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)

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

**Water balance**

\[ Q_{\text{Riv}} + Q_{\text{Prec}} = E + Q_{\text{Outf}} \]

**Salt balance**

\[ Q_{\text{Riv}} \times S_{\text{Riv}} = Q_{\text{Outf}} \times S_{\text{Outf}} \]

**Known terms are:**

- $Q_{\text{Prec}} = 35.5 \text{ km}^3/\text{yr}$; $Q_{\text{Outf}} = 9.7 \text{ km}^3/\text{yr}$;
- $S_{\text{Riv}} = 0.220 \text{ mS/cm}$; $S_{\text{Lake}} = S_{\text{Outf}} = 0.660 \text{ mS/cm}$

**Solutions:**

- $Q_{\text{Riv}} = 3 \times 9.7 = 29.1 \text{ km}^3/\text{yr}$; $E = 55 \text{ km}^3/\text{yr}$
- $E = 1.7 \text{ m/yr}$ (for surface area of 32,600 km$^2$)
- Flushing time = 1950 yr (for lake volume of 18,800 km$^3$)
Density of water = \( f(T, \text{TDS}, P, \text{gases}) \) – Lake Kivu

\[
\rho(T,S,CO_2,CH_4) = \rho(T) \cdot (1 + \beta \cdot S + \beta_{CO_2} \cdot CO_2 + \beta_{CH_4} \cdot CH_4)
\]

Density stratification in freshwater

\[
\text{Density}(z) = f(T(z), \text{TDS}(z), P(z), \text{Gases}(z))
\]

\[
\rho = \rho(T) \cdot (1 + \beta_{TDS} \cdot \text{TDS} + \beta_p \cdot P + \beta_{CO_2} \cdot [CO_2] + h.o.)
\]

Stability \( N^2(z) = f(T(z), \text{TDS}(z), P(z), \text{Gases}(z)) \)

\[
N^2 = g \cdot \left[ \alpha \cdot \left( \frac{\partial T}{\partial z} + \Gamma \right) - \beta_{TDS} \cdot \frac{\partial \text{TDS}}{\partial z} - \beta_p \cdot \frac{\partial P}{\partial z} - \beta_{CO_2} \cdot \frac{\partial [CO_2]}{\partial z} + h.o. \right]
\]
Seasonal stratification dynamics – Lake Kivu

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

Epilimnion
- CO₂ → C_{org}
- Outflow

Metalimnion
- Net ecosystem production
- Gross sedimentation
  (algae, CaCO₃)

Hypolimnion
- CH₄, HCO₃⁻
- OM degradation

Sediment-water interface
- Mineralization
- C_{org}
- Sediment
- Net sedimentation

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

Net ecosystem production
- (CH₂O)_{106} \cdot (NH₃)_{16} \cdot (H₃PO₄)
- Epilimnion (surface / sunlight)
- Productive layer

Gross sedimentation
- (CH₂O)_{106} \cdot (NH₃)_{16} \cdot (H₃PO₄)
- Hypolimnion (deep / dark)
- OM degradation

\[
\begin{align*}
106 \text{H₂CO}_3 + 16 \text{NO}_3^- + \text{HPO}_4^{2-} + 16 \text{H}_2\text{O} + 18 \text{H}^+ & \rightarrow \\
(\text{CH}_2\text{O})_{106} \cdot (\text{NH}_3)_{16} \cdot (\text{H}_3\text{PO}_4) & + 138 \text{O}_2
\end{align*}
\]

\[
\begin{align*}
106 \text{H}_2\text{CO}_3 + 16 \text{NO}_3^- + 2\text{HPO}_4^{2-} + 16\text{H}_2\text{O} + 18 \text{H}^+ & \rightarrow \\
(\text{CH}_2\text{O})_{106} \cdot (\text{NH}_3)_{16} \cdot (\text{H}_3\text{PO}_4) & + 138 \text{O}_2
\end{align*}
\]
Oxygen production (epi) / consumption (hypo)

Oxygen (mg/L)  /  Oxygen saturation (%)

Depth [m]

End of stratification period

12.10.11  /  12.30.11
Seasonal dynamics of dissolved solids (TDS)

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 ($V_{\text{Epi}}$ and $V_{\text{Hypo}}$), Surface area (A), Riverine flow (Q). How much Phosphorus input (t-P/year) is acceptable?

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

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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

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 km²

→ Areal P supply: 0.86 g P / m² / 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?

Oxygen-rich / nutrient-poor

Epilimnion

Hypolimnion

Biomass (OM)

Oxygen-poor / nutrient-rich

Sediment

Reservoir = Lake + withdrawal level options
Itezhi-Tezhi Reservoir (Zambia)

Kafue River

Itezhi Tezhi Dam

Lusaka

Kafue Flats

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)

**Upper Arrow**
- 290 m
- \( t = 50 \) days (17 m)
- \( t = 100 \) days (50 m)
- \( t = \) few days

**Lower Arrow**
- 200 m
- 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)  \( \tau = 13 \) days
\( \tau = 50 \) days (17 m)  \( \tau = \) 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?

Extracted heat water = 2 MW
COP = 5 \rightarrow \text{Useful heat} = 2.5 \text{ MW}
\rightarrow \text{Warmwater needs for many 1000s persons}
Example 3 – Extracting and discharging heat into lakes

\[
\text{COP} = \frac{\text{Usable heat}}{\text{electrical energy}}
\]

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 $^\circ$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$_2$S / 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

CH₄ formation:
~49 gC m⁻² yr⁻¹

CH₄ formation:
~93 gC m⁻² yr⁻¹

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

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

Overview
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:

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