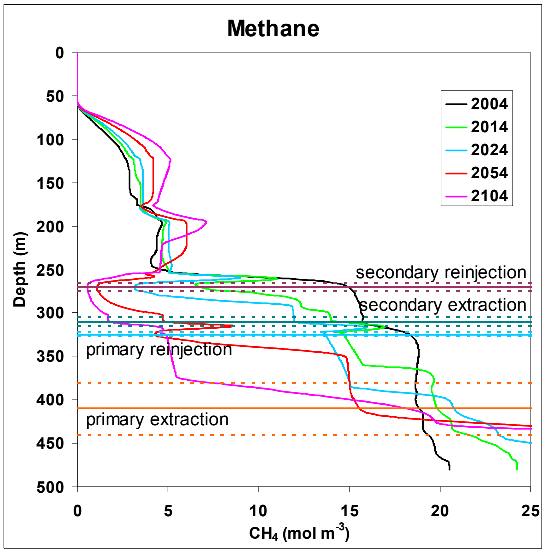


Figure 7.10.5 *Simulated CH_4 profiles for Scenario RZ4.*

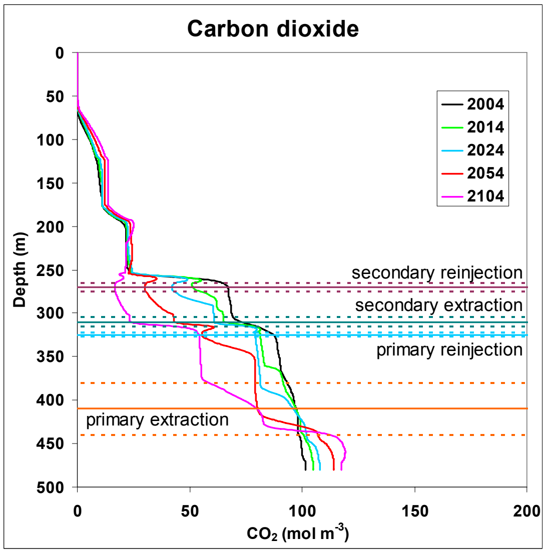


Figure 7.10.6 *Simulated CO_2 profiles for Scenario RZ4.*

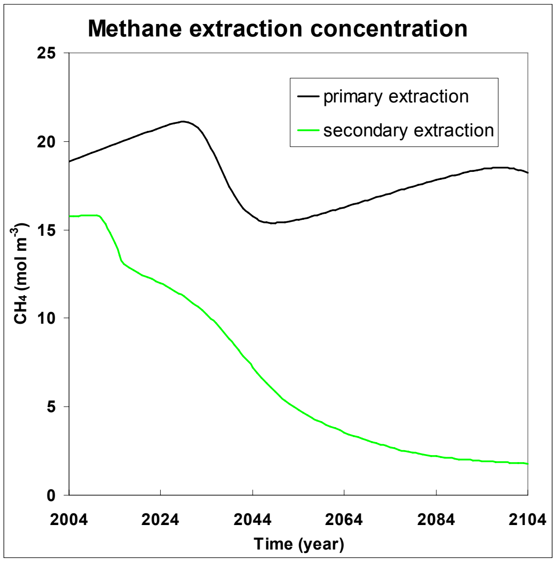


Figure 7.10.7 *Simulated CH_4 extraction concentration as a function of time for Scenario RZ4.*

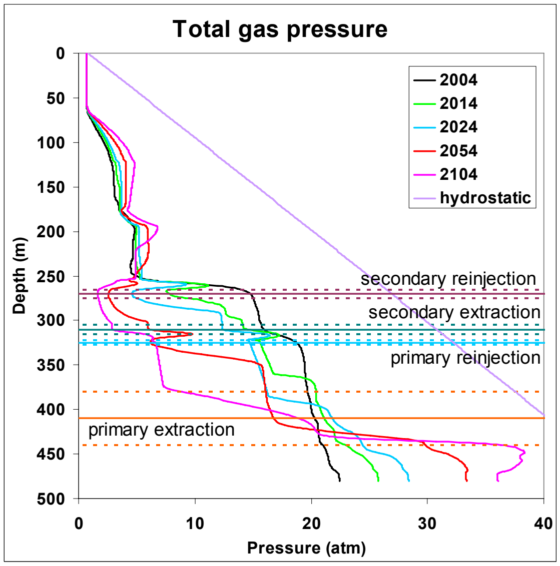


Figure 7.10.8 *Simulated total gas pressure profiles for Scenario RZ4.*

7.11 *Scenario RZ5: Resource Zone Reinjection*

***Scenario* RZ5**	
Extraction flow	70 m^3 s^{-1}
Fraction of CH_4 reinjected	3.4 %
Fraction of CO_2 reinjected	50 %
Withdrawal depth	400 m
Withdrawal range	160 m
Reinjection depth	270 m
Reinjection range	10 m

Design parameters - This *Scenario* RZ5 is intended as a continuation of RZ4. After the Upper RZ has been emptied of CH_4 by *Scenario* RZ4 (~25 yr), the CH_4-free space (Figure 7.10.5) is used by *Scenario* RZ5 for reinjection into a narrow range at 270 m depth at the upper boundary of the Upper RZ. The withdrawal is foreseen over the entire Lower RZ from 320 m to the maximum depth. However, if this broad range causes disadvantages (too low CH_4 concentrations) at the upper boundary of the Lower RZ, the withdrawal range can be confined to the lower reaches, without changing the concept. Also for RZ5, the withdrawal and reinjection are vertically separated, so that no recirculation can occur from the reinjection outlet to the intake pipe. The draw-down lake volume (104 km^3) is replaced 2.13-times during the 100 yr of simulation (extraction volume: 221 km^3).

As there are only slight salinity gradients in the RZ and as the CH_4 extraction increases the density of the reinject-water, it is important to remove a large fraction of CO_2 (here 50%) in order to keep the reinject-water on top of the Lower RZ and not to cause convective mixing with the RZ. This is most crucial for this *Scenario* RZ6.

As for the other RZ *Scenarios*, the extraction does not induce additional (relative to natural) up- or downwelling in the PRZ or the IZ (Figure 7.11.1). Therefore we do not expect any changes of the overall stratification or of the lake internal (nutrient) fluxes.

Table 7.11 ***Evaluation of Scenario RZ5***

	No Extraction			***Scenario* RZ5**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	1.9	2.4	2.9	10^3 tyr^{-1}
NH_4 upflux 80 m depth	15.9	21.0	26.0	15.9	21.0	26.0	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	8.0	7.4	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	42.3	35.4	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	20.5	6.6	km^3
CH_4 harvested (iii)					40.1	61.6	km^3
Average energy output					238	183	MW
CO_2 in lake	290	315	336	290	216	172	km^3
CO_2 removed from lake					100	163	km^3

Stability and safety - As evident from Figures 7.11.3 to 7.11.6, the changes to the lake stratification occur only in the RZ (lowest 200 m) and the lake above 265 m depth is not affected (see explanations for RZ1). Therefore, the Schmidt stability remains at the natural (undisturbed) level (Table 7.11).

After 100 yr, the safety margin would be minimal at 200 m depth at 927 J m^{-3} (Figure 7.11.2), which is still a very safe level.

Nutrients - The nutrient transport to the *Biozone* (Table 7.11) does not increase during the 100 yr of simulation compared to the natural fluxes to the surface (see explanations for RZ1).

Methane and energy - As for the other RZ *Scenarios,* there is no additional loss of CH_4 due to the extraction operation. Due to the draw-down approach, a strong vertical gradient of CH_4 remains in the RZ (CH_4-free reinject-water is stacked on top of the CH_4-containing deep-water (Figure 7.11.5). Therefore, after 30 to 40 yr of extraction, the intake CH_4 concentration drops within one decade by a factor of ~2 (from ~20 to 10 mol m^{-3}; Figure 7.11.7). As the intake stretches over a wide vertical range with CH_4 concentrations below the threshold, the option will be to reduce the intake range and to restrict to higher concentrations in the deeper range.

The harvested amount of CH_4 during 100 yr is ~61.6 km^3 and the corresponding electrical energy production is ~183 MW (Table 7.11).

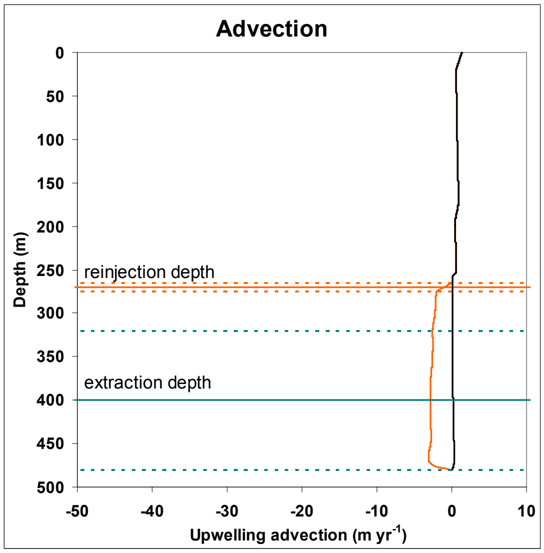


Figure 7.11.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario RZ5 (orange), compared with Scenario O (black).*

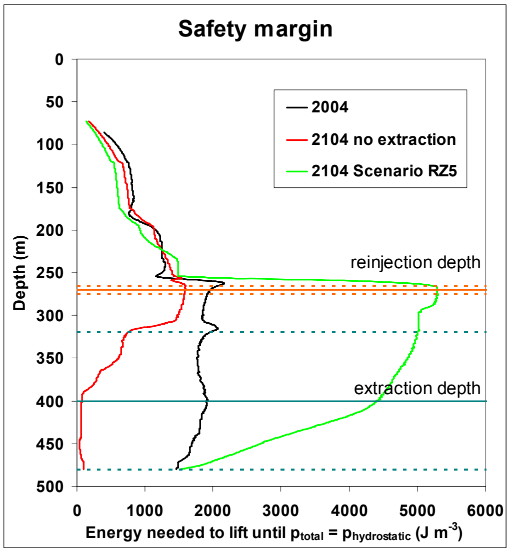


Figure 7.11.2 *Safety margin for Scenario RZ5, compared to Scenario O.*

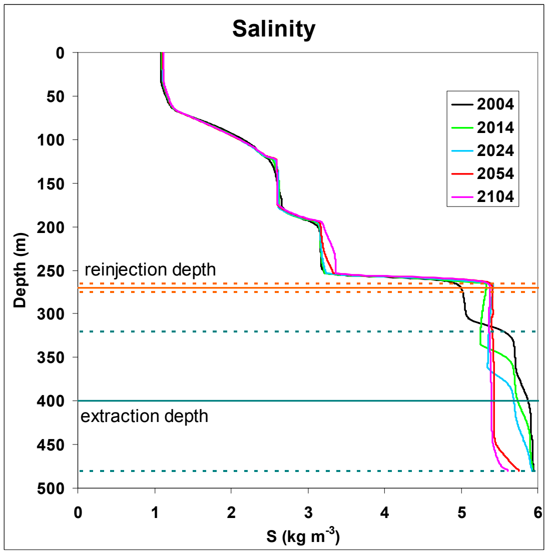


Figure 7.11.3 *Simulated salinity profiles for Scenario RZ5.*

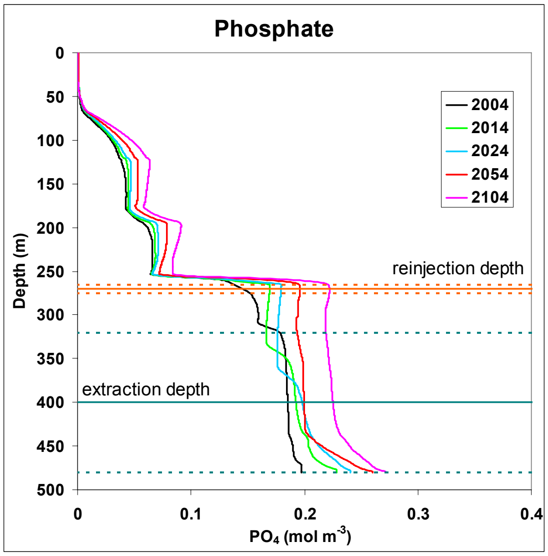
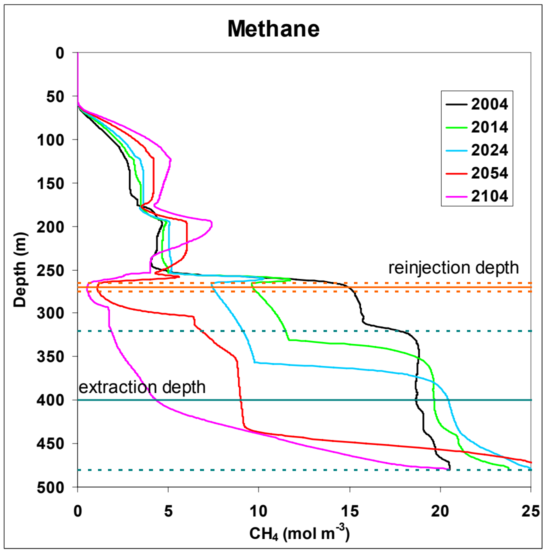


Figure 7.11.4 *Simulated PO_4 profiles for Scenario RZ5.*



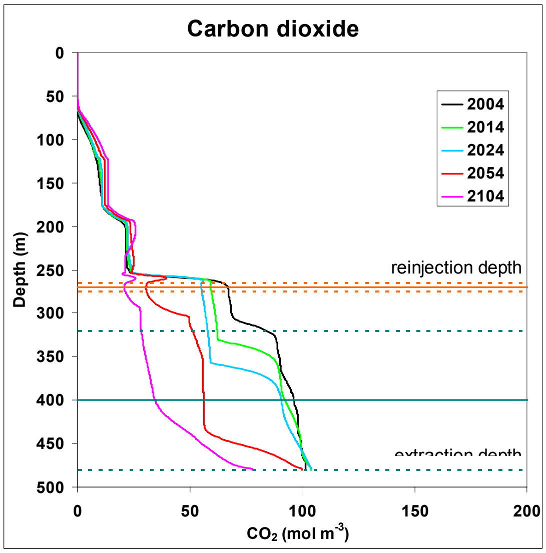
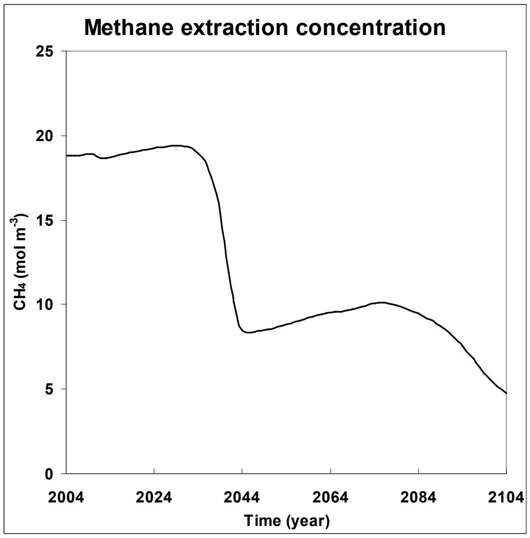


Figure 7.11.5 *Simulated CH_4 profiles for Scenario RZ5.*

Figure 7.11.6 *Simulated CO_2 profiles for Scenario RZ5.*



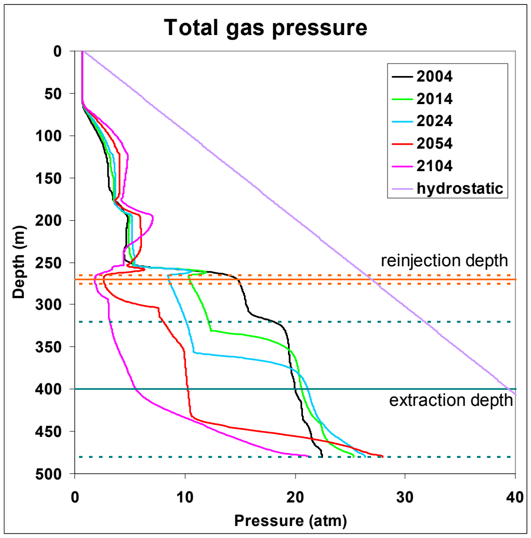


Figure 7.11.7 *Simulated CH_4 extraction concentration as a function of time for Scenario RZ5.*

Figure 7.11.8 *Simulated total gas pressure profiles for Scenario RZ5.*

7.12 Scenario RZ6: Resource Zone Reinjection

Scenario RZ6	
Extraction flow	70 $m^3 s^{-1}$
Fraction of CH_4 reinjected	6 % --> 3.4 %
Fraction of CO_2 reinjected	60/55 % --> 50 %
Withdrawal depth	RZ4 --> RZ5
Withdrawal range	RZ4 --> RZ5
Reinjection depth	RZ4 --> RZ5
Reinjection range	RZ4 --> RZ5

Design parameters - This *Scenario* RZ6 is designed as the combination of RZ4 (first leg) and RZ5 (second leg). The time scale to switch from RZ4 to RZ5 may depend on the extraction rate and is flexible. For the model calculation the switch was set to 50 yr (Figure 7.12.7), when the upper intake reaches non-harvestable CH_4 concentrations. Although a shorter timescale will most probably be necessary to maintain the CH_4 extraction efficiency. The idea of RZ6 is to use CH_4 in the Upper RZ faster (than in the Lower RZ, see RZ4) in order to create CH_4-free space at the upper edge of the RZ (Figure 7.10.5). During the following extraction with *Scenario* RZ6, this CH_4-free layer is then used as the reinjection range (see RZ5). For both *Scenarios* the extraction flow is 70 $m^3 s^{-1}$. For details of RZ4 and RZ5, see Sections 7.10 and 7.11, respectively.

The lake volume between extraction and reinjection is 104 km^3 compared to the extracted volume of 221 km^3 in 100 yr of simulation. Therefore, the lake volume would be recycled 2.13-times during 100 yr of extraction. As explained for RZ5 the somewhat larger CO_2 removal in the lower extraction (see table above) is intended to keep the density profile stable in the Lower RZ.

Again, as for the other RZ *Scenarios*, there is no additional (relative to natural) up- or downwelling induced in the PRZ or the IZ by the extraction process (Figure 7.12.1). Therefore we do not expect any changes of the overall stratification or of the lake internal (nutrient) fluxes.

Table 7.12 ***Evaluation of Scenario RZ6***

	No Extraction			***Scenario* RZ6**			
	2004	**2054**	**2104**	**2004**	**2054**	**2104**	
PO_4 upflux 80 m depth	1.9	2.4	2.9	1.9	2.4	2.9	10^3 tyr^{-1}
NH_4 upflux 80 m depth	15.9	21.0	26.0	15.9	21.0	25.9	10^3 tyr^{-1}
Schmidt stability	8.8	8.7	8.7	8.8	8.4	7.6	10^{14} J
CH_4 in lake (i)	64.6	81.7	96.3	64.6	48.7	35.9	km^3
CH_4 harvestable (ii)	42.3	58.9	69.0	42.3	24.5	6.0	km^3
CH_4 harvested (iii)					32.1	61.5	km^3
Average energy output					190	182	MW
CO_2 in lake	290	315	336	290	242	182	km^3
CO_2 removed from lake					76	151	km^3

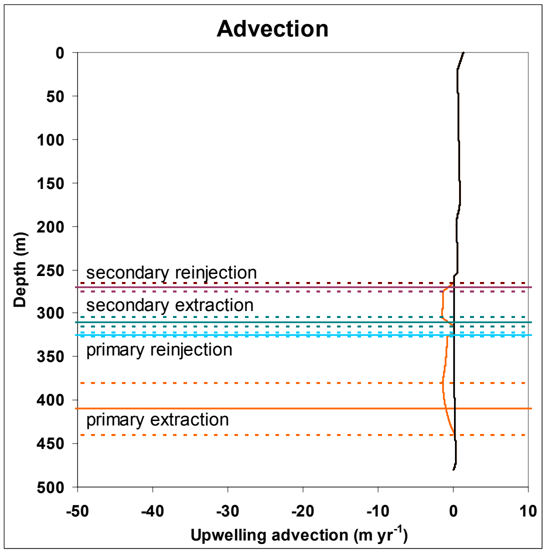
Stability and safety - As evident from Figures 7.12.3 to 7.12.6, the changes to the lake stratification occur only in the RZ (lowest 200 m) and the lake above 275 m depth is not affected (see RZ4, RZ5). Therefore, the Schmidt stability remains at the natural (undisturbed) level (Table 7.12).

After 100 yr, the safety margin would be minimal at 200 m depth at 970 J m^{-3} (Figure 7.12.2), at a still very safe level.

Nutrients - The nutrient transport to the *Biozone* (Table 7.12) does not increase during the 100 yr of simulation compared to the natural fluxes to the surface (see explanations for RZ1).

Methane and energy - As for the other RZ *Scenarios,* there is no additional loss of CH_4 due to the extraction operation. Due to the draw-down approach, a strong vertical gradient of CH_4 remains in the RZ (CH_4-free reinject-water is stacked on top of the CH_4-containing deep-water, Figure 7.12.5). After ~25 and ~70 yr of extraction, the intake CH_4 concentration drops in two steps from originally ~20 to ~5 mol m^{-3}; Figure 7.12.7). As the intake ranges over a wide vertical range with CH_4 concentrations below the threshold, the option will be to reduce the intake range and to restrict to higher concentrations in the deeper range of the lake.

The harvested amount of CH_4 during 100 yr is ~61.5 km^3 and the corresponding electrical energy production is ~182 MW (Table 7.12).



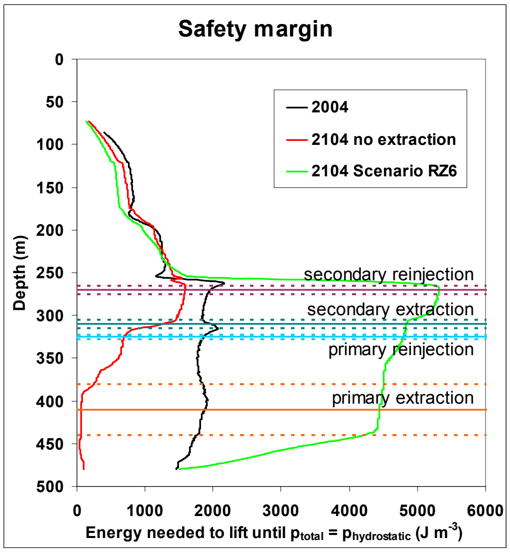
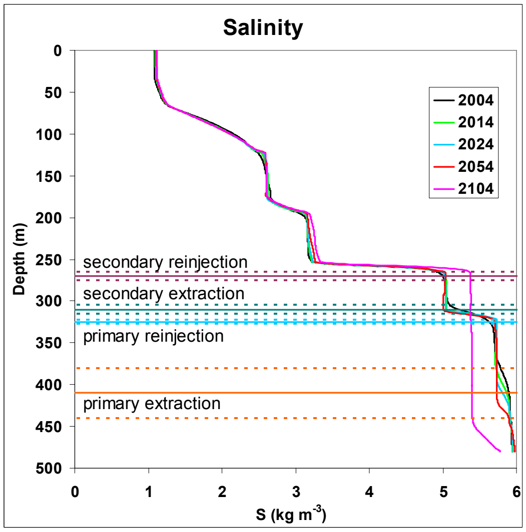


Figure 7.12.1 *Simulated profiles of vertical velocity (+: upwelling; -: downwelling) for Scenario RZ6 (orange), compared with Scenario O (black).*

Figure 7.12.2 *Safety margin for Scenario RZ6, compared to Scenario O.*



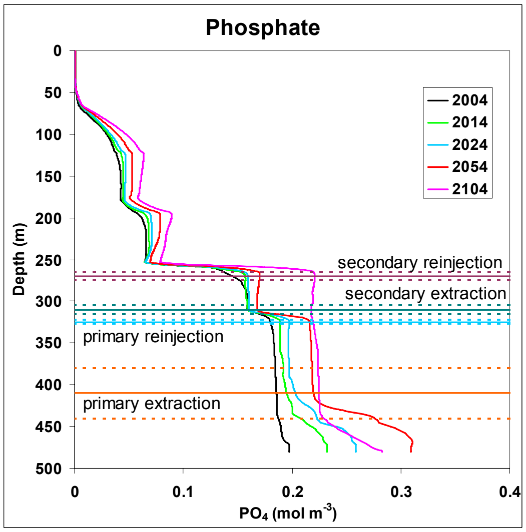


Figure 7.12.3 *Simulated salinity profiles for Scenario RZ6.*

Figure 7.12.4 *Simulated PO_4 profiles for Scenario RZ6.*

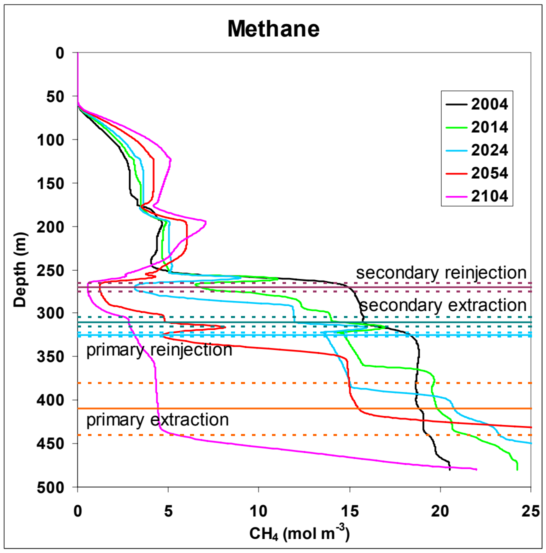


Figure 7.12.5 *Simulated CH_4 profiles for Scenario RZ6.*

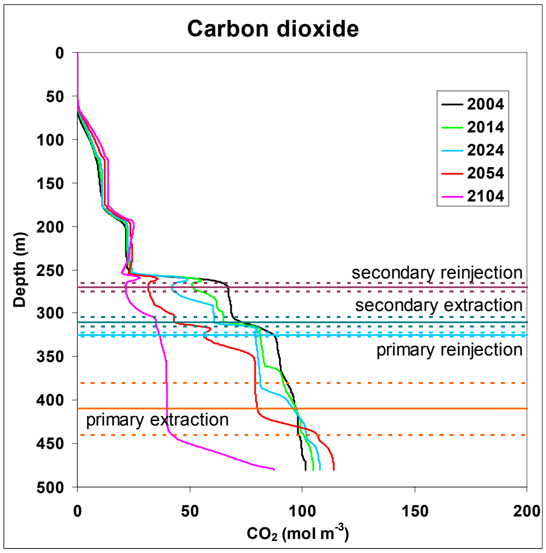


Figure 7.12.6 *Simulated CO_2 profiles for Scenario RZ6.*

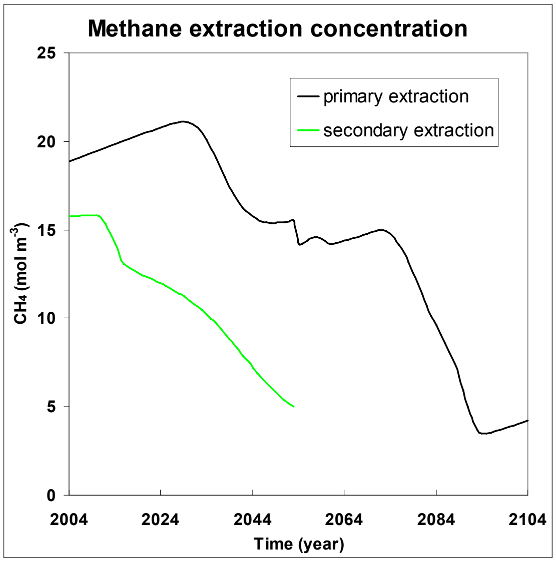


Figure 7.12.7 *Simulated CH_4 extraction concentration as a function of time for Scenario RZ6.*

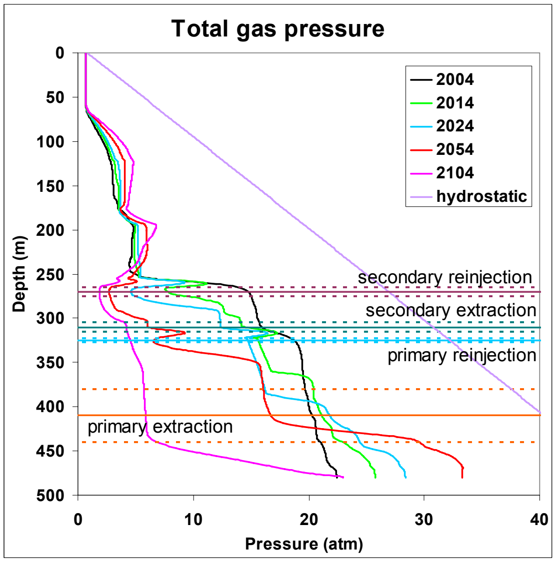


Figure 7.12.8 *Simulated total gas pressure profiles for Scenario RZ6.*

7.13 Summary of Attributes for all Scenarios

In the following Table 7.13 the *Attributes*, listed in the Tables 7.1 to 7.12, are compiled for the purpose of comparison. The implications of the different *Attributes* are discussed in the Section 7.1 to 7.12. A cross-comparison of the important *Attributes* is provided in the Consequence Table 2.4.1.

Table 7.13 ***Design Parameters used for all Scenarios and comparison of the Attributes after 0, 50 and 100 yr of simulations***

Scenario		0	IZ1	IZ2	IZ3	IZ4	IZ5	PR1	RZ1	RZ2	RZ3	RZ4	RZ5	RZ6
Design Parameters														
CH_4 re-injected	%		5.9	30	15	5.9	30	5.9	5	5	3.4	6	3.4	RZ4->5
CO_2 re-injected	%		60	60	90	60	60	60	78	78	46	60 (1) 55 (2)	50	RZ4->5
Dilution water withdrawal depth	m		40	10	50									
Dilution factor	-		2	1.1	1									
Withdrawal (1)	$m^3 s^{-1}$		70	70	70	70	70	70	70	52.5	52.5	23	70	RZ4->5
Withdrawal depth (1)	m		475	320	350	475	320	475	475	400	400	410	400	RZ4->5
Withdrawal range (1)	m		10	10	20	10	10	10	10	160	160	60	160	RZ4->5
Re-injection depth (1)	m		150	90	90	150	190	240	290	400	400	325	270	RZ4->5
Re-injection range (1)	m		100	40	20	100	10	60	30	160	160	5	10	RZ4->5
Withdrawal (2)										17.5	17.5	47		RZ4->5
Withdrawal depth (2)	m									290	290	310		RZ4->5
Withdrawal range (2)	m									30	30	10		RZ4->5
Re-injection depth (2)	m									290	290	270		RZ4->5
Re-injection range (2)	m									30	30	10		RZ4->5
2004														
PO_4 flux 80 m depth	10^3 tyr^{-1}	1.9	4.0	2.5	2.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
NH_4 flux 80 m depth	10^3 tyr^{-1}	15.9	34.3	20.9	24.6	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
Schmidt stability	10^{14} J	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
CH_4 in the lake (i)	km^3	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6	64.6
CH_4 extractable (ii)	km^3	42.3	42.3	42.3	42.3	42.3	42.3	42.3	42.3	42.3	42.3	42.3	42.3	42.3
CO_2“ in the lake	km^3	290	290	290	290	290	290	290	290	290	290	290	290	290
Scenario		**0**	**IZ1**	**IZ2**	**IZ3**	**IZ4**	**IZ5**	**PR1**	**RZ1**	**RZ2**	**RZ3**	**RZ4**	**RZ5**	**RZ6**

Table 7.13 *Continuation*

Scenario		0	IZ1	IZ2	IZ3	IZ4	IZ5	PR1	RZ1	RZ2	RZ3	RZ4	RZ5	RZ6
2054														
PO_4 flux in 80 m depth	10^3 tyr^{-1}	2.4	11.7	3.9	6.3	4.8	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
PO_4 flux vs. scenario 0		-	4.9	1.6	2.6	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
NH_4 flux in 80 m depth	10^3 tyr^{-1}	21.0	113.9	37.3	61.8	43.8	20.9	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Schmidt stability	10^{14} J	8.7	3.2	5.6	4.5	5.1	7.7	7.6	8.9	8.8	8.0	8.4	8.0	8.4
Stability vs. scenario 0		-	0.37	0.64	0.52	0.59	0.89	0.87	1.02	1.01	0.92	0.97	0.92	0.97
CH_4 in the lake (i)	km^3	81.7	28.7	56.2	47.4	35.9	60.1	35.5	44.1	54.2	53.2	48.9	42.3	48.7
CH_4 extractable (ii)	km^3	58.9	14.2	31.8	24.4	7.6	33.8	5.1	20.9	33.9	33.1	24.3	20.5	24.5
CH_4 to turbines (iii)	km^3		47.3	20.8	32.6	47.2	20.3	47.1	38.3	28.3	29.3	33.7	40.1	32.1
Sum (i) +(iii)	km^3		75.9	77.0	80.0	83.1	80.4	82.6	82.4	82.4	82.5	82.5	82.5	80.8
Sum (ii) +(iii)	km^3	58.9	61.4	52.6	56.9	54.8	54.1	52.2	59.2	62.2	62.4	58.0	60.6	56.6
Average energy	MW		281	123	193	280	120	279	227	168	174	200	238	190
CO_2 in the lake	km^3	315	164	213	207	220	257	231	269	276	233	243	216	242
CO_2 removed	km^3		86	51	16	86	52	86	47	44	93	74	100	76
2104														
PO_4 flux in 80 m depth	10^3 tyr^{-1}	2.9	8.1	3.0	4.6	5.2	3.4	2.9	2.9	2.9	2.9	2.9	2.9	2.9
PO_4 flux vs. scenario 0			2.8	1.0	1.6	1.8	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0
NH_4 flux in 80 m depth	10^3 tyr^{-1}	26.0	82.1	29.4	44.7	46.1	30.4	26.2	26.0	26.0	26.0	26.0	26.0	25.9
Schmidt stability	10^{14} J	8.7	1.7	5.3	4.1	4.2	7.2	7.0	8.7	8.7	7.5	7.9	7.4	7.6
Stability vs. scenario 0		-	0.19	0.61	0.48	0.48	0.82	0.81	1.0	1.0	0.87	0.91	0.85	0.87
CH_4 in the lake (i)	km^3	96.3	18.2	60.8	49.3	31.5	61.7	30.4	39.3	51.2	49.8	44.1	35.4	35.9
CH_4 extractable (ii)	km^3	69.0	3.3	33.8	22.4	9.2	33.7	4.5	12.1	28.1	26.9	15.1	6.6	6.0
CH_4 to turbines (iii)	km^3		71.4	30.5	46.2	67.8	30.5	66.4	57.5	45.9	47.3	53.0	61.6	61.5
Sum (i) +(iii)	km^3		89.6	91.3	95.5	99.3	92.2	96.8	96.8	97.1	97.1	97.1	96.9	97.4
Sum (ii) +(iii)	km^3	69.0	74.6	64.3	68.5	77.0	64.2	70.9	69.6	74.0	74.2	68.1	68.2	67.5
Average energy	MW		212	90	137	201	90	197	171	136	140	157	183	182
CO_2 in the lake	km^3	336	86	193	177	182	241	204	251	263	199	209	172	182
CO_2 removed	km^3		119	69	22	120	79	133	85	79	151	125	163	151
Scenario		**0**	**IZ1**	**IZ2**	**IZ3**	**IZ4**	**IZ5**	**PR1**	**RZ1**	**RZ2**	**RZ3**	**RZ4**	**RZ5**	**RZ6**

IZ = Reinjection into Intermediate Zone; PR = Reinjection into Potential Resource Zone; RZ = Reinjection into Resource Zone
Descriptions of Scenarios in Table 2.3.2 and Section 5
Definition of Attributes in Section 6.

8. Appendix

8.1 AQUASIM

In order to support environmental scientists in finding an “adequate” model for the system investigated, often numerical software is necessary, which allows performing simulations using different models. The tasks of such models are:

- performing simulations,
- assessing the identifiably,
- estimating the values of model parameters (using measured data), and
- estimating prediction uncertainty.

The computer program AQUASIM (***Computer Program for Identification and Simulation of Aquatic Systems***) was developed to perform such analyses for technical and natural aquatic systems (Reichert 1994).

The lake compartment describes stratification, substance transport and transformation in the water column of the lake and at the sediment surface. The user of the program is free in specifying any set of dynamic model variables (concentrations, temperature, etc) and transformation processes within the compartments. Calculated results can be plotted to the screen (window interface version only), written to a post-script file for transfer to a printer, or written to a text file for external post-processing (Reichert 1994). Detailed descriptions, user manuals and tutorial models (demo version) can be downloaded at (see short description): **http://www.aquasim.eawag.ch/**.

The relative and absolute accuracies of the dynamic model variables were set according to the recommendation given in the AQUASIM manual (Reichert 1994), where detailed explanations are available (http://www.aquasim.eawag.ch). The accuracies for the simulated dynamic model variables (S, T, CH_4, CO_2) were set according to those recommendation and are listed in Table 8.1.

Table 8.1 ***Relative and absolute accuracies of dynamic model variables***

State variable	Value range	Units	Rel. accuracy	Abs. accuracy
Salinity S	1 to 6	kg m^{-3}	$1x10^{-6}$	$1x10^{-5}$
Temperature T	23 to 26	°C	$1x10^{-6}$	$1x10^{-4}$
CH_4	0 to 35	mol m^{-3}	$1x10^{-6}$	$1x10^{-4}$
CO_2	0 to 200	mol m^{-3}	$1x10^{-6}$	$1x10^{-3}$
PO_4	0 to 0.5	mol m^{-3}	$1x10^{-6}$	$1x10^{-6}$
NH_4	0 to 10	mol m^{-3}	$1x10^{-6}$	$1x10^{-5}$

8.2 Model parameters

Detailed explanations of the model parameters and their values, listed below (Tables 8.2.1 and 8.2.2), are given in Section 4. Detailed explanations concerning the assumed parameter errors (expressed in one standard deviation) are given in the sensitivity analysis Section 8.7 (Appendix). The following symbols are used:

z = depth [m] (positive downward)

A(z) = lake cross sectional area [km^2] as a function of depth (Figure 4.3.1).

dA/dz = area gradient [m^2 m^{-1} = m] as a function of depth shown in Figure 4.3.2. Because the cross sectional area of the lake decreases with depth, the areal gradient dA/dz [m] is negative.

$N^2 = (g/\rho)*(d\rho/dz)$ [s^{-2}] is water column stability (N = Brunt Väisälä frequency)

g = gravitational acceleration = 9.7758 m s^{-2}

p_{air} = atmospheric pressure = 0.843466 atm (1460 m above sea level)

T_{abs} = absolute temperature = T [°C] + 273.15°C

Table 8.2.1 ***Values and standard deviations (assumed) of parameters used for sensitivity analysis***

Parameters for sensitivity analysis	**Parameter value**	**Units**	**Standard deviation**
Areal CH_4 formation rate, $CH_{4,\text{formation rate}}$	120 10	g-C m^{-2} yr^{-1} mol m^{-2} yr^{-1}	12 1
Geothermal heat flux, $H_{geothermal}$	0.02	W m^{-2}	0.002
Turbulent diffusion K(z) above 120 m depth(1)	~$1.0x10^{-5}$, decreasing with depth	m^2 s^{-1}	10%
Energy dissipation ε below 120 m depth	$1.0x10^{-10}$	W kg^{-1}	$1.0x10^{-11}$
Ratio of double-diffusive transport K_T/K_S	10	-	1
Maximum of turbulent diffusion for salt below 120 m depth, $K_{S,\,max}$(1)	$1.0x10^{-5}$	m^2 s^{-1}	$1.0x10^{-6}$

(1) For the double-diffusive zone, we estimated the apparent diffusion coefficient to be different for heat (K_T) and for salt (K_S). We set the ratio K_T/K_S = 10, based on the analysis of measure profiles (Schmid et al 2010).

Table 8.2.2 ***Water input parameters and assumed standard deviations for the uncertainty analysis***

Water input parameters	Parameter value	Units	Std. dev.
Surface water input: S	0.1	kg m^{-3}	0.01
Surface water input: T	23.1	°C	0.1
Surface water input: PO_4	0.004	mol m^{-3}	0.0004
Surface water input: NH_4	0.043	mol m^{-3}	0.0043
Water input at 180 m depth: Q	22	m^3 s^{-1}	2.2
Water input at 180 m depth: S	2.1	kg m^{-3}	0.21
Water input at 180 m depth: T	23.7	°C	0.1
Water input at 180 m depth: CH_4	0	mol m^{-3}	0.040
Water input at 180 m depth: $CO_{2,total}$ (1)	28	mol m^{-3}	2.8
Water input at 180 m depth: PO_4	0.017	mol m^{-3}	0.0017
Water input at 180 m depth: NH_4	0.52	mol m^{-3}	0.052
Water input at 250 m depth: Q	15	m^3 s^{-1}	1.5
Water input at 250 m depth: S	2.7	kg m^{-3}	0.27
Water input at 250 m depth: T	23.3	°C	0.1
Water input at 250 m depth: CH_4	1.8	mol m^{-3}	0.18
Water input at 250 m depth: $CO_{2,total}$ (1)	45	mol m^{-3}	4.5
Water input at 250 m depth: PO_4	0.032	mol m^{-3}	0.0032
Water input at 250 m depth: NH_4	0.65	mol m^{-3}	0.065
Water input at 310 m depth: Q	1	m^3 s^{-1}	0.1
Water input at 310 m depth: S	3.4	kg m^{-3}	0.34
Water input at 310 m depth: T	25.2	°C	0.1
Water input at 310 m depth: CH_4	1.9	mol m^{-3}	0.19
Water input at 310 m depth: $CO_{2,total}$ (1)	53	mol m^{-3}	5.3
Water input at 310 m depth: PO_4	0	mol m^{-3}	0.0016
Water input at 310 m depth: NH_4	1.4	mol m^{-3}	0.14
Water input at 365 m depth: Q	1.5	m^3 s^{-1}	0.15
Water input at 365 m depth: S	5.5	kg m^{-3}	0.55
Water input at 365 m depth: T	24.5	°C	0.1
Water input at 365 m depth: CH_4	0	mol m^{-3}	0.19
Water input at 365 m depth: $CO_{2,total}$ (1)	130	mol m^{-3}	13
Water input at 365 m depth: PO_4	0.012	mol m^{-3}	0.0012
Water input at 365 m depth: NH_4	1.4	mol m^{-3}	0.14
Water input at 425 m depth: Q	0.8	m^3 s^{-1}	0.08
Water input at 425 m depth: S	5.8	kg m^{-3}	0.58
Water input at 425 m depth: T	25.3	°C	0.1
Water input at 425 m depth: CH_4	0	mol m^{-3}	0.19
Water input at 425 m depth: $CO_{2,total}$ (1)	130	mol m^{-3}	13
Water input at 425 m depth: PO_4	0	mol m^{-3}	0.0019
Water input at 425 m depth: NH_4	0	mol m^{-3}	0.040
Water input at 465 m depth: Q	1.25	m^3 s^{-1}	0.125
Water input at 465 m depth: S	6	kg m^{-3}	0.6
Water input at 465 m depth: T	26	°C	0.1
Water input at 465 m depth: CH_4	11	mol m^{-3}	1.1
Water input at 465 m depth: $CO_{2,total}$ (1)	170	mol m^{-3}	17
Water input at 465 m depth: PO_4	0.12	mol m^{-3}	0.012
Water input at 465 m depth: NH_4	3.0	mol m^{-3}	0.30

(1) CO_2 input is in form of $CO_{2,total}$. Speciation (Section 8.3) is defined by alkalinity (and pH) and varies (but only slightly) with time.

8.3 Formulas used in the model

Total gas pressure

$p_{total} = p_{CH4} + p_{CO2} + p_{N2,\,air}$ [atm]

assuming nitrogen is in equilibrium with the atmosphere in the whole lake.

Hydrostatic pressure

$p_{hydrostatic} = 1000\ \mathrm{kg\ m^{-3}} * g * z * 0.986923\times10^{-5}\ \mathrm{atm\ Pa^{-1}} + p_{air}$ [atm]

$g = 9.7758\ \mathrm{m\ s^{-2}}$, z = depth [m]

Partial pressure of nitrogen (N_2) in the air

$p_{N2,\,air} = 0.78084 * p_{air}$ [atm]

Partial pressure of CO_2 in the air

$p_{CO2,\,air} = 0.000383 * p_{air}$ [atm]

Partial pressure of CH_4 in the air

$p_{CH4,\,air} = 1.75\times10^{-6} * p_{air}$ [atm]

Alkalinity

$Alk = S * 11.96$ [mol m^{-3}]

(Correlation coefficient of 0.999976 for the measurements of 2006)

Partial pressure of dissolved CO_2

$p_{CO2} = H_2CO_3 / H_{CO2}$ [atm]

Henry constant for CO_2

$H_{CO2} = H0_{CO2} * P_{correction\ CO2} * f_{CO2}/p_{CO2} * 1000\ \mathrm{L\ m^{-3}})$

[mol m^{-3} atm^{-1}]

$f_{CO2}/p_{CO2} = \exp((B_{CO2} * p_{hydrostatic} * 101325\ \mathrm{Pa\ atm^{-1}}) / (8.3145\ \mathrm{J\ mol^{-1}\ K^{-1}} * T_{abs}))$

$B_{CO2} = (3.1653\times10^{-5} * T_{abs}^3 - 0.032796 * T_{abs}^2 + 12.0408 * T_{abs} - 1636.75) * 10^{-6}$

[m^3 mol^{-1}] (Esper et al 1995)

$H0_{CO2} = \exp(-58.0931 + 90.5069 * (100 / T_{abs}) + 22.294 * \ln(T_{abs} / 100) + S * (0.027766 - 0.025888 * (T_{abs} / 100) + 0.0050578 * (T_{abs} / 100)^2))$

[mol L^{-1} atm^{-1}] (Weiss 1974)

$P_{correction\ CO2} = \exp((-101325\ \mathrm{Pa\ atm^{-1}}\ (p_{hydrostatic} - 1\ \mathrm{atm}) * v_{mol,CO2}) / (8.3145\ \mathrm{J\ mol^{-1}\ K^{-1}} * T_{abs}))$ [-]

(Weiss 1974)

$v_{mol,CO2} = 3.23\times10^{-5}\ \mathrm{m^3\ mol^{-1}}$ is the partial molal volume of dissolved CO_2

Speciation of carbonates

$a_{CO2} = (1 + 10^{(pH - pK1)} + 10^{(2 * pH - pK1 - pK2)})^{-1}$ [-]

Carbonic acid

$H_2CO_3 = a_{CO2} * CO_{2,total}$ [mol m^{-3}]

Bicarbonate

$HCO_3^- = H_2CO_3 * 10^{(pH - pK1)}$ [mol m^{-3}]

Carbonate

$CO_3^{2-} = HCO_3^- * 10^{(pH - pK2)}$ [mol m^{-3}]

pH in equilibrium with alkalinity and CO_2 partial pressure

pH is calculated from the solution for the charge balance, based on alkalinity (Alk) and the distribution of the charges of HCO_3^- and of CO_3^{2-}.

$pH = -Log_{10}$ (H [mol L^{-1}]),
where H (concentration of protons) is given by the quadratic solution of

$H = 1000\ m^3\ L^{-1} * (10^{-pK1} * (Alk-CO_{2,total}) + (2 * Alk)^{-1} * [10^{-2*pK1} * (Alk-CO_{2,total})^2 - 4 * Alk * 10^{-(pK1+pK2)} * (Alk - 2 * CO_{2,total})]^{1/2})$ [mol L^{-1}]

First dissociation constant of CO_2

$pK_1 = 3404.71 / T_{abs} + 0.032786 * T_{abs} - 14.8435 - 0.071692 * S^{0.5} * (200.1/T_{abs} + 0.322) + 0.0021487 * S$ [-] (Cai and Wang 1998)

Second dissociation constant of CO_2

$pK_2 = 2902.39 / T_{abs} + 0.02379 * T_{abs} - 6.498 - 0.3191 * S^{0.5} * (-129.24 / T_{abs} + 1.4381) + 0.0198 * S$ [-] (Cai and Wang 1998)

CO_2 surface equilibrium concentration

$H_2CO_{3\ surface\ eq.} = H_{CO2} * p_{CO2,\ air}$ [mol m^{-3}]

Partial pressure of CH_4

$p_{CH4} = CH_4 / H_{CH4}$ [atm]

Henry constant for CH_4

$H_{CH4} = H0_{CH4} * P_{correction\ CH4} * f_{CH4}/p_{CH4} * 1000\ L\ m^{-3} / 0.986923\ atm\ bar^{-1}$
[mol m^{-3} atm^{-1}]

$H0_{CH4} = \exp(S * (0.027766 - 0.025888 * (T_{abs}/100) + 0.0050578*(T_{abs}/100)^2))* 1 / (10^{-5} * \exp(127.174 - 155.576/T_{abs} * 100 - 65.2553 * \ln(T_{abs} / 100) + 6.16976 * T_{abs} / 100)) * 55.5$ [mol L^{-1} bar^{-1}]
(Rettich et al 1981; Weiss 1974)

$f_{CH4}/p_{CH4} = \exp((B_{CH4} * p_{hydrostatic} * 101325\ Pa\ atm^{-1}) / (8.3145\ J\ mol^{-1}\ K^{-1} * T_{abs}))$
[-] (Weiss 1974)

$B_{CH4} = (8.708x10^{-6} * T_{abs}^3 - 0.009513 * T_{abs}^2 + 3.73 * T_{abs} - 539.7) * 10^{-6}$
[m^3 mol^{-1}] (Esper et al 1995)

$P_{\text{correction CH4}}$ = $\exp((-101325 \text{ Pa atm}^{-1} (p_{\text{hydrostatic}} - 1 \text{ atm}) * v_{\text{mol,CH4}})/ (8.3145 \text{ J mol}^{-1} \text{ K}^{-1} * T_{\text{abs}}))$ [-]

(Weiss 1974)

$v_{\text{mol,CH4}}$ = $3.6\text{x}10^{-5}$ m^3 mol^{-1} is the partial molal volume of dissolved CH_4

CH_4 surface equilibrium concentration

$CH_{4 \text{ surface eq.}} = H_{CH4} * p_{CH4, \text{ air}}$ [mol m^{-3}]

Water density

$\rho(S, T, CH_4, CO_2) = 1000 \text{ L m}^{-3} * \rho(T) * (1 + 0.75\text{x}10^{-3} \text{ m}^3 \text{ kg}^{-1} * S + 0.284\text{x}10^{-6} \text{ m}^3 \text{ g}^{-1} * 44.0099 \text{ g mol}^{-1} * CO_2 - 1.25\text{x}10^{-6} \text{ m}^3 \text{ g}^{-1} * 16.04 \text{ g mol}^{-1} * CH_4)$ [kg m^{-3}]

(Schmid et al 2004)

S = salinity [kg m^{-3}]

$\rho(T) = 0.999839 + 6.7914\text{x}10^{-5} * T - 9.0894\text{x}10^{-6} * T^2 + 1.0171\text{x}10^{-7} * T^3 - 1.2846\text{x}10^{-9} * T^4 + 1.1592\text{x}10^{-11} * T^5 - 5.0125\text{x}10^{-14} * T^6$ [kg L^{-1}]

(Chen and Millero 1977)

Turbulent vertical diffusion coefficient

a) From surface to 120 m depth:

K (0 m)	= $2\text{x}10^{-4}$ m^2 s^{-1}
K (18 m)	= $2\text{x}10^{-4}$ m^2 s^{-1}
K (35 m)	= $1\text{x}10^{-5}$ m^2 s^{-1}
K (58 m)	= $5\text{x}10^{-6}$ m^2 s^{-1}
K (68 m)	= $1\text{x}10^{-6}$ m^2 s^{-1}
K (120 m)	= $1.92\text{x}10^{-7}$ m^2 s^{-1}

b) Below 120 m depth:

$K = 0.15 * \varepsilon / N^2$ [m^2 s^{-1}]

(factor 0.15 taken from Wüest and Lorke (2003))

Maximal turbulent vertical heat diffusion coefficient (below 120 m depth)

$K_{max} = 1\text{x}10^{-4}$ m^2 s^{-1}

Geothermal heat flux rate

$$r_{\text{geo thermal heat flux}} = -\frac{dA/dz * H_{\text{geothermal}}}{A(z) * \rho C_p} \qquad [°C\ s^{-1}]$$

($\rho C_p = 4.18\text{x}10^6$ J m^{-3} K^{-1}; $H_{\text{geothermal}} = 0.02$ W m^{-2})

CH_4 oxidation rate

$r_{\text{CH4 oxidation}} = 10^{-6}$ s^{-1} (if z < 60 m depth) or 0 (else)

(the process is self-limited as the rate is multiplied with the CH_4 concentration; the absolute value of this rate is irrelevant as long as large enough to remove most of the CH_4).

Primary production rate

$r_{primary\ production} = 10^{-6}\ s^{-1}$ (if $z < 50$ m depth) or 0 (else)
(the process is self-limited as the rate is multiplied with the PO_4 concentration; the absolute value of this rate is irrelevant as long as large enough).

Methane formation rate

$$r_{CH_4\ formation} = -\frac{dA/dz * CH_{4\,area\ formation\ rate}}{A(z)} \qquad [\mathrm{mol\ m^{-3}\ s^{-1}}]$$

($CH_{4,\ formation\ rate} = 3.2\mathrm{x}10^{-7}$ mol m^{-2} s^{-1} is the areal rate of CH_4 *formation at the sediment; in this report $CH_{4,\ formation\ rate}$ = 120 g-C m^{-2} yr^{-1} also given in units of C).*

8.4 Dynamic processes and stoichiometry

Dynamic processes describe transformations by their temporal rate of change of the dynamic model variables. Usually, a biological or chemical process transforms several substances in fixed stoichiometric proportions. Therefore, it is advantageous to separate a “common” factor as a process rate, and to describe a process by this rate and by stoichiometric coefficients for all substances involved in the process. The contribution of a process to the temporal change of the concentration of a substance is then given as the product of the “common” process rate and the substance-specific stoichiometric coefficient.

This decomposition of process rates into a “common” process rate and individual stoichiometric coefficients is not unambiguous. To make it unambiguous, one of the stoichiometric coefficients is set to unity (Reichert 1994). We use the following coefficients in this model:

The **geothermal heat flux** with the rate $r_{geothermal\ heat\ flux}$ affects
T: +1

Primary production with the rate $r_{primary\ production} * PO_4$ affects
PO_4: -1
NH_4: -13.9
CO_2: -216
(PO_4-limitation for algal growth; $r_{primary\ production}$ contains also Michaelis-Menten limitation in NH_4)

The **aerobic CH_4 oxidation** with the rate $r_{CH4\ oxidation} * CH_4$ affects
CH_4: -1
CO_2: +1
(Self-limiting process in CH_4)

Biomass mineralization with the rate $r_{CH4\ formation}$ affects
CH_4: +1

CO_2: +1
NH_4: +0.14
PO_4: +0.0089
(Values from the measured stoichiometric coefficients of the organic material found in the sediment traps and cores in 2007 (molar ratios):
C:P = 216, and N:P = 13.9 and C:N = 15.8 (Pasche et al submit);
note that the carbon is transformed in equal parts to CH_4 and CO_2).

8.5 Exchange at the lake surface

The surface exchange can either be an input (inflow, gas exchange gain) or an output (outflow, gas exchange loss), here described as a flow across the lake surface. Note that this flux represents a mass (or temperature) flux per unit lake surface area and per unit of time. A positive flux value represents a flux into the lake, a negative value a flux out of the lake. The fluxes are driven by the differences of the concentrations (temperature) between the surface water (dynamic model variables) and the concentration in the atmosphere. In the model, we use the following parameterizations (Reichert 1994):

Gas exchange velocity
$v_{\text{gas exchange}}$ = gas exchange velocity = $1.0\text{x}10^{-5}$ m s^{-1}
(typical value for an average surface wind speed of about 3 m s^{-1}; positive flux = flux into lake water; negative flux = flux from water to atmosphere).

CH_4 surface flux (in / out)
$v_{\text{gas exchange}} * (CH_{4\text{ surface eq.}} - CH_4)$ [mol m^{-2} s^{-1}]

CO_2 surface flux (in / out)
$v_{\text{gas exchange}} * (CO_{2,\text{surface eq.}} - CO_2)$ [mol m^{-2} s^{-1}]

Temperature surface flux
$1\text{x}10^{-3} * (23.06\ °C - T_{\text{surface}})$ [°C m s^{-1}]

8.6 Standard units used

The standard units used in the model are:

[s]	for time
[m]	for length
[kg]	for masses
[mol]	for amounts (number) of a substance (gases, nutrients)
[atm]	for pressures (1 atm = 101,325 Pa).

8.7 Sensitivity analysis

The sensitivity analysis combines the tasks of **uncertainty analysis** and **identifiability analysis.**

(*i*) ***Uncertainty analysis*** - In uncertainty analysis, the uncertainty of model parameters is propagated to the uncertainty of the model results. In the current version of AQUASIM only the simplest error propagation method is implemented: The linearized propagation of standard deviations of uncorrelated parameters.

(ii) ***Identifiability analysis*** - The goal of the identifiability analysis is to check if model parameters can be uniquely determined by using the available (measured) data and to estimate the uncertainty of the parameter estimations.

The parameter values and their assumed uncertainty (expressed as one standard deviation) used in the model are listed in Tables 8.2.1 and 8.2.2 (Appendix). For temperature the standard deviation was set to 0.1 °C. For all parameters defining concentrations (state variables) the following assumptions have been made: (i) for subaquatic sources with concentration value 0 (zero) the standard deviation was set to 1% of the measured profile value (Table 8.8) at its corresponding depth; (ii) for all the other parameters a standard deviation of 10% was assumed (Table 8.2.2). Similar uncertainties for all parameters were used in order to compare the sensitivity of the model results to these parameters. We expect that the real uncertainties, especially of concentrations in the inflow water of the subaquatic sources, are higher than 10%. In that sense, the sensitivity plots shown below should not be interpreted in terms of absolute uncertainties. However, an uncertainty of 15 or 20% for all concentrations would not change the message to be drawn from the figures.

The lower and upper boundaries of the dynamic model variables (concentrations, temperature) are shown in Figures 8.7.1 to 8.7.6 for the years 2054 and 2104 (100 yr of simulation). The output errors result from the errors of the parameters used in the model (Tables 8.2.1 and 8.2.2).

The contributions to the errors of the dynamic model variables (concentrations, temperature), which are influenced by the 10 most important factors, are shown in Figures 8.7.7 to 8.7.12.

It is obvious, that most of the uncertainty of the simulated model variables stems from the estimated values of the subaquatic sources. The deepest source at 465 m depth has generally the strongest influence on the simulated model variables (Figures 8.7.7 to 8.7.12). The analysis shows also that the salinity and CO_2 content of the deepest sources have an (indirect) influence on the distribution of the gases and nutrients, because salinity and CO_2 influence the density and thereby the stratification.

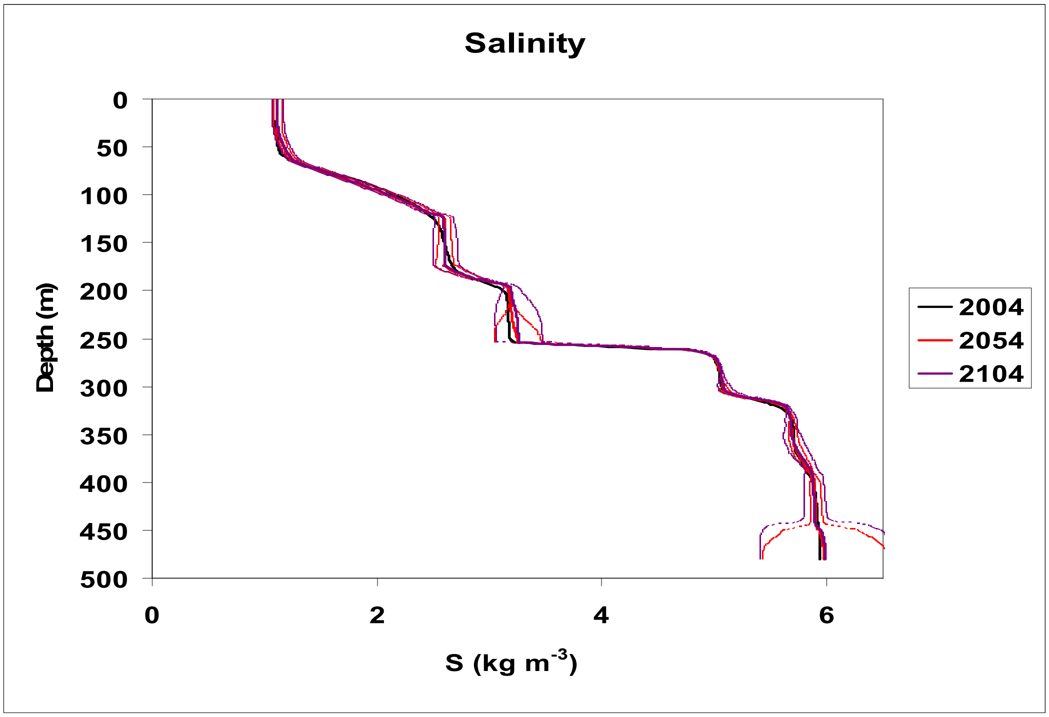


Figure 8.7.1 *Lower and upper boundaries for salinity (one standard deviation). The three reaches of large uncertainties are due to subaquatic sources at the corresponding depth.*

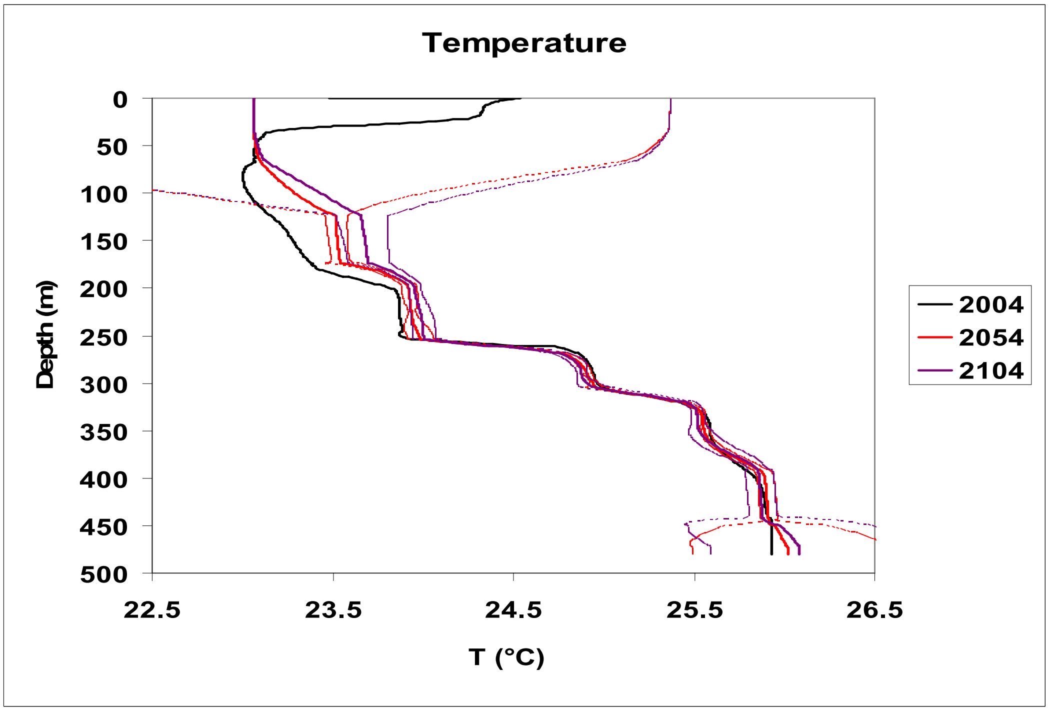


Figure 8.7.2 *Lower and upper boundaries for temperature (one standard deviation). The large uncertainties in 250 m depth and at the deepest location are due to subaquatic sources. The uncertainty at the surface is due to inadequate boundary conditions (natural variability).*

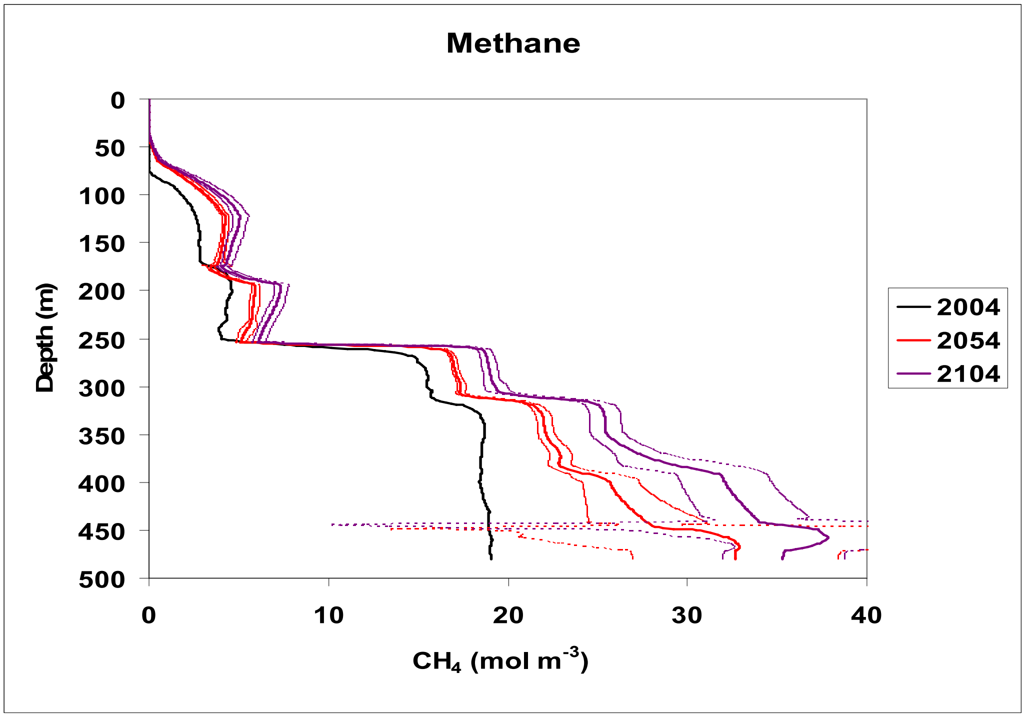


Figure 8.7.3 *Lower and upper boundaries for CH_4 (one standard deviation). Local maxima of the uncertainties are due to subaquatic sources (error in flow) and the overall uncertainty is due to the poorl-known CH_4 new formation rate.*

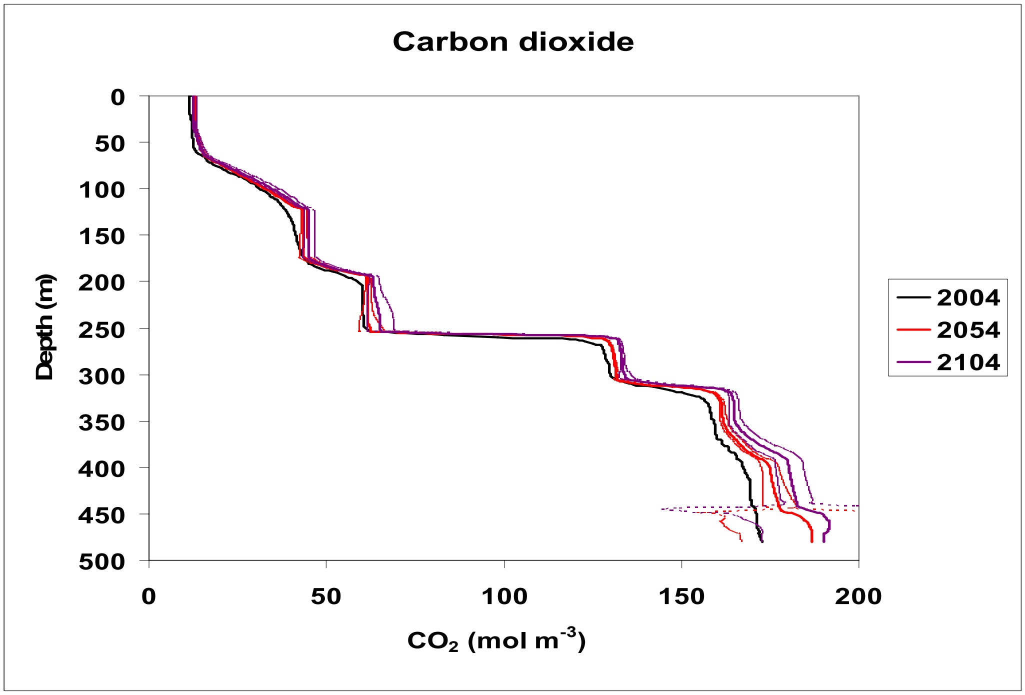


Figure 8.7.4 *Lower and upper boundaries for $CO_{2,total}$ (one standard deviation). Local maxima of the uncertainties are due to subaquatic sources and the overall uncertainty is due to the poorly-known rate of degradation of organic matter.*

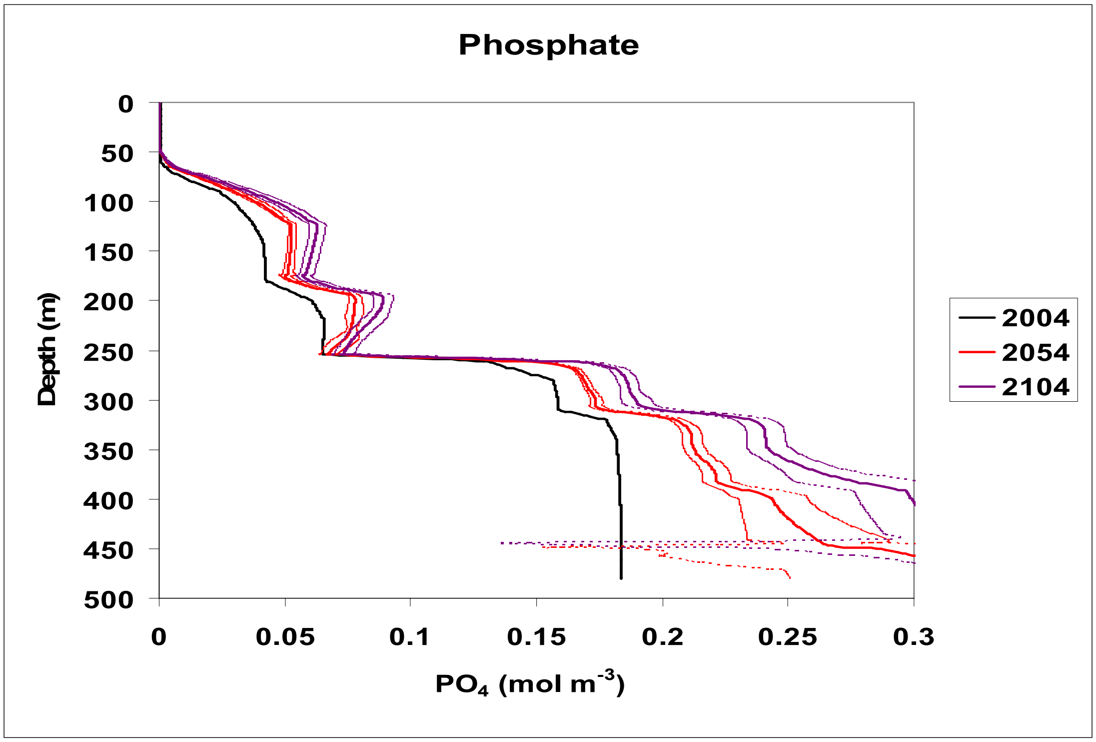


Figure 8.7.5 *Lower and upper boundaries for* PO_4 *(one standard deviation). Local maxima of the uncertainties are due to subaquatic sources (error in flow and* PO_4 *content) and the overall uncertainty is due to the poorly-known rate of degradation of organic matter.*

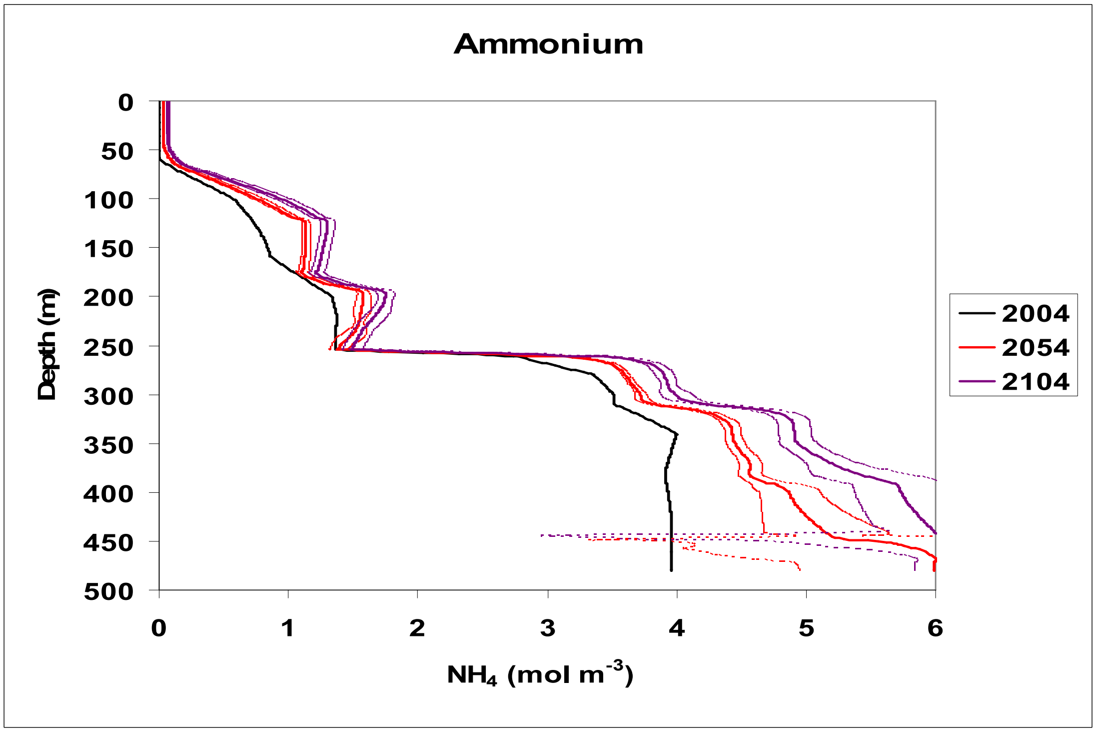


Figure 8.7.6 *Lower and upper boundaries for* NH_4 *(one standard deviation). Local maxima of the uncertainties are due to subaquatic sources (error in flow and* NH_4 *content) and the overall uncertainty is due to the poorly known rate of degradation of organic matter.*

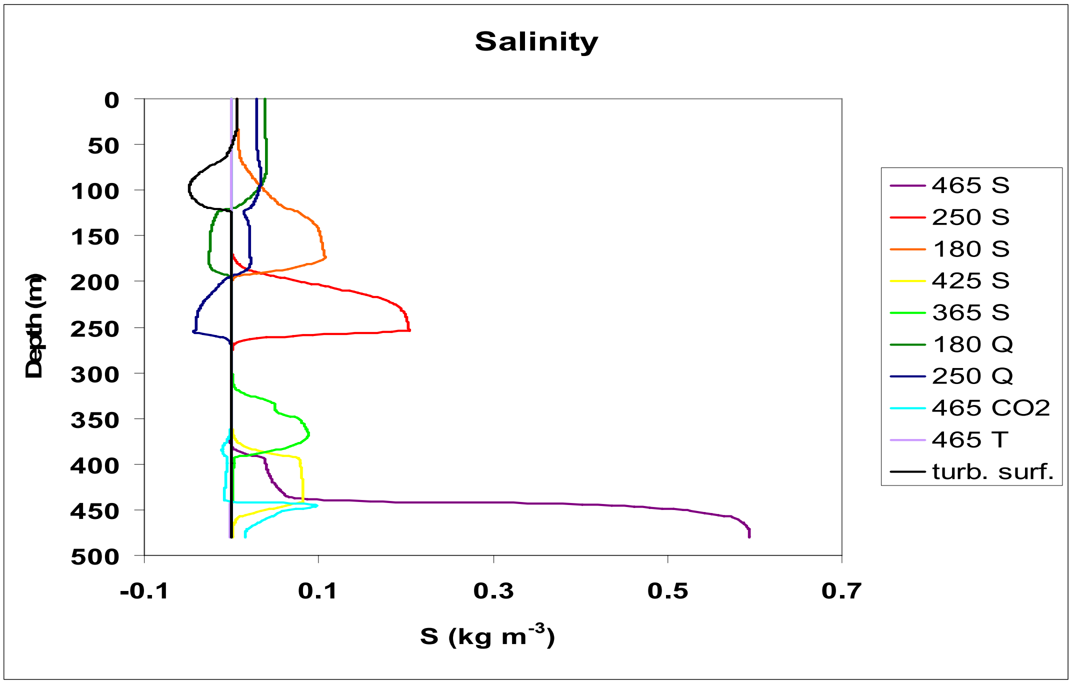


Figure 8.7.7 *Error contributions for salinity determined by identifiability analysis: The large uncertainty contributions are due to the errors of the concentrations of the three deepest sources.*

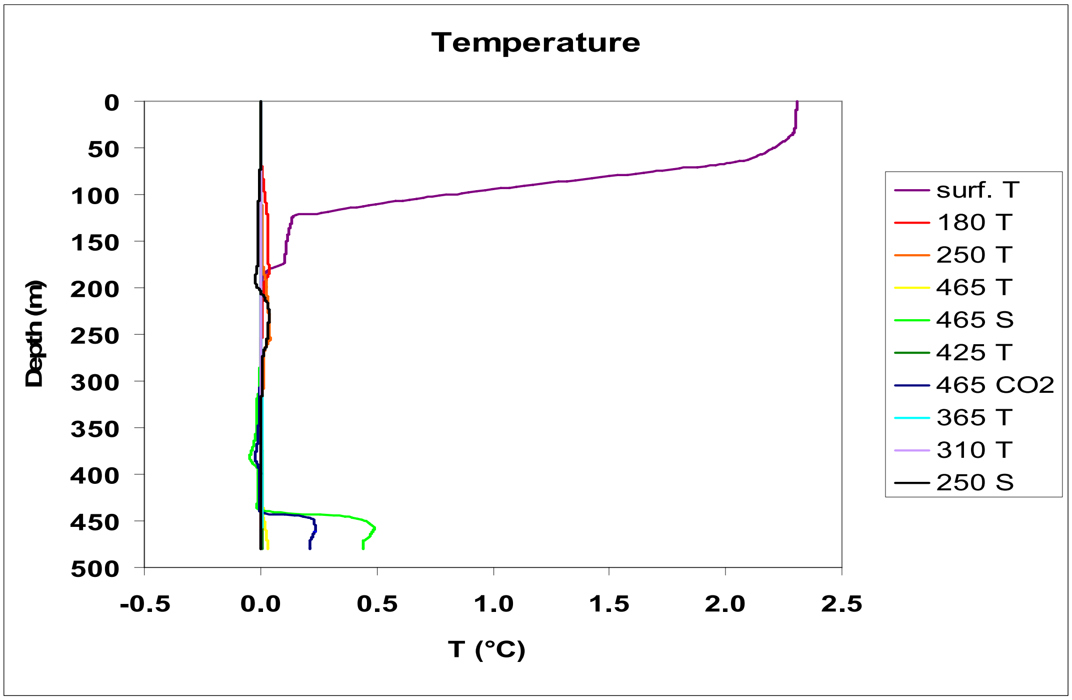


Figure 8.7.8 *Error contributions for temperature determined by identifiability analysis. The largest contribution is due to the variable surface temperature. It is interesting to note that the temperature at maximum depth is more (indirectly) influenced by the salinity and* CO_2 *content of the sources than by their temperatures.*

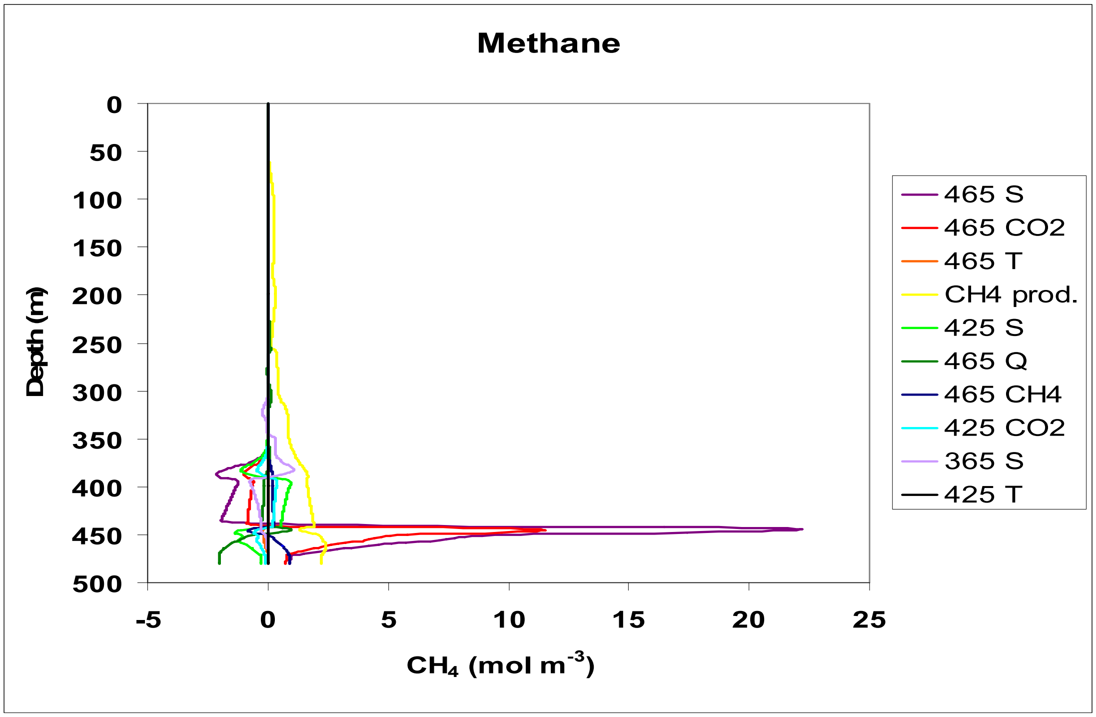


Figure 8.7.9 *Error contributions for CH_4 determined by identifiability analysis. The large uncertainty contributions are due to the error of the CH_4 new formation rate. Note again the strong (indirect) influence by the salinity and CO_2 content of the deepest sources.*

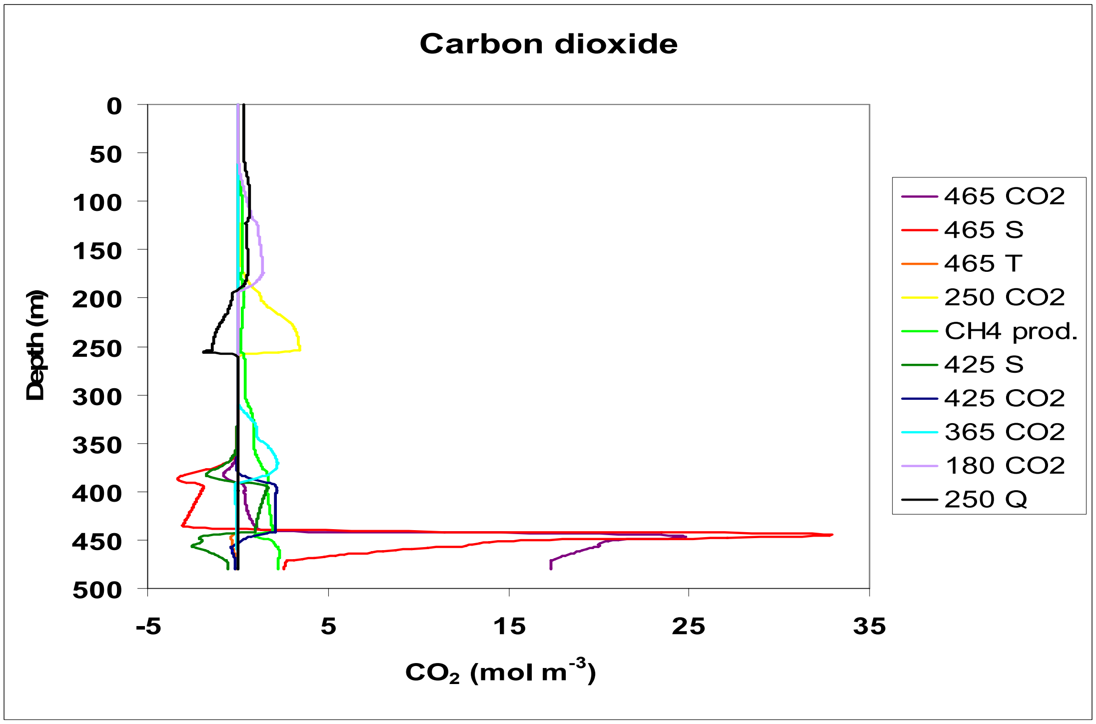


Figure 8.7.10 *Error contributions for CO_2 determined by identifiability analysis. The large uncertainty contributions are due to the concentrations errors of the deep-water subaquatic sources. In the deepest reaches, salinity influences the density and thereby the CO_2 vertical distribution.*

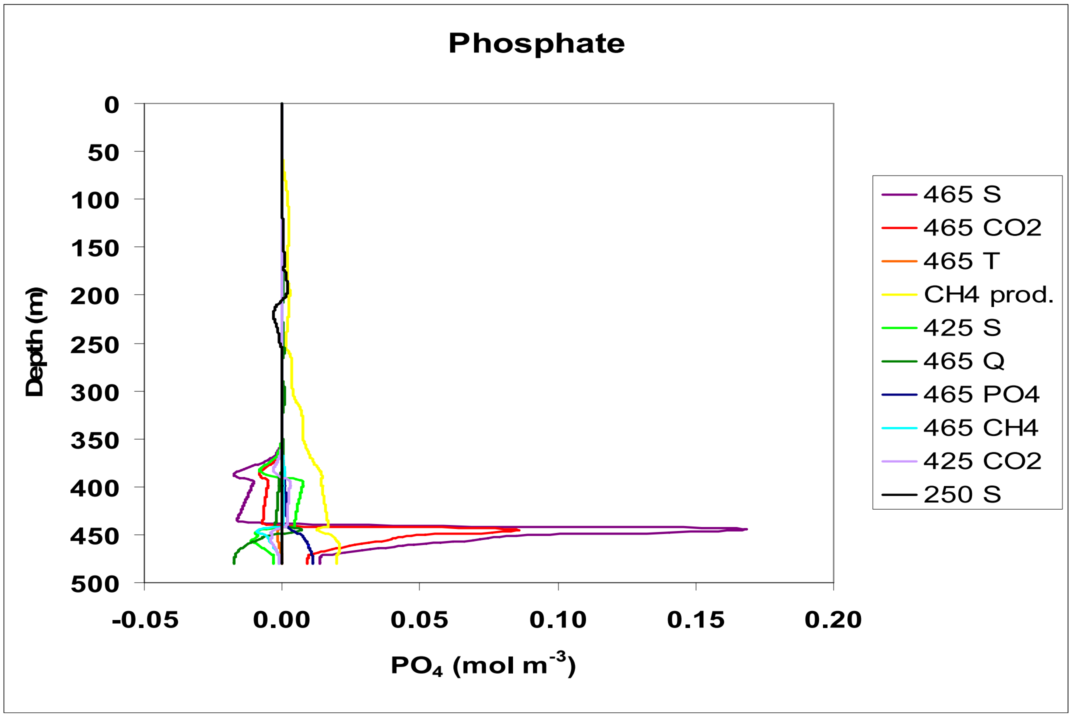


Figure 8.7.11 *Error contributions for PO_4 determined by identifiability analysis. The large uncertainty contributions are due to the rate of degradation of organic matter. Note again the strong (indirect) influence by the salinity and CO_2 content of the deepest sources.*

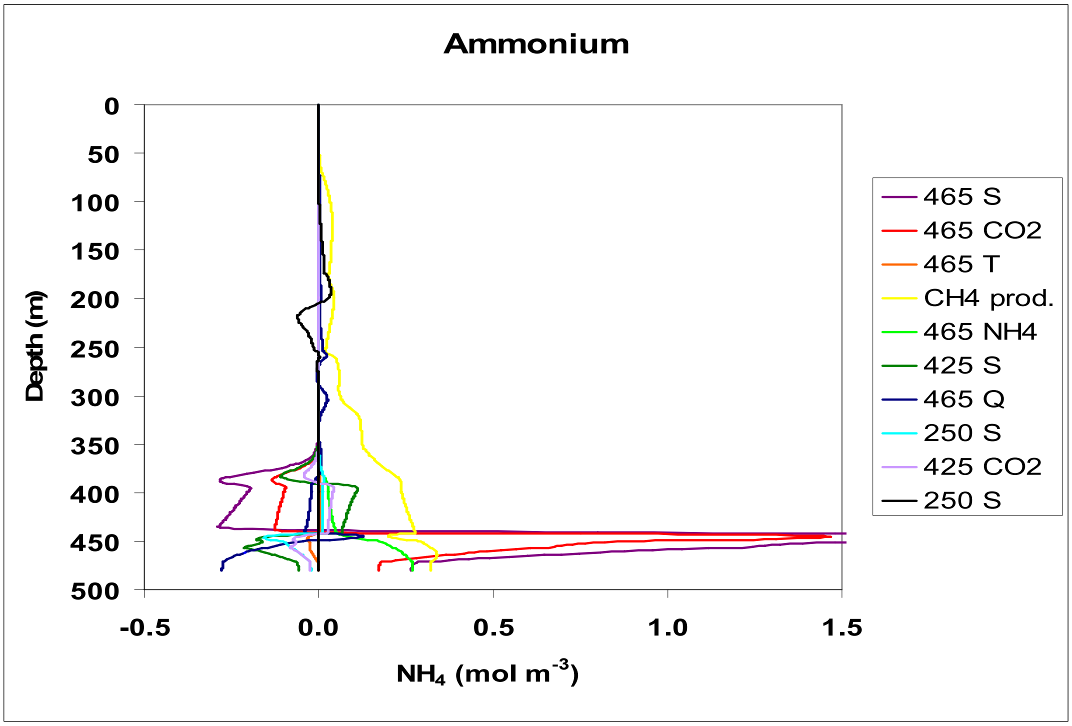


Figure 8.7.12 *Error contributions for NH_4 determined by identifiability analysis. The large uncertainty contributions are due to the rate of degradation of organic matter. Note again the strong (indirect) influence by the salinity and CO_2 content of the deepest sources.*

8.8 Data profiles used in the model

Table 8.8 ***Vertical profiles (2004) of S, T, CH_4, CO_2, PO_4, NH_4, density and w used for the model simulations***

Depth	**Area**	**Vol**	**S**	**T**	**CH_4**	**$CO_{2,\ total}$**	**PO_4**	**NH_4**	**Density**	**w**
m	km^2	km^3	kg m^{-3}	°C	mol m^{-3}	mol m^{-3}	mol m^{-3}	mol m^{-3}	kg m^{-3}	m yr^{-1}
0	2’368	551.3	1.074	23.48	0	11.70	0.00037	0	998.373	1.520
20	2’256	505.0	1.078	24.29	0	11.51	0.00036	0	998.174	0.577
40	2’141	461.0	1.106	23.12	0	12.18	0.00035	0	998.490	0.612
60	2’022	419.3	1.166	23.06	0.105	13.18	0.00037	0.0039	998.558	0.648
80	1’903	380.0	1.666	23.00	0.729	21.41	0.01286	0.2733	999.036	0.689
100	1’789	343.0	2.146	23.03	1.791	31.09	0.02917	0.5706	999.488	0.733
120	1’675	308.3	2.442	23.13	2.538	37.71	0.03658	0.7047	999.754	0.783
140	1’580	275.7	2.575	23.24	2.819	40.67	0.04114	0.8075	999.857	0.830
160	1’486	245.0	2.620	23.31	2.842	42.01	0.04208	0.8643	999.890	0.882
180	1’386	216.2	2.708	23.42	4.046	44.85	0.04251	1.0949	999.943	0.784
190	1’335	202.6	2.899	23.61	4.495	51.91	0.05120	1.2124	1000.118	0.553
200	1’284	189.5	3.120	23.81	4.603	58.56	0.06034	1.3300	1000.315	0.480
220	1’205	164.6	3.166	23.87	4.297	60.06	0.06559	1.3721	1000.359	0.512
240	1’127	141.2	3.173	23.88	3.873	60.33	0.06530	1.3667	1000.373	0.547
250	1’091	130.1	3.178	23.87	4.043	60.82	0.06529	1.3666	1000.383	0.566
260	1’055	119.4	4.280	24.44	10.18	98.47	0.12213	2.5862	1001.411	0.136
270	1’019	109.0	4.990	24.87	14.80	127.5	0.14180	3.0255	1002.104	0.141
280	984	98.93	5.032	24.92	15.33	128.4	0.15585	3.3453	1002.123	0.146
300	920	79.70	5.062	24.96	15.46	129.9	0.15861	3.5097	1002.149	0.156
310	870	70.73	5.193	25.09	15.67	135.2	0.15867	3.5135	1002.276	0.149
320	820	62.26	5.525	25.39	17.39	150.0	0.17669	3.6871	1002.596	0.137
330	770	54.29	5.666	25.54	18.43	156.9	0.17965	3.8409	1002.728	0.146
340	720	46.82	5.697	25.58	18.70	158.1	0.18175	3.9932	1002.750	0.156
360	594	33.62	5.711	25.60	18.58	159.5	0.18237	3.9563	1002.775	0.157
380	459	23.02	5.781	25.70	18.47	163.4	0.18290	3.9106	1002.850	0.162
400	362	14.76	5.874	25.84	18.42	167.5	0.18326	3.9317	1002.936	0.173
420	274	8.354	5.904	25.89	18.67	169.4	0.18361	3.9546	1002.965	0.198
440	187	3.702	5.914	25.91	18.93	169.7	0.18362	3.9551	1002.965	0.246
460	84	0.939	5.932	25.93	19.10	171.3	0.18362	3.9551	1002.988	0.322
480	12	0.012	5.932	25.93	19.03	172.6	0.18362	3.9551	1003.007	0
485	0	0								0

Data sources:	Schmid et al (2005a,b)
Legend:	Vol is the total vertically integrated lake volume below the given depth; S = salinity; T = temperature; $CO_{2,total}$ is the sum of all carbonate components as defined in Section 4.10: w = the upwelling velocity (uplift water flow Q(z) divided by lake area A(z) at depth z).

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