**African lakes and reservoirs -**

**Assessments of stratification-related management problems**

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# Typical environmental engineering questions

## Practical lake problems considered in this hour

→ Closing the water (and/or salt) balance

→ Maintaining oxic deep-water for downstream rivers / for drinking water

→ Using lake water heat for heating / cooling

→ Effect of hydropower operation

→ Extraction of methane from Lake Kivu

→ System analytical approach

# Basics of lake functioning

## Key elements characterising lake-ecological functioning

→ Hydrological balance (riverine and subaquatic inflows, evaporation)

→ Seasonal stratification (temperature, salinity / dissolved solids)

→ Seasonal deep (convective) mixing ($O_2$-replenishment)

→ Primary production / OM degradation (nutrient level; Redfield-stoichiometry)

→ Particle budget (algal production, allochthonous inflow, sedimentation)

# Establishing water balances using salinity (conductivity) – Lake Tanganyika

**Water balance**

$$Q_{Riv} + Q_{Prec} = E + Q_{Outf}$$

**Salt balance**

$$Q_{Riv} \times S_{Riv} = Q_{outf} \times S_{Outf}$$

**Known terms are:** $Q_{Prec}$ = 35.5 km$^3$/yr; $Q_{Outf}$ = 9.7 km$^3$/yr;

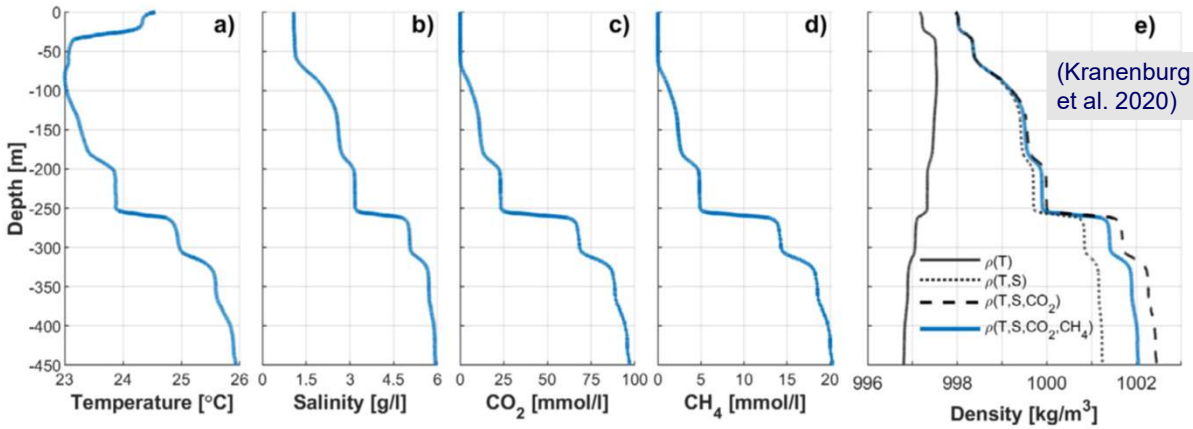
$S_{Rivr}$ = 0.220 mS/cm; $S_{Lake} = S_{Outf}$ = 0.660 mS/cm

**Solutions:** $Q_{Riv}$ = 3x9.7 = 29.1 km$^3$/yr; E = 55 km$^3$/yr

E = 1.7 m/yr (for surface area of 32,600 km$^2$)

Flushing time = 1950 yr (for lake volume of 18,800 km$^3$)

## Density of water = f(T, TDS, P, gases) – Lake Kivu




(Kranenburg et al. 2020)

$$\rho(T,S,CO_2,CH_4) = \rho(T)\cdot(1+\beta\cdot S+\beta_{CO2}\cdot CO_2+\beta_{CH4}\cdot CH_4)$$

## Density stratification in freshwater

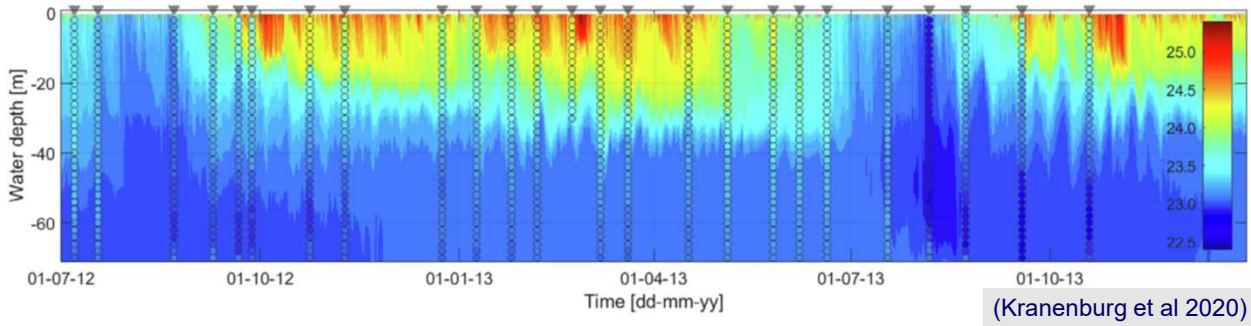
**Density(z) = f(T(z), TDS(z), P(z), Gases(z))**

$$\rho = \rho(T)\cdot\left(1+\beta_{TDS}\cdot TDS+\beta_P\cdot P+\beta_{CO2}\cdot[CO_2]+h.o.\right)$$

**Stability $N^2$(z) = f(T(z), TDS(z), P(z), Gases(z))**

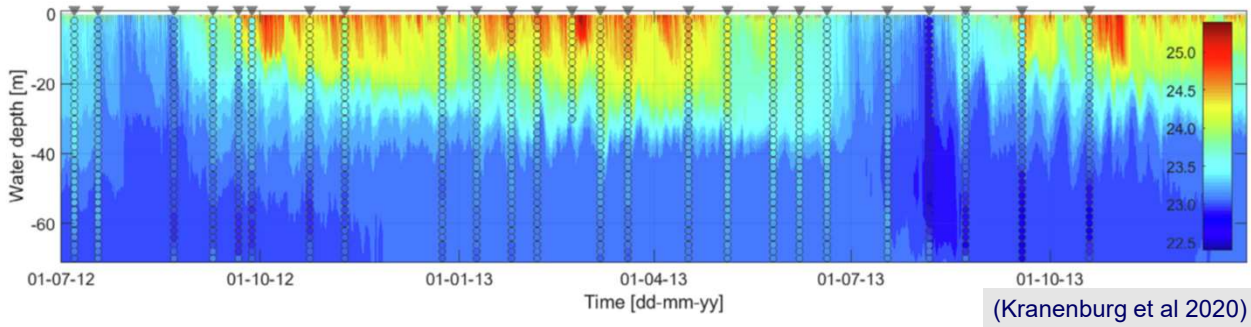
$$N^2 = g\cdot\left[\alpha\cdot\left(\frac{\partial T}{\partial z}+\Gamma\right)-\beta_{TDS}\cdot\frac{\partial TDS}{\partial z}-\beta_P\cdot\frac{\partial P}{\partial z}-\beta_{CO2}\cdot\frac{\partial[CO_2]}{\partial z}+h.o.\right]$$

## Seasonal stratification dynamics – Lake Kivu




(Kranenburg et al 2020)

## Seasonal temperature stratification – Lake Kivu




(Kranenburg et al 2020)

### Characteristics

→ Seasonal cycle: stratified – homogenized – stratified

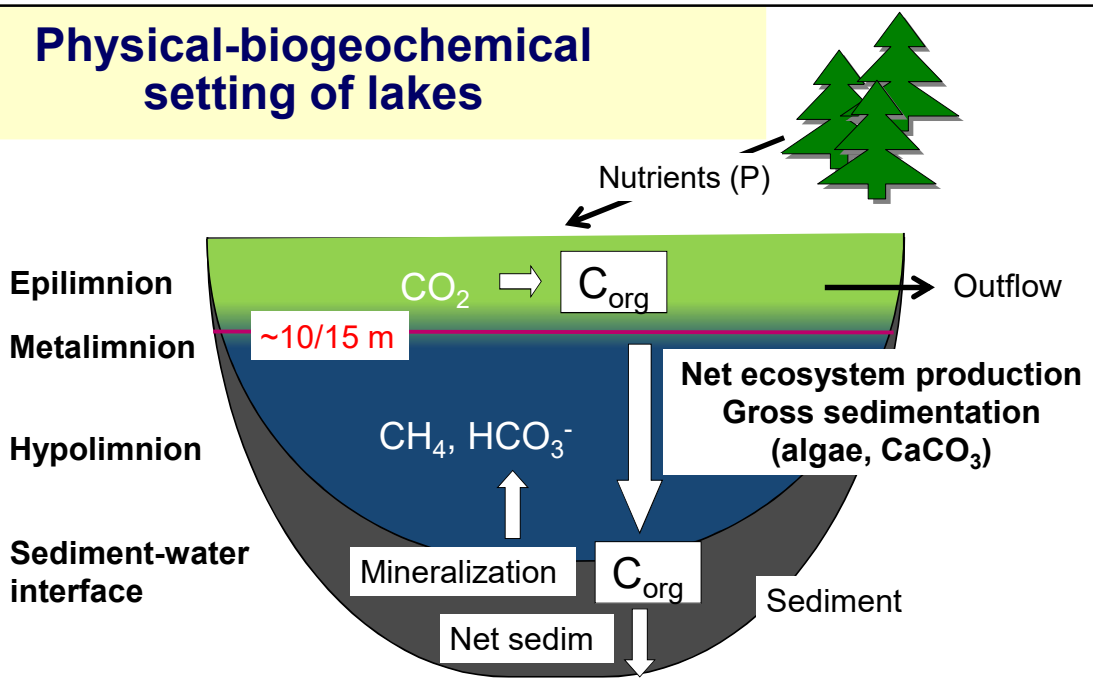
→ Dry season (Jun/Jul/Aug) cools surface → homogenous Temp profile in Sep

→ Water column stability $N^2$ is strongest in transition zone (~20 m; metalimnion)

→ Metalimnion: Vertical diffusion weak/suppressed (~dissipation/stability; $\varepsilon/N^2$)

→ Separation of processes in epilimnion versus hypolimnion

## Physical-biogeochemical setting of lakes




## Primary production / degradation of algae
## Redfield ratios for C, N, P

P

N

C

$106\ H_2CO_3 + 16\ NO_3^- + HPO_4^{2-} + 16\ H_2O + 18\ H^+ \rightarrow$

$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\ O_2$

Net ecosystem production — Gross sedimentation

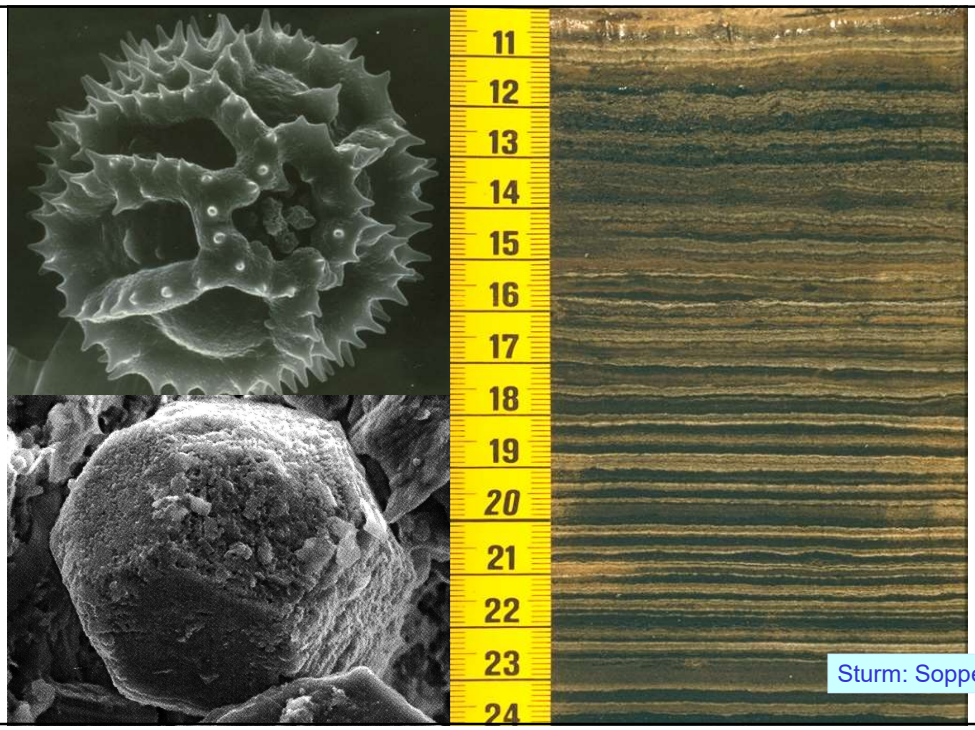
$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\ O_2 \rightarrow$

$106\ H_2CO_3 + 16\ NO_3^- + HPO_4^{2-} + 16H_2O + 18\ H^+$

Net sedimentation

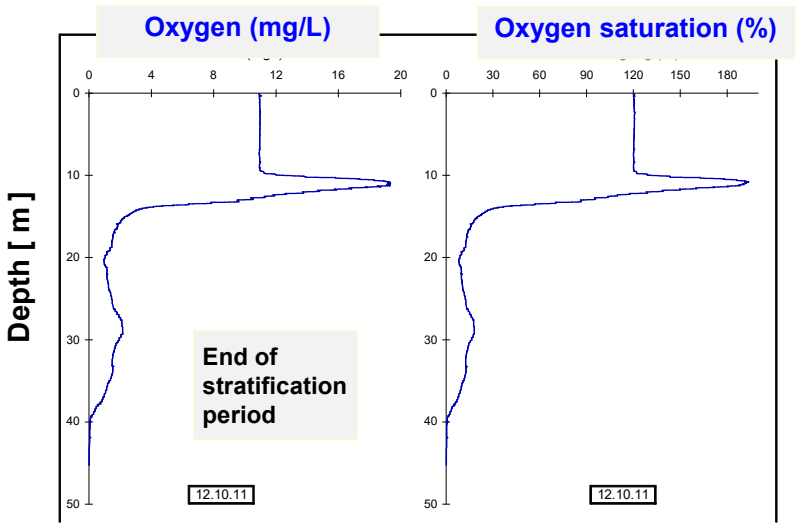
Epilimnion
(surface / sunlight)
Productive layer

Hypolimnion
(deep / dark)
OM degradation

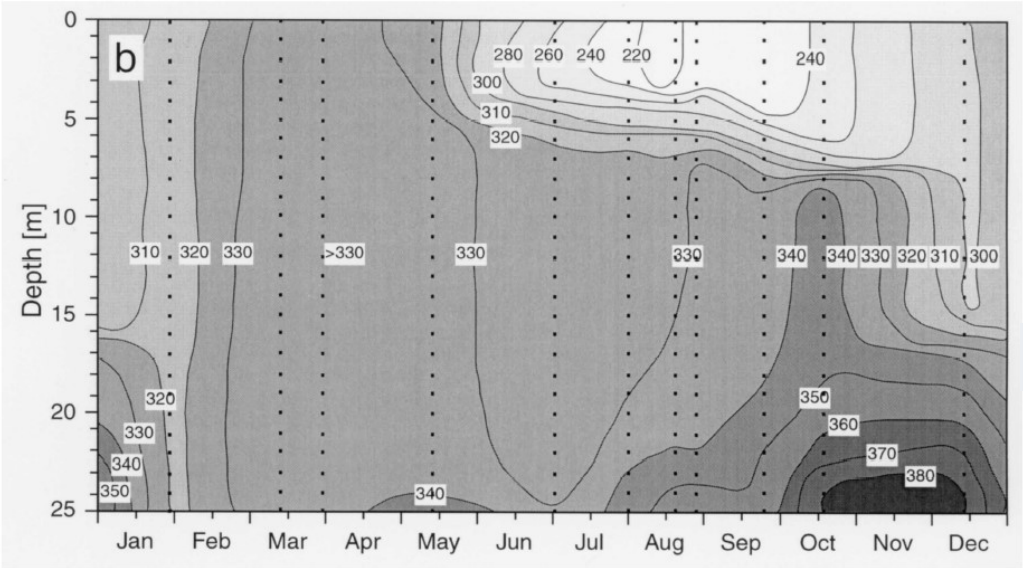



Sturm: Soppensee 1996

## Oxygen production (epi) / consumption (hypo)



## Seasonal dynamics of dissolved solids (TDS)




(Gruber et al 2020)

## Example 1 – Acceptable nutrient (P) load / dimensioning of STPs

**Problem setting – your goal is to maintain the hypolimnion of a drinking water lake / reservoir in oxic conditions during all seasons**

**Question – You know: Volume ($V_{Epi}$ and $V_{Hypo}$), Surface area (A), Riverine flow (Q). How much Phosphorus input (t-P/year) is acceptable?**

**Reasoning for Sewage Treatment Plants (STPs)**

**P in water → algal production in surface layer → deep $O_2$-depletion**

**Prescribe limiting $O_2$-depletion → limiting P input to waters → estimate tolerable P load to lake / reservoir**

## Example 1 – Acceptable nutrient (P) load / dimensioning of STPs

$106\ H_2CO_3 + 16\ NO_3^- + HPO_4^{2-} + 16\ H_2O + 18\ H^+ \rightarrow$

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10 m

10 m

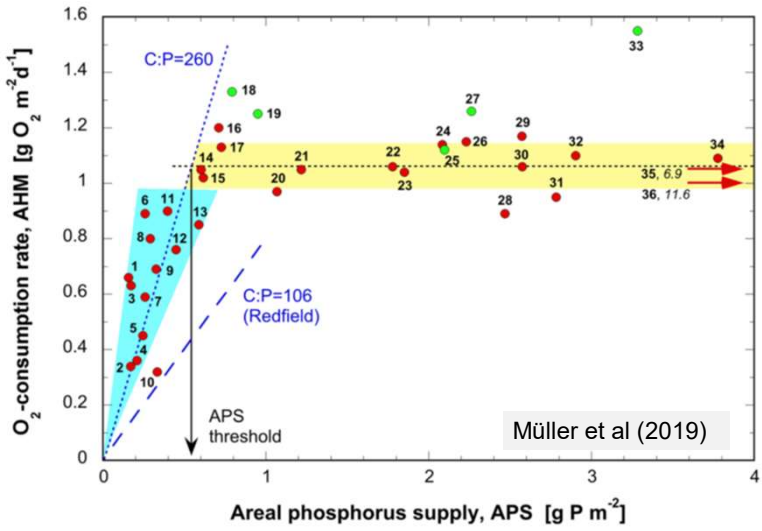
**Budget calculations based on Redfield**

**Available $O_2$:** 12 – 4 $gO_2\ m^{-3}$ → 80 $gO_2\ m^{-2}$ → 2.5 $molO_2\ m^{-2}$

**Conversion to Carbon C:** → 2.5 mol $m^{-2}$ *(106/138) = 1.92 molC $m^{-2}$ = 23 gC $m^{-2}$

**Conversion to Phosphorus P:** → 1.92 mol *(1/106) = 0.018 molP → **0.56 gP $m^{-2}$**

## Example 1 – Acceptable nutrient (P) load / dimensioning of STPs




**Previous calculation (last slide):**

**0.56 g P $m^{-2}$ /season**

**Research: Oxygen depletion as a function of P supply:**

**0.6 g P $m^{-2}$ /season**

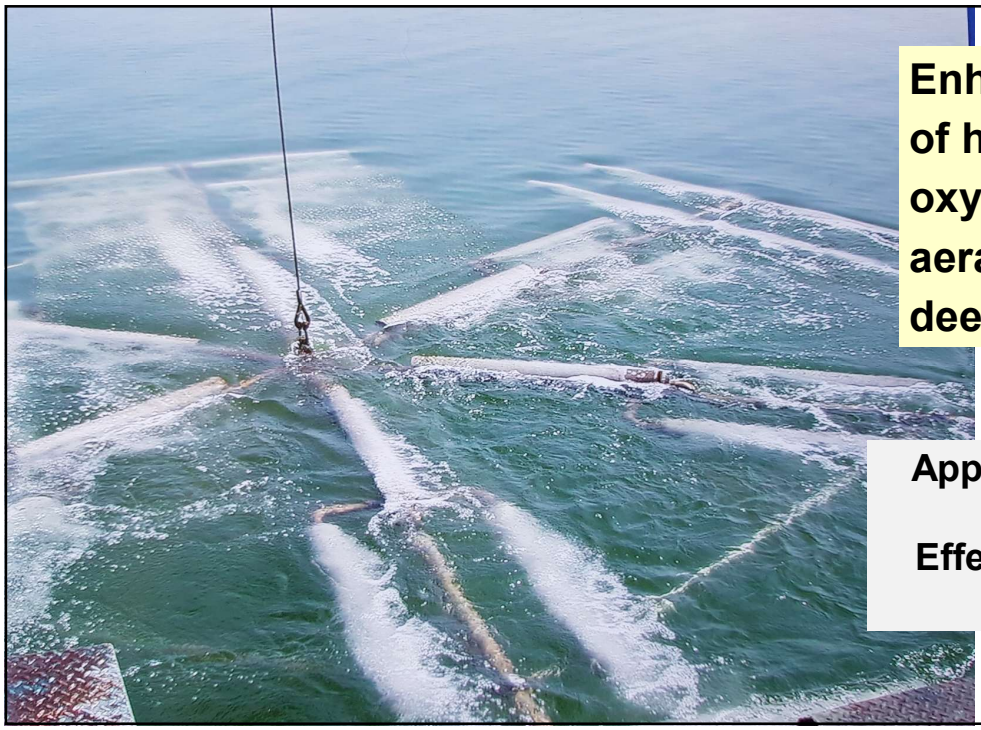
## Example: P balance of Lake Kivu

Estimated P input (research): 2050 t-P / year

Lake surface area: 2370 $km^2$

→ Areal P supply: 0.86 g P / $m^2$ / year

→ Slightly eutrophic



**Enhancement of hypolimnetic oxygen by aeration of deep water**

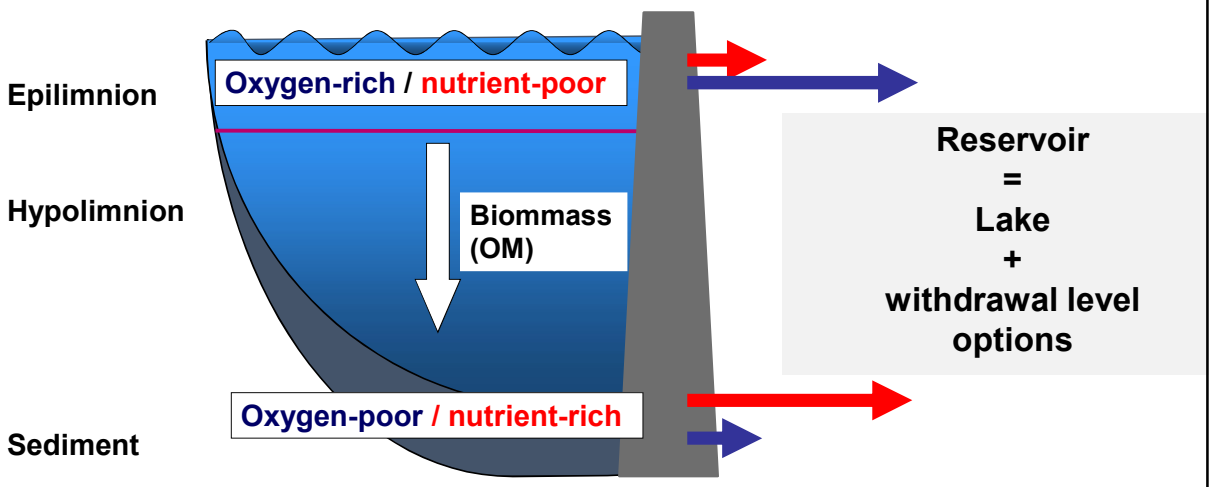
**Apparent depletion = Effective depletion - aeration**

## Example 2 – Selective withdrawal for up- and downstream water quality

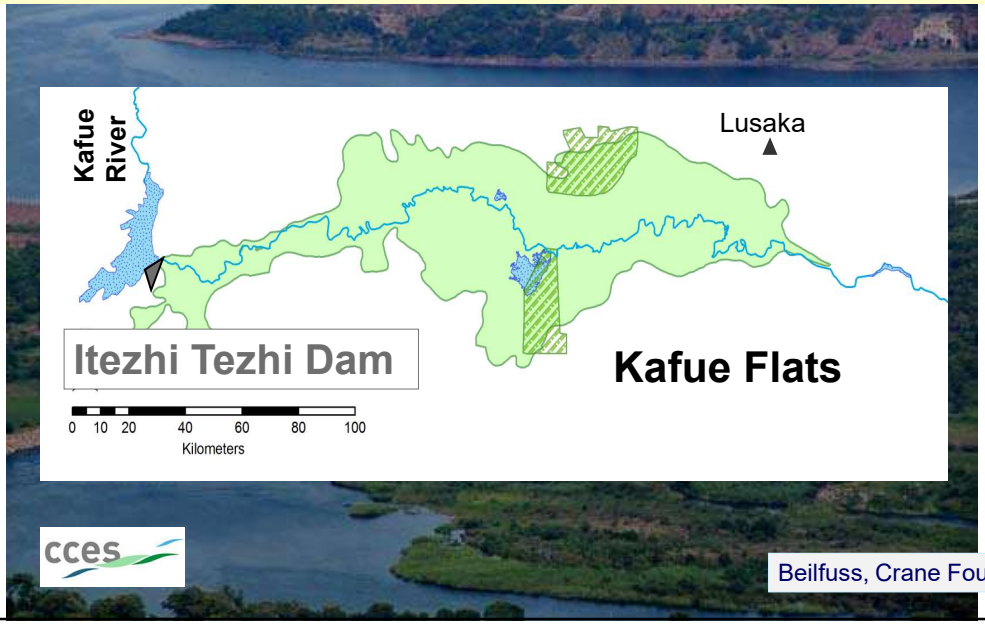
**Problem setting – The depth level of water extraction / abstraction affects the upstream and downstream water quality of lakes / reservoirs**

**Question – How can downstream oxygen levels be optimized? How is turbidity of drinking water minimized? How is nutrient / PP in upstream reservoir affected?**

## Example 2 – Selective withdrawal for up- and downstream water quality



# Itezhi-Tezhi Reservoir (Zambia)

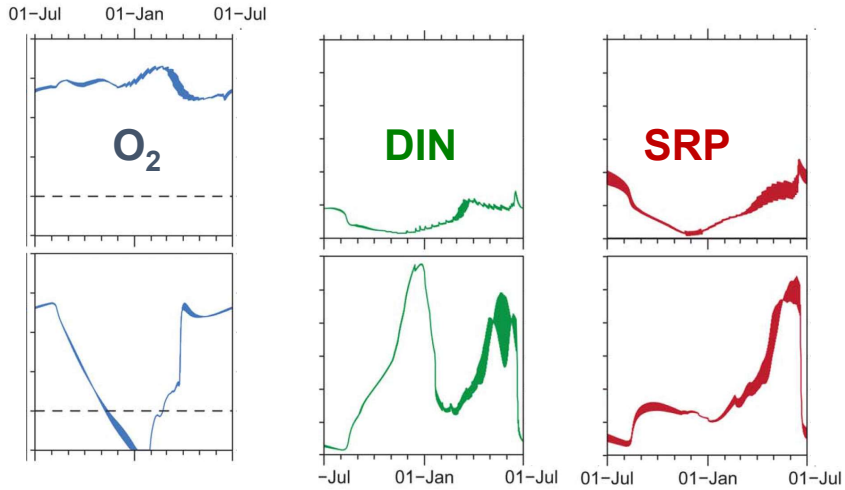



Beilfuss, Crane Foundation

# Kafue Flats – downstream of Itezhi Tezhi

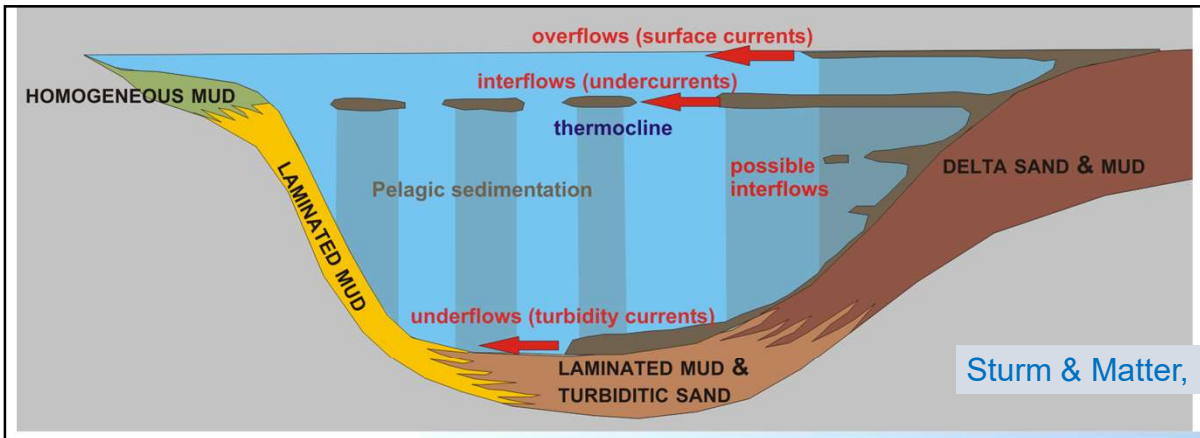
Beilfuss, Crane Foundation

# Example 2 – Selective withdrawal for up- and downstream water quality

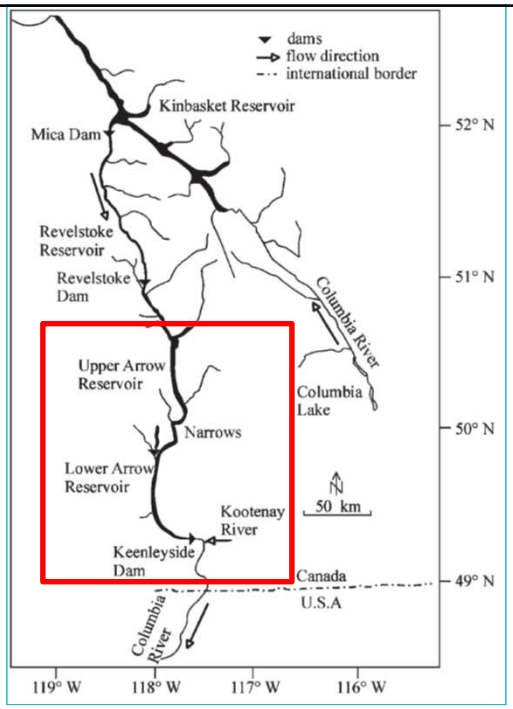



**Upper panel = surface outlet**

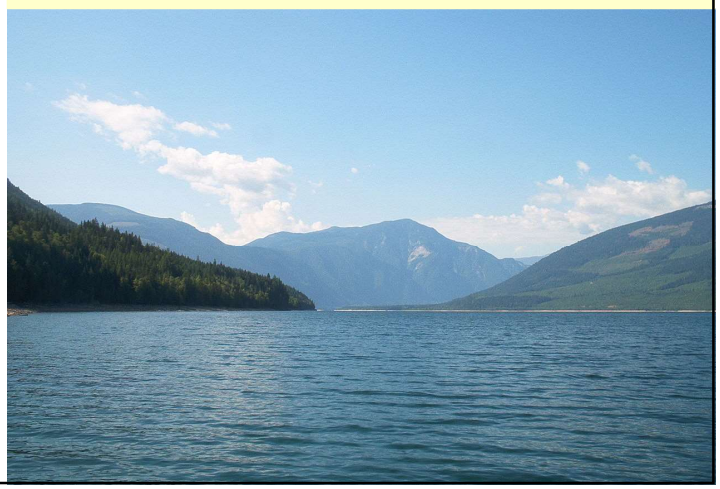
**Lower panel = deep outlet**

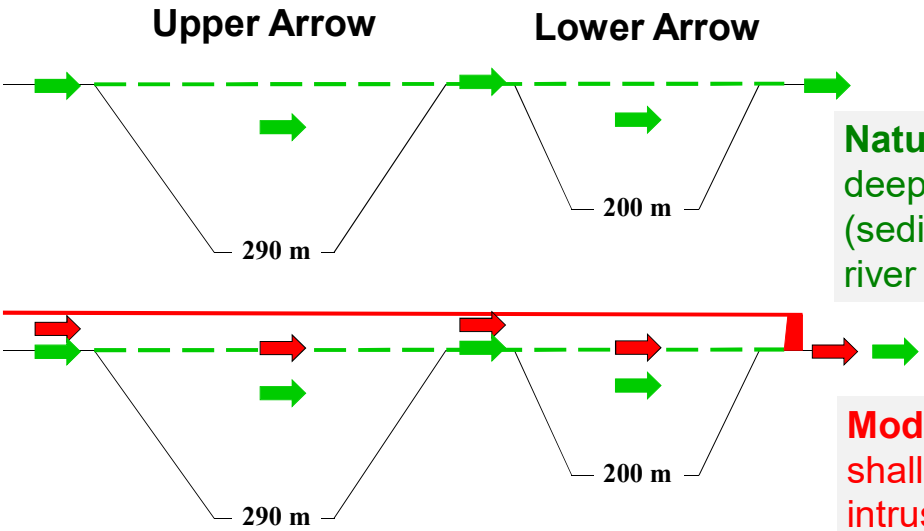



Sturm & Matter, 1978




# Example 2 – Selective withdrawal effect on PP (Arrow Lakes; BC)






**Natural (pre-dam)**
deep riverine intrusion (sediment and cool river water)

**Modified (dam)**
shallow riverine intrusion (less sediment and warmer river water)

$\tau$ = 100 days (50 m)

$\tau$ = 50 days (17 m)

$\tau$ = 13 days

$\tau$ = few days

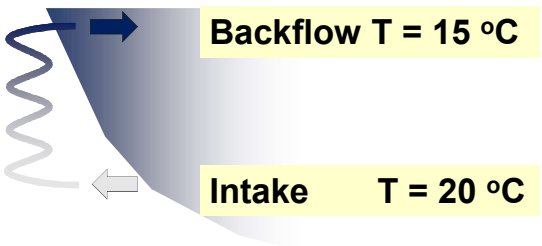
## Example 3 –
## Extracting and discharging heat into lakes

**Problem setting – Environmental heat can be used for warm water production (district heating systems) to reduce fossil fuel. Lakes and rivers alongside cities are ideally suited for using such water heat.**

**Question – Given the heat needs for warming or cooling. How much will you change the temperature and stratification in lakes / reservoirs? Rivers ?**

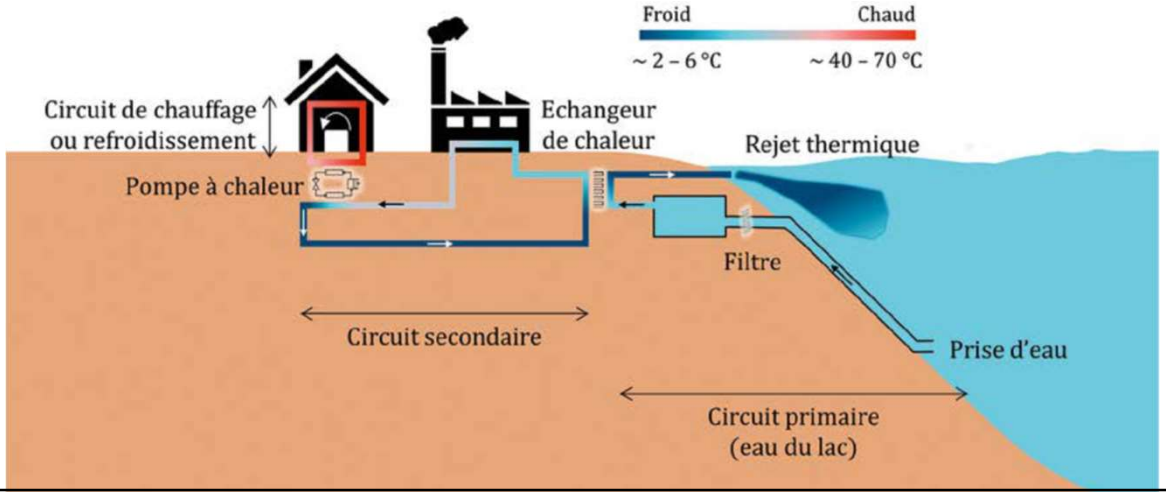
## Example 3 –
## Extracting and discharging heat into lakes

**$\Delta T = 5\ ^{o}C$**
**Q = 100 L/s**



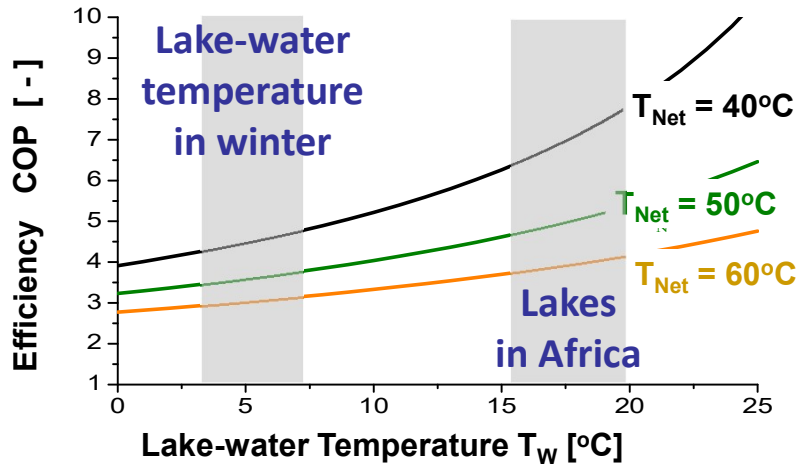

**Extracted heat water = 2 MW**
**COP = 5 → Useful heat = 2.5 MW**
**→ Warmwater needs for many 1000s persons**

# Example 3 – Extracting and discharging heat into lakes




# Example 3 – Extracting and discharging heat into lakes

**COP) = Usable heat / electrical energy**




**Advantages for Africa**

→ COP is higher

→ Smaller gap to target Temp

→ Solar PV available all seasons

Gaudard et al 2019

## Back of the envelop calculation

Assumption for heat need per person: 100 W

Assumption for acceptable $\Delta T$ change in lake: 0.1 $^{o}C$

→ Water volume per person: 7000 $m^3$ / year

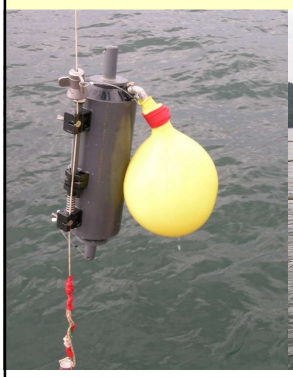
→ Almost endless resource for large lakes / rivers

## Example 4 – Methane extraction Lake Kivu

**Problem setting – The deep waters of Lake Kivu contain large amounts of methane. The goal is to extract as much methane**
**(i) without jeopardizing the lake ecological integrity and**
**(ii) without risking a gas eruption.**

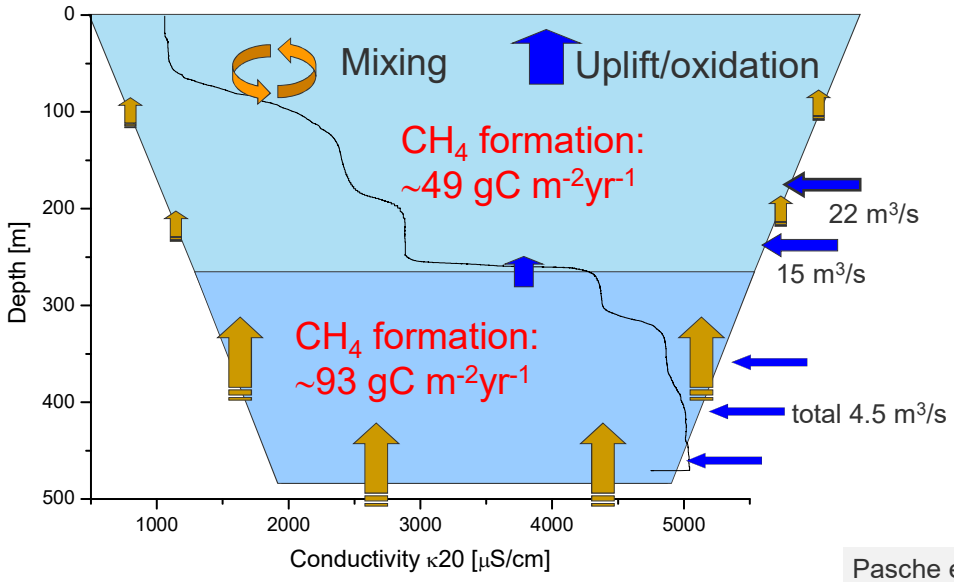
**Question – How can methane be extracted from a gas mixture of $CO_2$, / $H_2S$ / $CH_4$? How can the depth level for re-injection water be optimized, while (i) Maintaining lake ecological integrity, minimise eruption risk and maximise methane harvest?**

# Example 4 –
# Methane extraction Lake Kivu



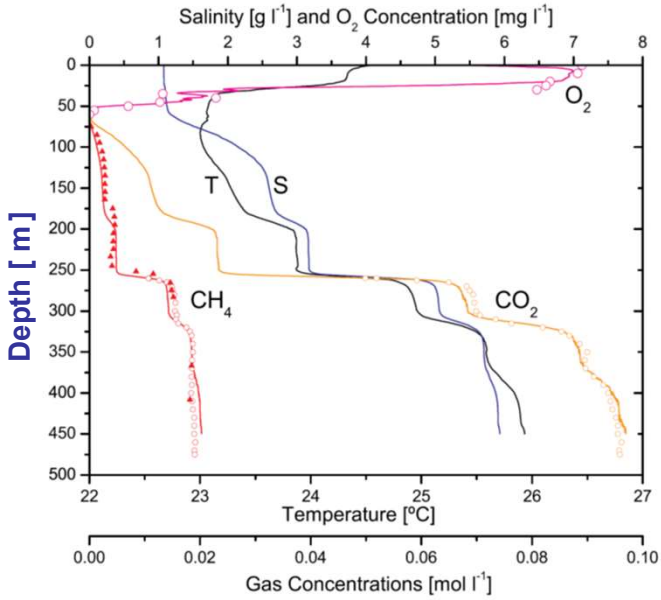
**Fascinating environmental engineering optimization problem:**
**Goals**
**→ reduce methane / risk → maintain ecology → maximise methane extraction**

# Natural methane formation – uplift – oxidation




Pasche et al. 2011

## Stratification-induced gas accumulation




**Practical goals**

→ Maintain stratification (now very strong)

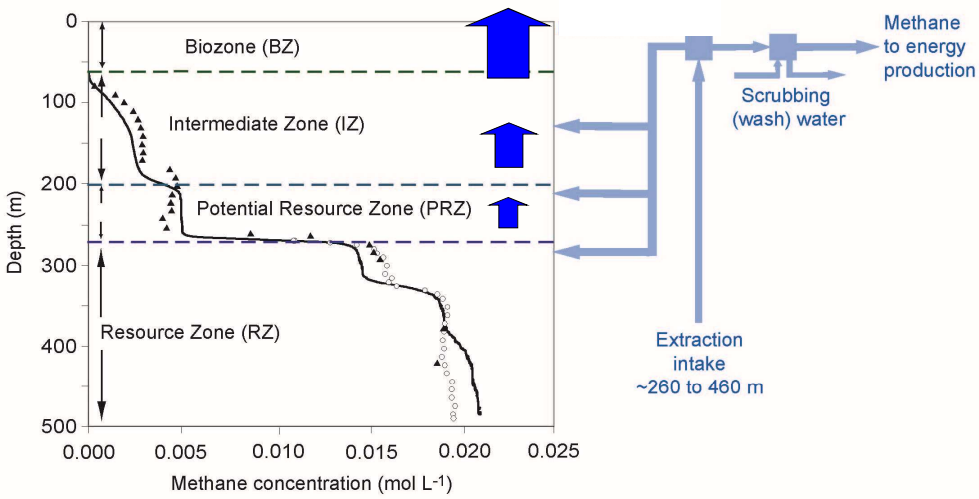
→ No changes to oxic surface layer

→ No up-flux of salt and nutrients

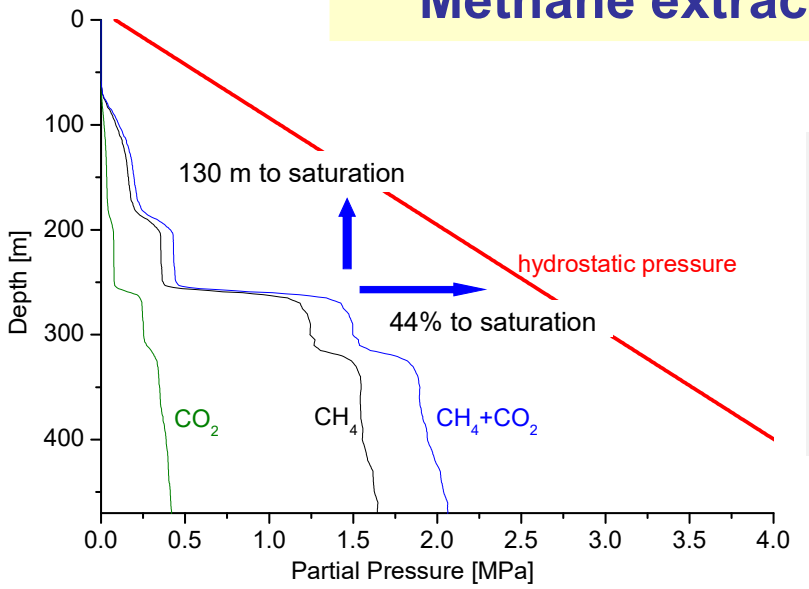
→ No dilution of high $CH_4$-water

Schmid et al 2005

## Example 4 – Methane extraction Lake Kivu

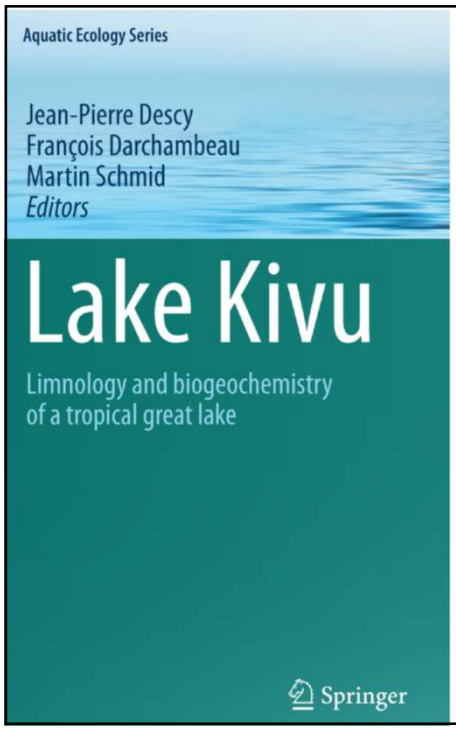


# Example 4 – Methane extraction Lake Kivu




**An example of a variable to be controlled**

→ Shortest distance to saturation should be as large as possible




## For further reading

→ I can recommend the Springer book
(freely available on the internet)

For any other publication / report
→ just send me an e-mail at:

**alfred.wueest@eawag.ch**