The physics of inland waters
(a) Lake ecosystems

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Geophysical Research Letters
RESEARCH LETTER
10.1002/2014GL060641

Key Points:
- Earth has 117 million lakes > 0.002 km^2
- Large and intermediate lakes dominate the total surface area of lakes
- Power law-based extrapolations do not adequately estimate lake abundance

A global inventory of lakes based on high-resolution satellite imagery

Charles Verpoorter[1,2], Tiit Kutser[2,3], David A. Seekell[4,5], and Lars J. Tranvik[2]

[1]INSU-CNRS, UMR 8187, LOG, Laboratoire d'Océanologie et des Géosciences, Université du Littoral Cote d'Opale, ULCO, Wimereux, France, [2]Department of Ecology and Genetics/Limnology, Uppsala University, Uppsala, Sweden, [3]Estonian Marine Institute, University of Tartu, Tallinn, Estonia, [4]Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA, [5]Now at Department of Ecology and Environmental Sciences, Umeå University, Umeå, Sweden

117 million lakes > 0.002 km^2 covering 3.7% of Earth's non-glaciated land area

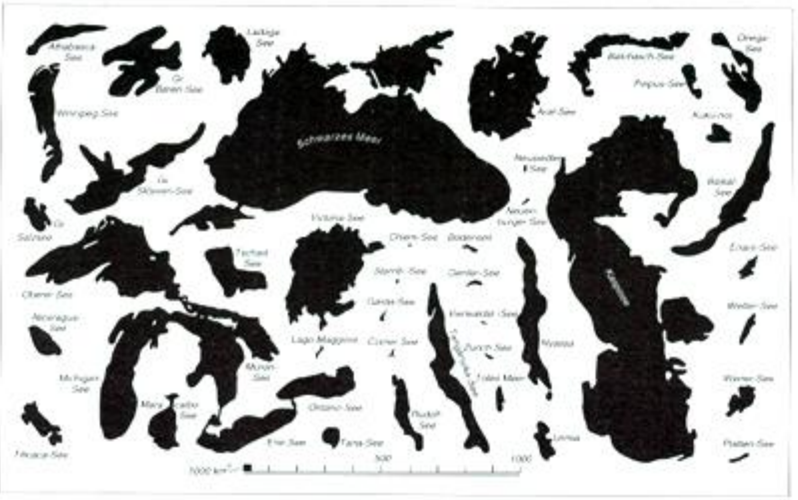


Abb. 3-3: Größenvergleich einiger Seen der Erde (aus Ruttner 1962), zum Vergleich auch Schwarzes Meer

Area:
Exchange with atmosphere

Perimeter:
Exchange with terrestrial environment

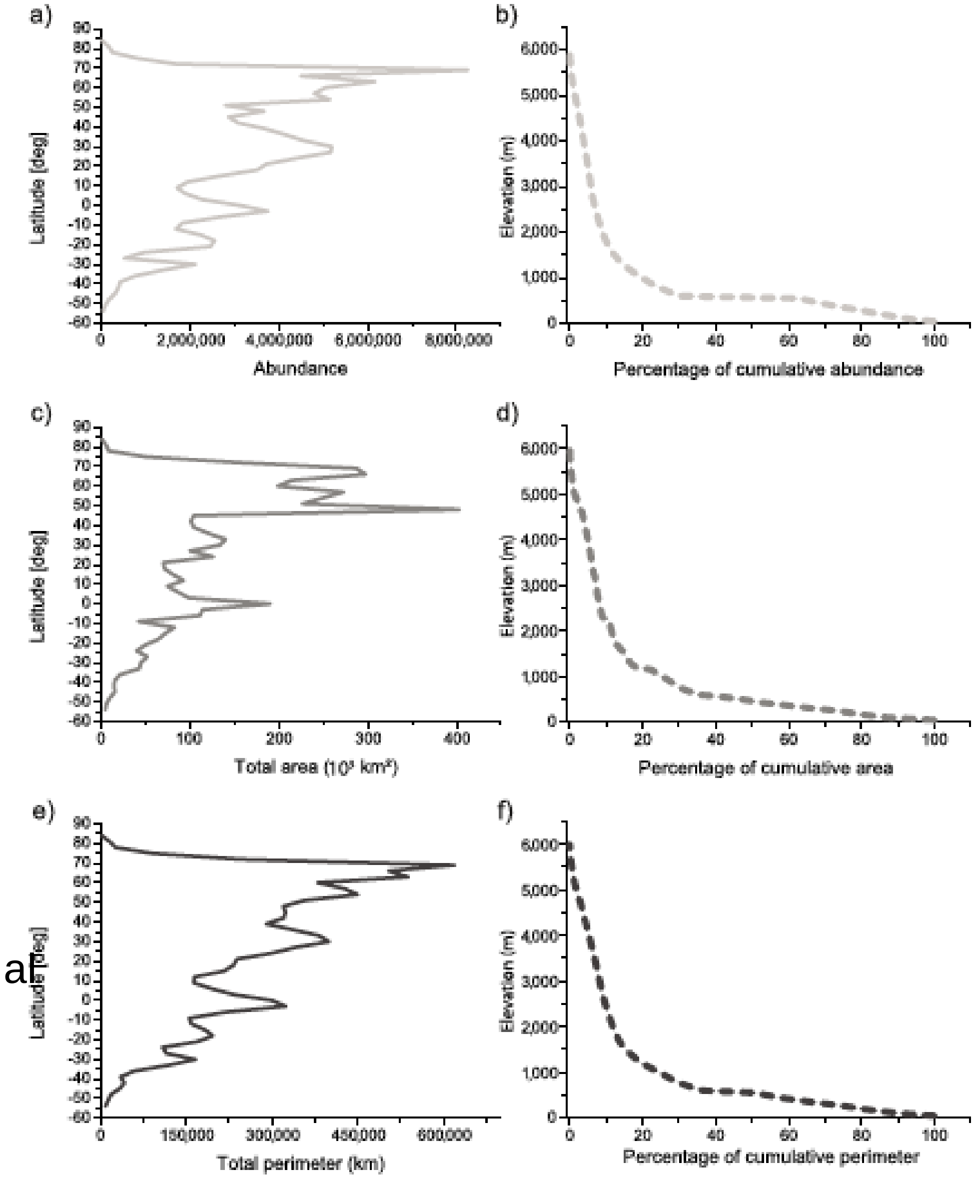
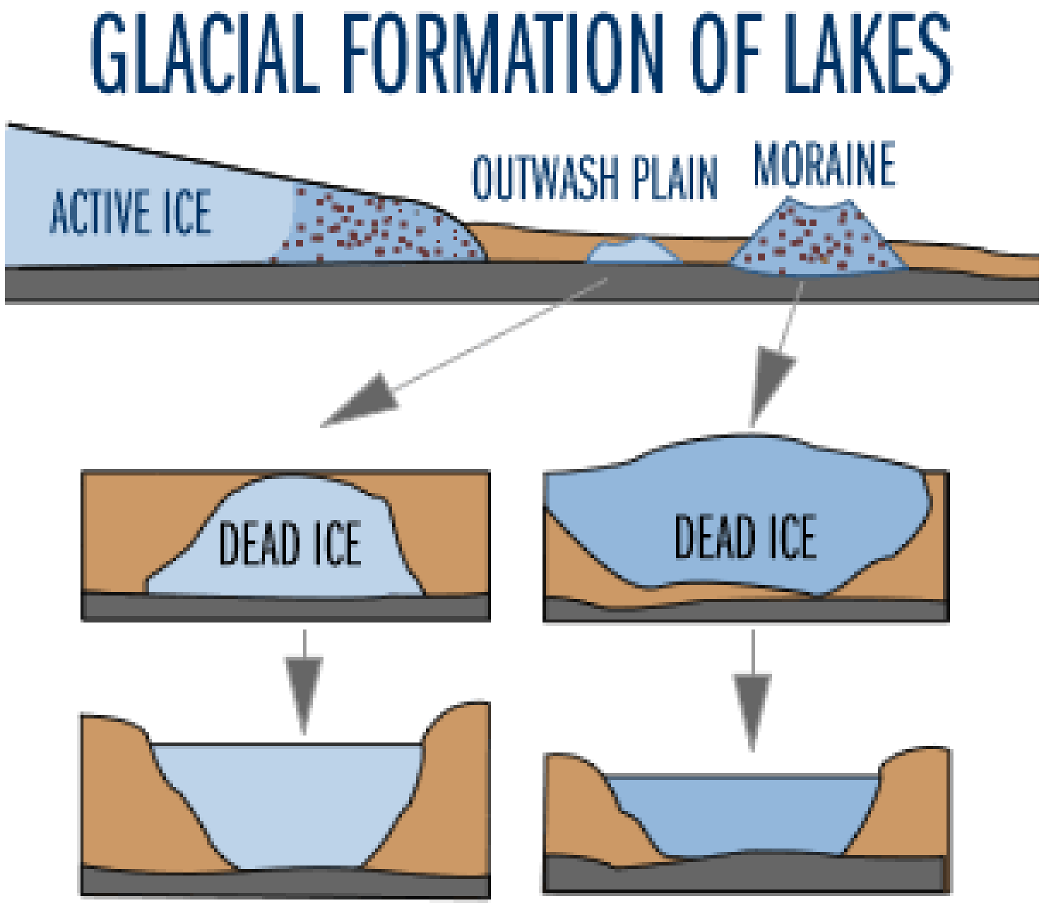


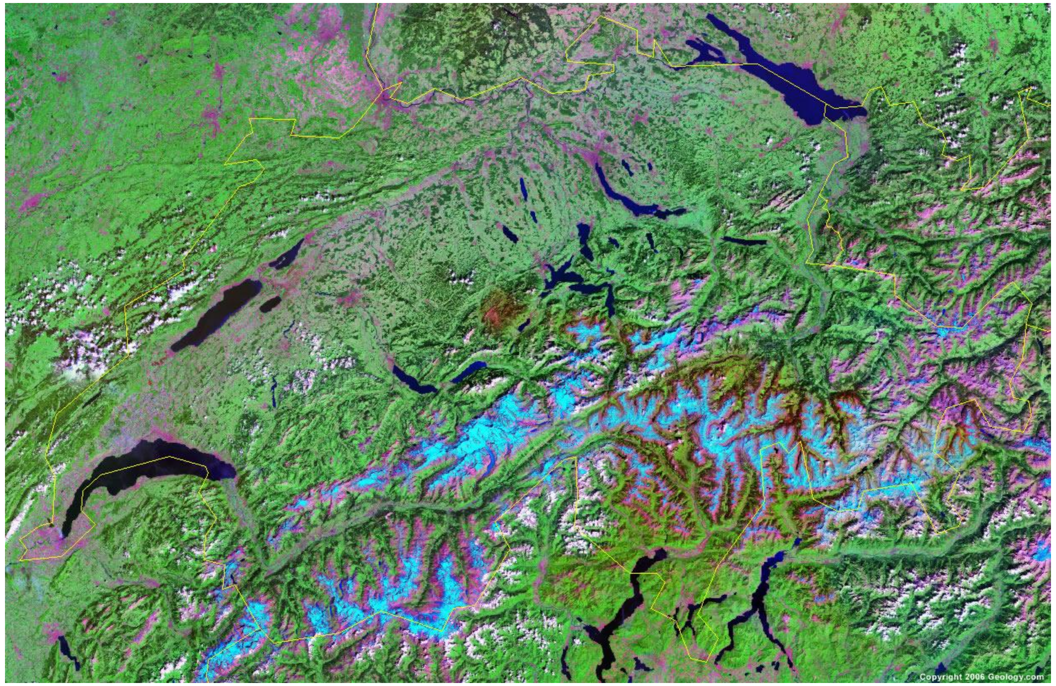
Figure 3. Latitudinal and elevation distribution of the GLOWABO database for all size categories (excluding Caspian Sea). The latitudinal distribution of water bodies of (a) abundance, (c) total area, and (e) total perimeter. Numbers were aggregated in steps of 3° latitude (see full lines). The elevation distribution of water bodies of (b) percentage of cumulative abundance, (d) percentage of cumulative area, and (f) percentage of cumulative perimeter. Numbers were cumulated in steps of elevation of 50 m (see dashed lines).

Why do lake basins have different geometries?

The genesis of lakes

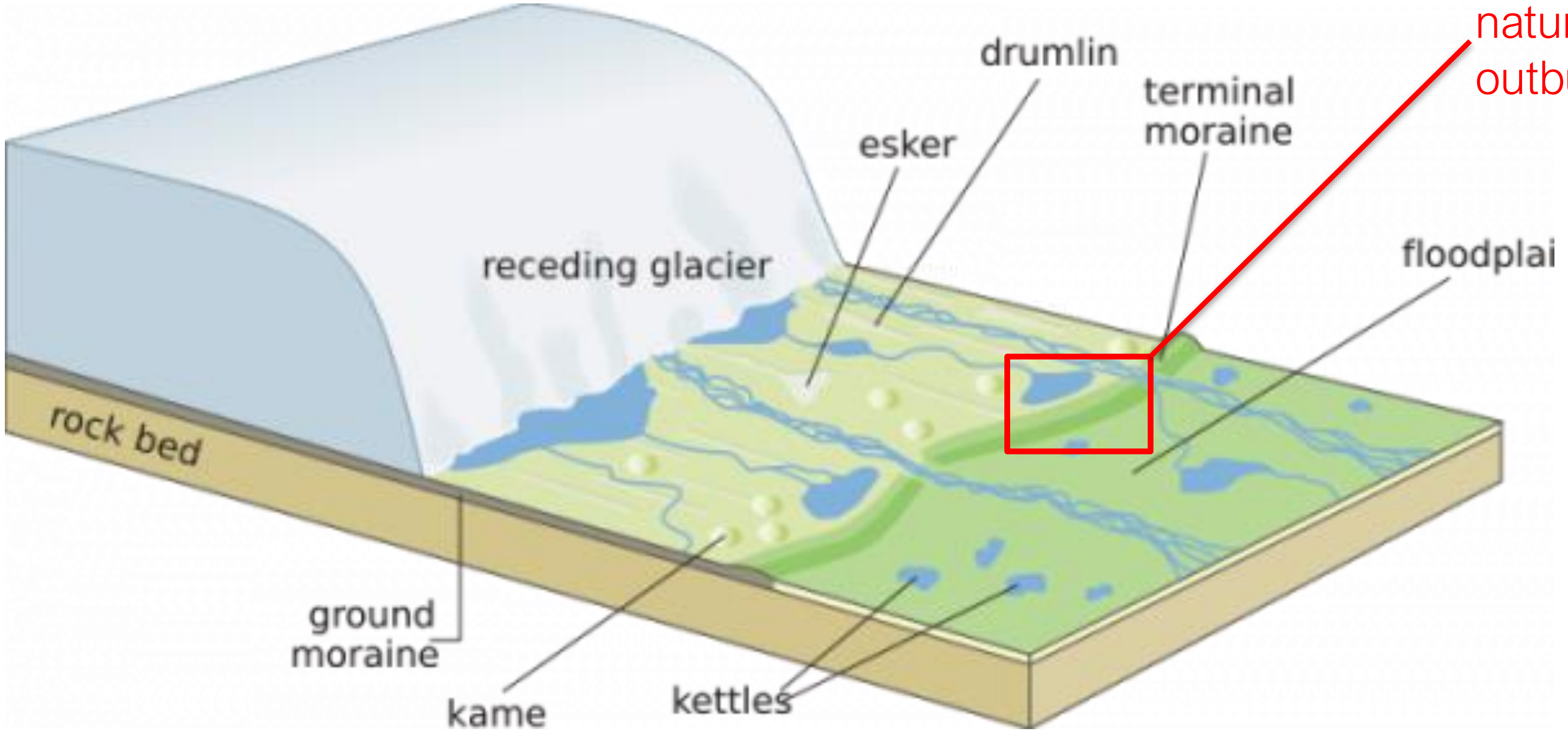
Glacier lakes





Lakes that form from the melting of dead ice (disconnected from the active galcier, hence not nurtured by the glacier)

Glacier lakes

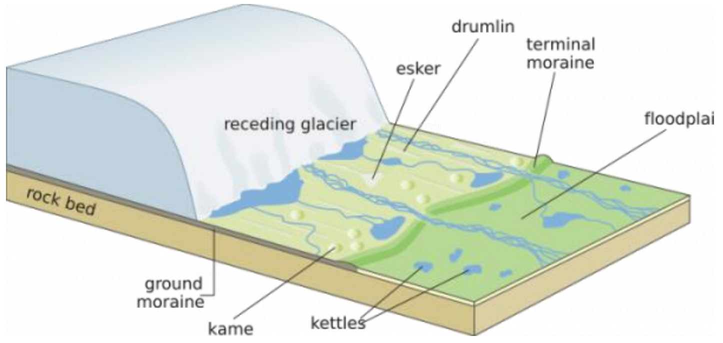


Terminal moraines can serve as natural dams (Glacier lake outburst floods)

- Glacier forefields are highly dynamic systems
- Undergo rapid geomorphological change
- Various nascent ecosystems

http://upload.wikimedia.org/wikipedia/commons/thumb/d/da/Receding_glacier-en.svg/800px-Receding_glacier-en.svg.png

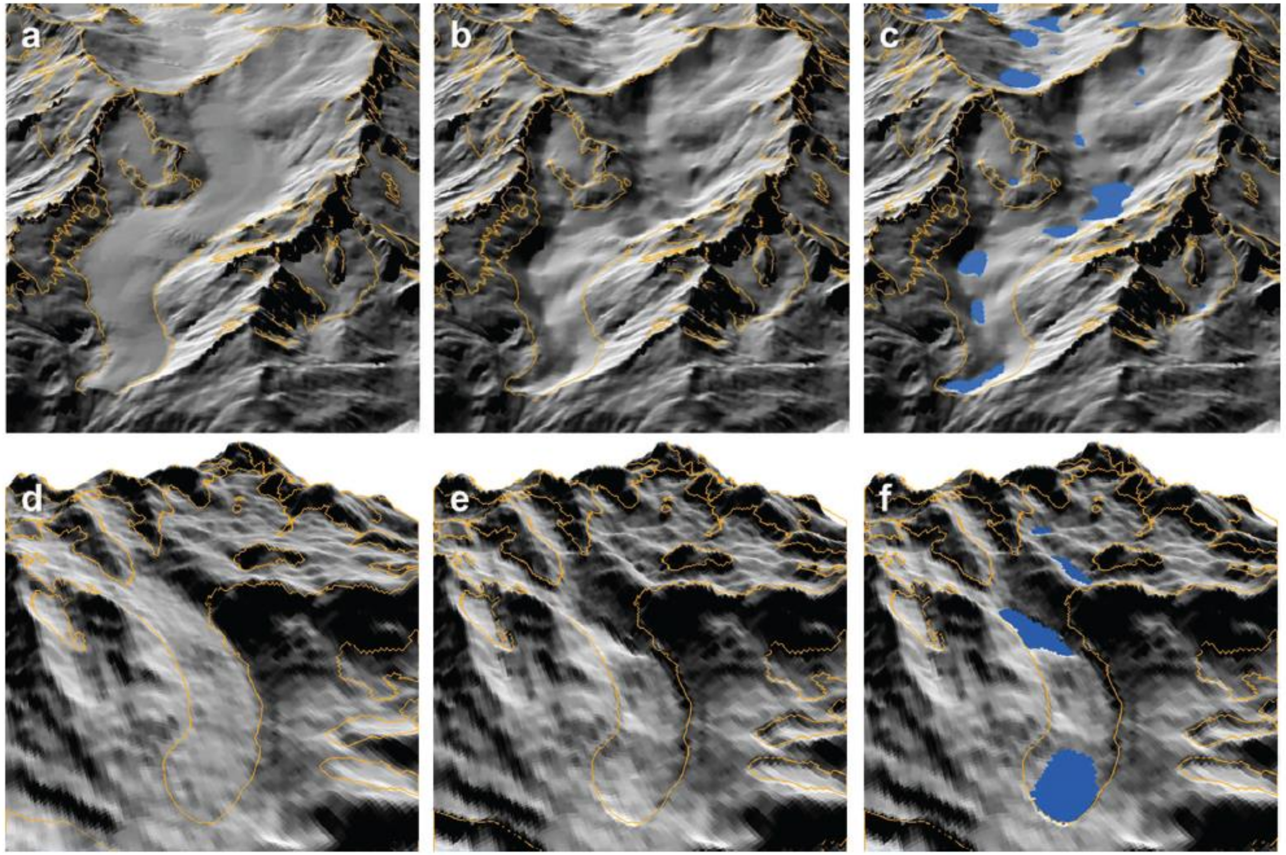
Glacier lake outburst floods (GLOFs)



Annals of Glaciology 57(71) 2016 doi: 10.3189/2016AoG71A627 119

Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya–Karakoram region

A. LINSBAUER,[1,2] H. FREY,[1] W. HAEBERLI,[1] H. MACHGUTH,[3] M.F. AZAM,[4,5]
S. ALLEN[1,6]



Rhone Glacier, CH

Parbati Glacier, Himalaya

Fig. 3. Sequence of pictures to visualize the modelling approach: oblique view of (a–c) Rhone glacier, Switzerland (46°35′ N, 8°25′ E, where data quality is high and the model was developed); and (d–f) a glacier sample in the Parbati valley from the western Himalaya test region (32°10′ N, 77°30′ E). (a, d) Glacier surface (original DEM); (b, e) glacier bed topography modelled with GlabTop2; and (c, f) bed topography with detected overdeepenings shown in blue. The glacier outlines are displayed in orange.

- Owing to climate-induced glacier melt, new lakes form
- Overdeepenings (in blue) can form new lakes
- Potential for future aquatic life and hydropower

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Future emergence of new ecosystems caused by glacial retreat

https://doi.org/10.1038/s41586-023-06302-2

Received: 16 February 2023

J. B. Bosson[1]✉, M. Huss[2,3,4], S. Cauvy-Fraunié[5], J. C. Clément[6], G. Costes[1], M. Fischer[7,8], J. Poulenard[9] & F. Arthaud[6]

- Distribution of overdeepening of the terrain as glaicers melt
- Numerous small and shallow lakes
- Potential for new lakes

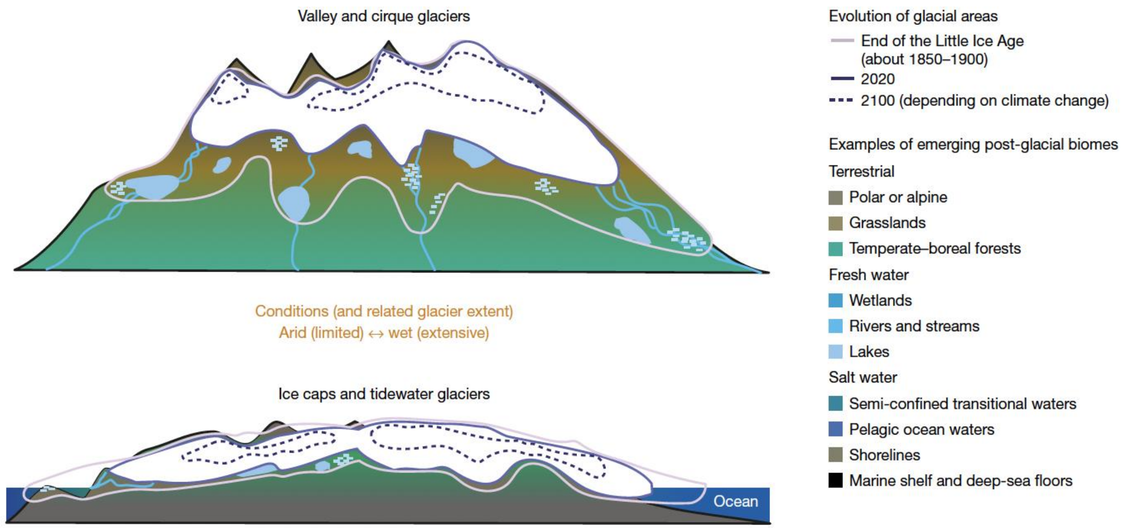
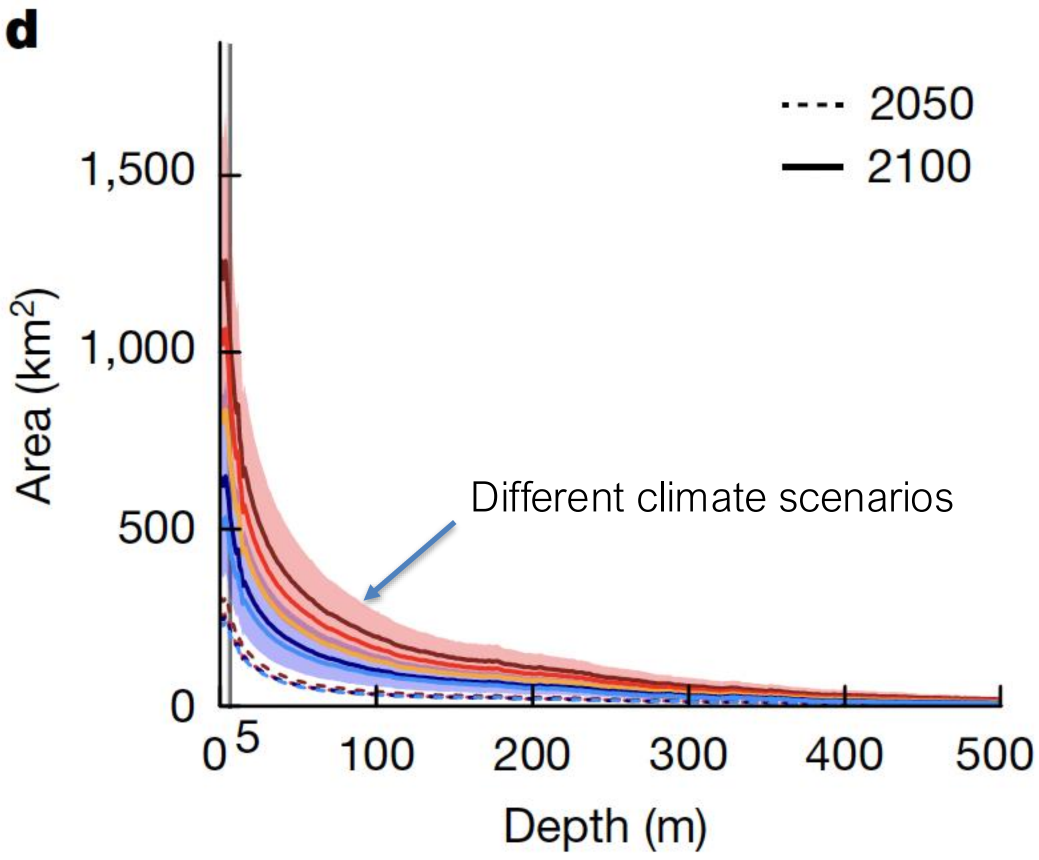
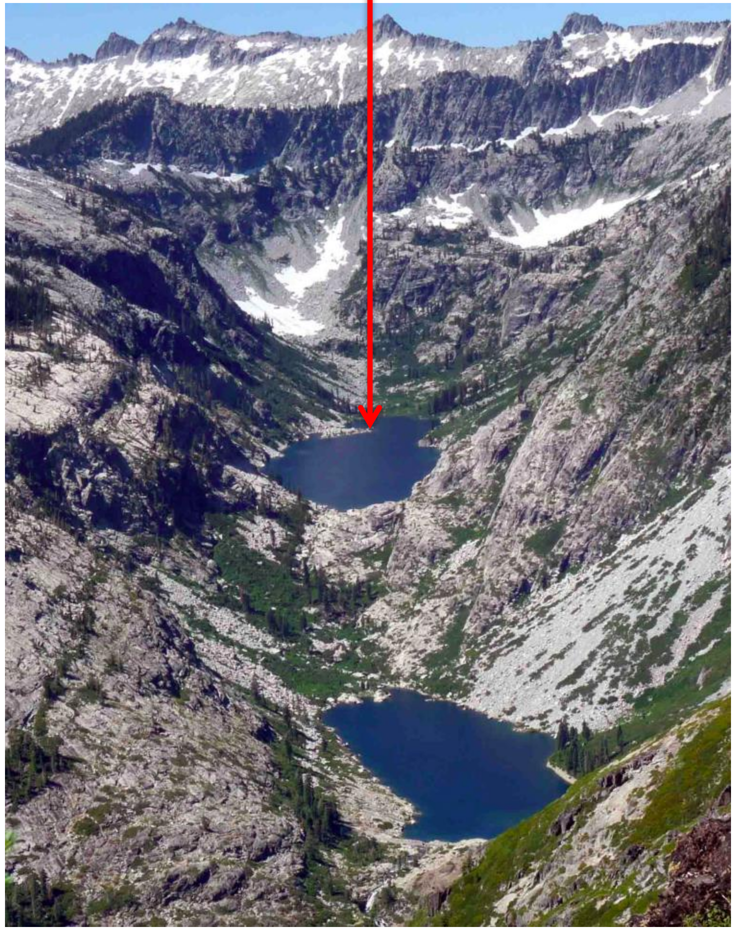


Fig. 1 | Schematic of glacier retreat and the emergence of post-glacial ecosystems. Changes are illustrated for mountain (top) and polar (bottom) regions in a climate that is unfavourable to glaciers, as experienced globally since 1900. Different types of post-glacial biome[18], in which diverse ecosystems may emerge, are shown.

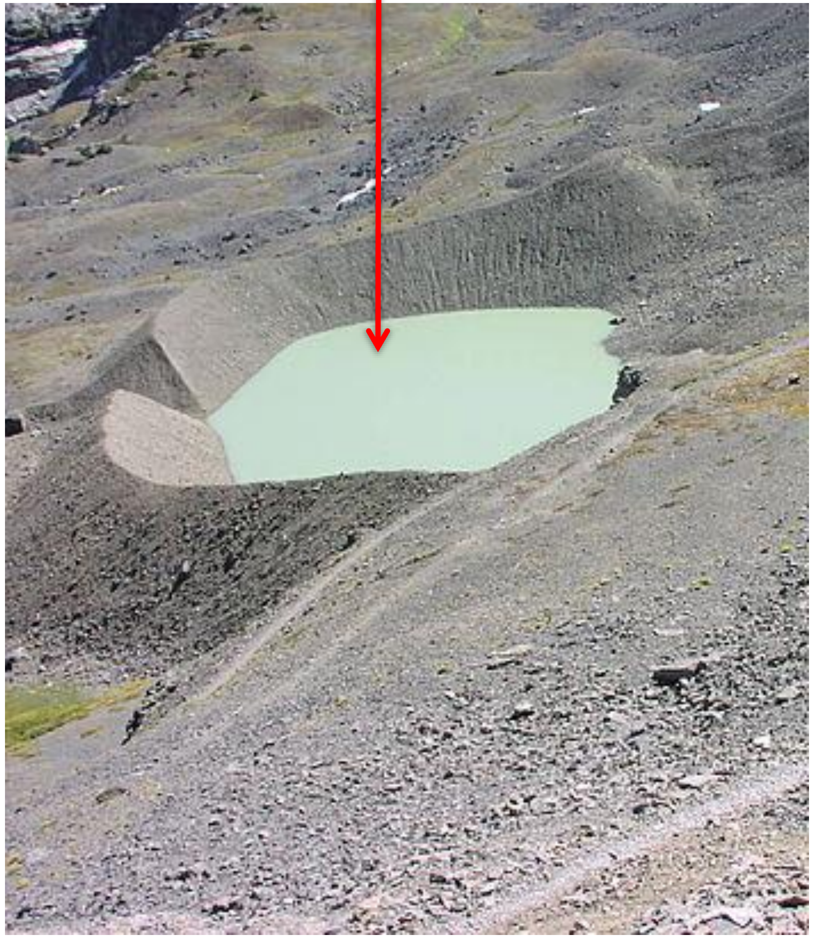


Glacier lakes

Low turbidity



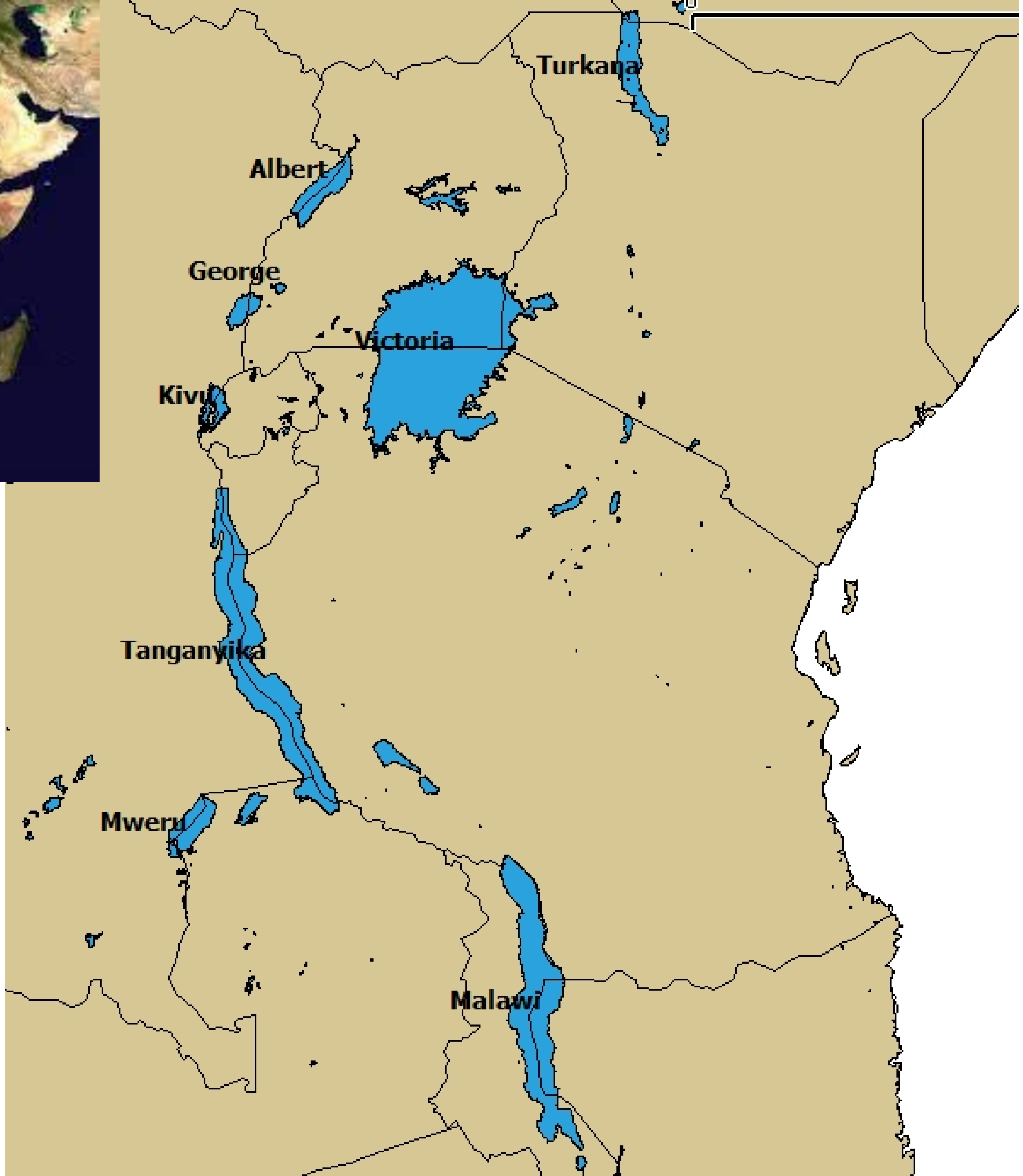
High turbidity



- Turbidity is a function of lake age and glacier influence
- Affects ligh regime, primary production, food webs and biogeochemistry

Rift lakes

African Great Lakes

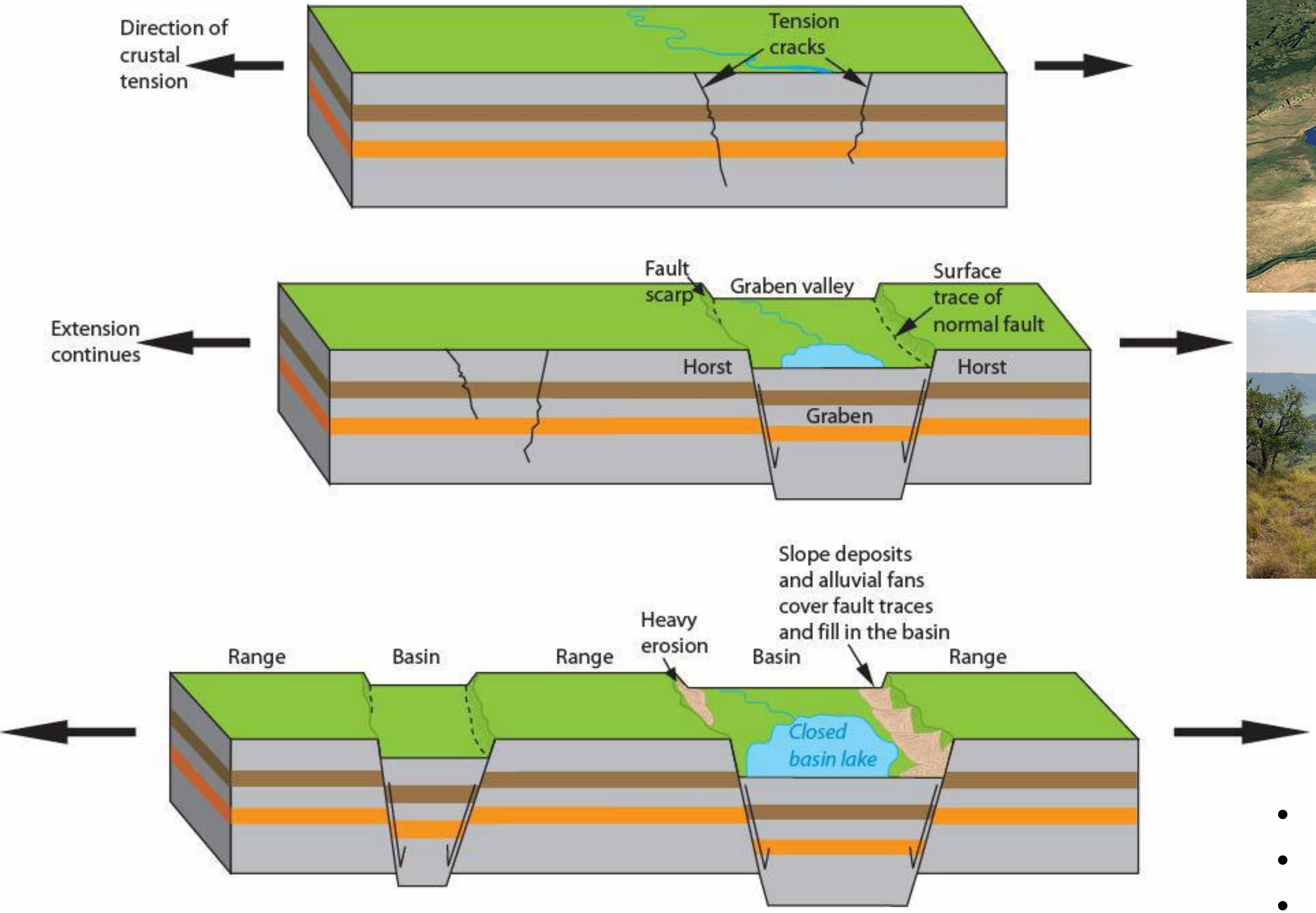


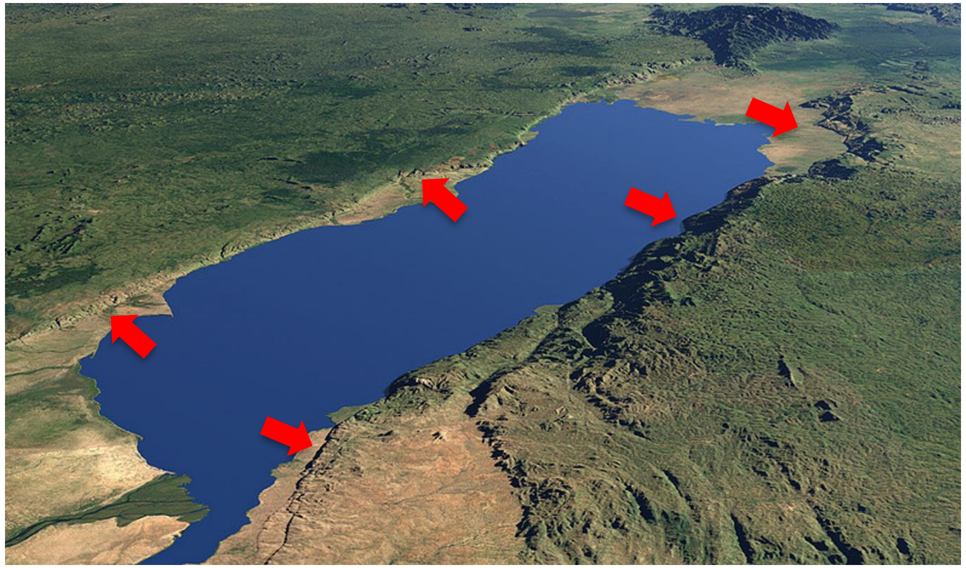
Rift lakes

Lake Albert

Lake Tanganyika

Rift lake formation

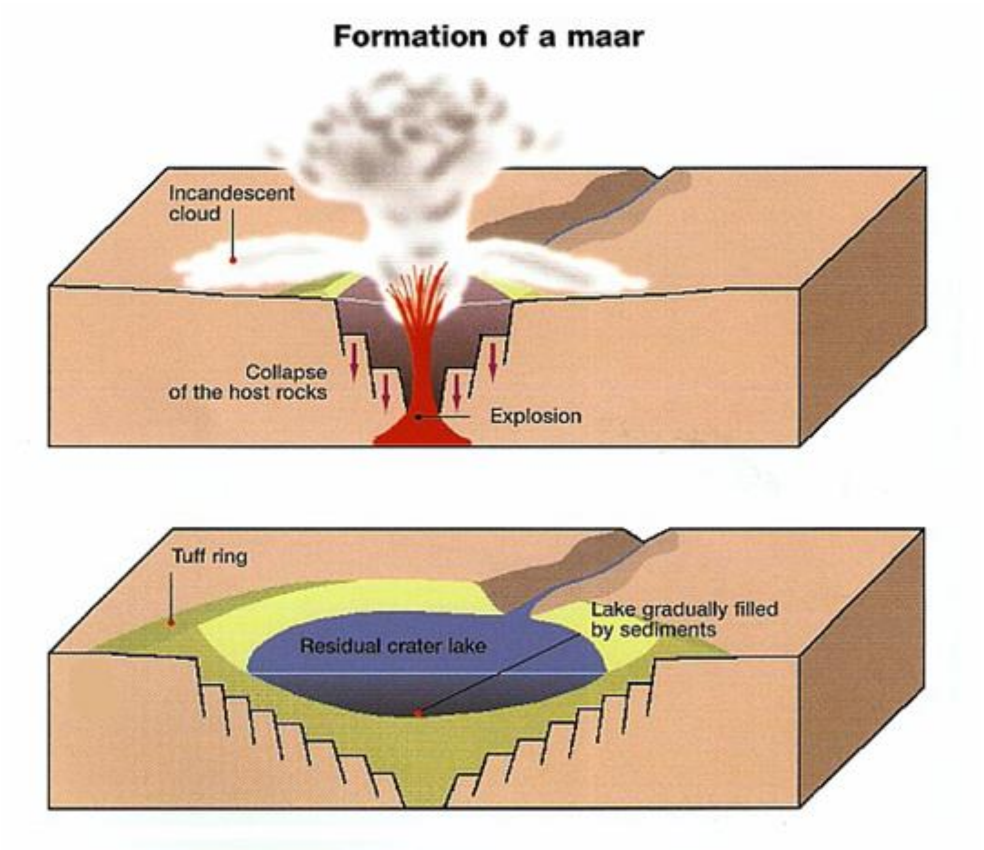




- Endhoreic lakes
- High evaporation
- Elevated salinity

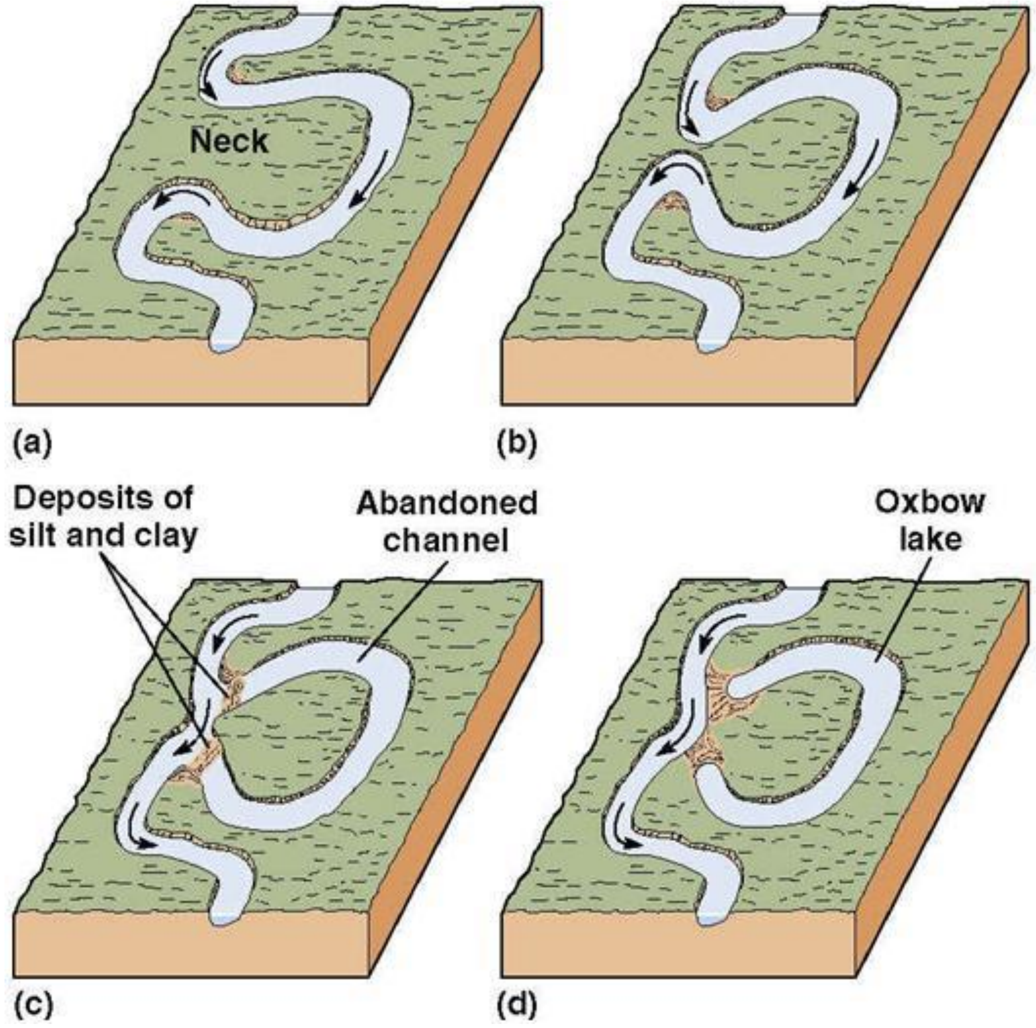
Maar lakes

Result from volcanic activities



Oxbow lakes

Result from the meandering of rivers



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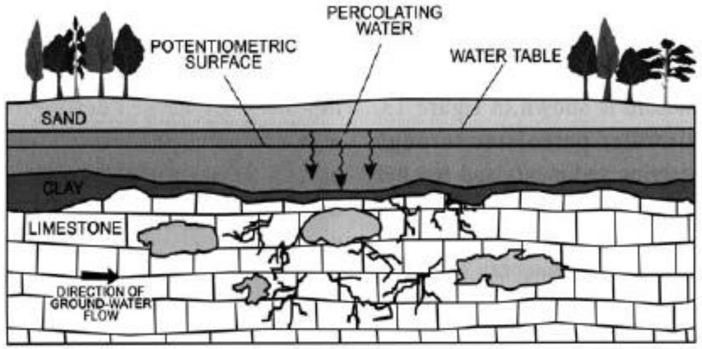
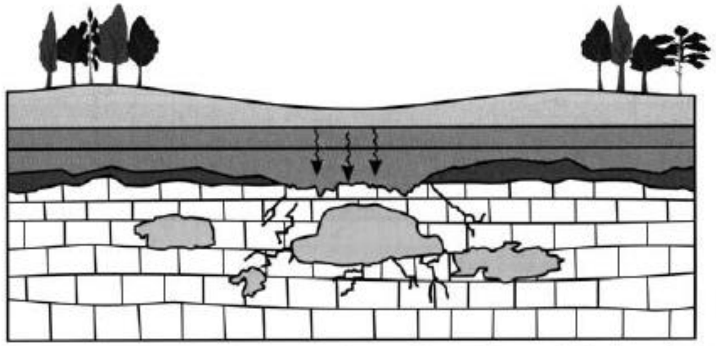
Sinkhole lakes

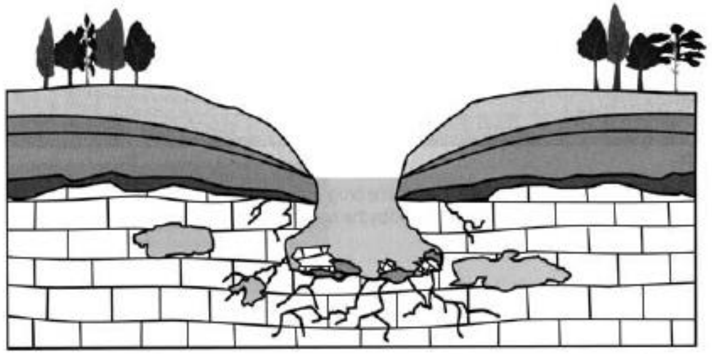
Result from the weathering of limestone (karst)



No evidence of land subsidence, small- to medium-sized cavities in the rock matrix. Water from surface percolates through to rock, and the erosion process begins.



Cavities in limestone continue to grow larger. Note missing confining layer that allows more water to flow through to the rock matrix. Roof of the cavern is thinner, weaker.

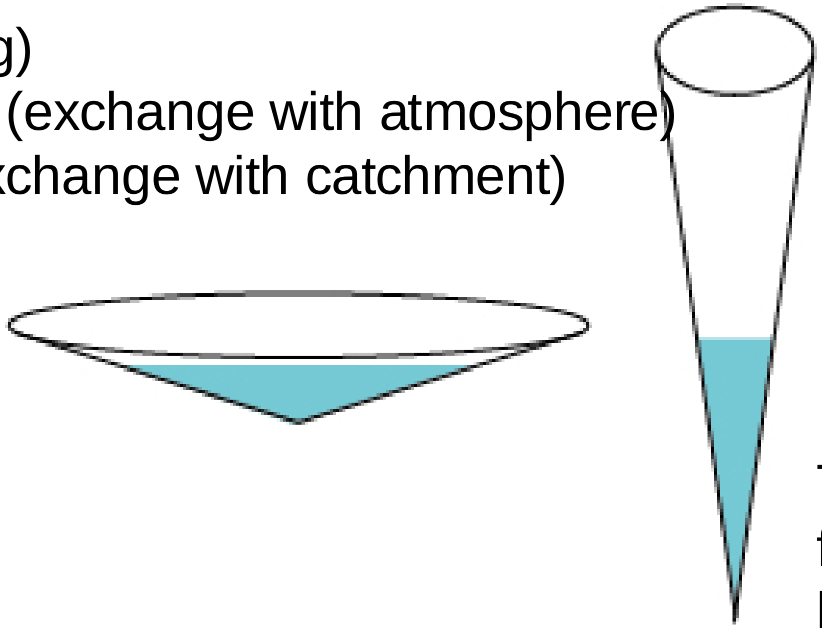


As ground-water levels drop during the dry season, the weight of the overburden exceeds the strength of the cavern roof, and the overburden collapses into the cavern, forming a sinkhole.

Lake geometry and function

Basic lake geometry given by

- Depth (mixing)
- Surface area (exchange with atmosphere)
- Perimeter (exchange with catchment)



The morphology of the lake basin is relevant for lake hydrology, biogeochemistry, biodiversity and management

Lake bathymetry

Spatial distribution of water depth

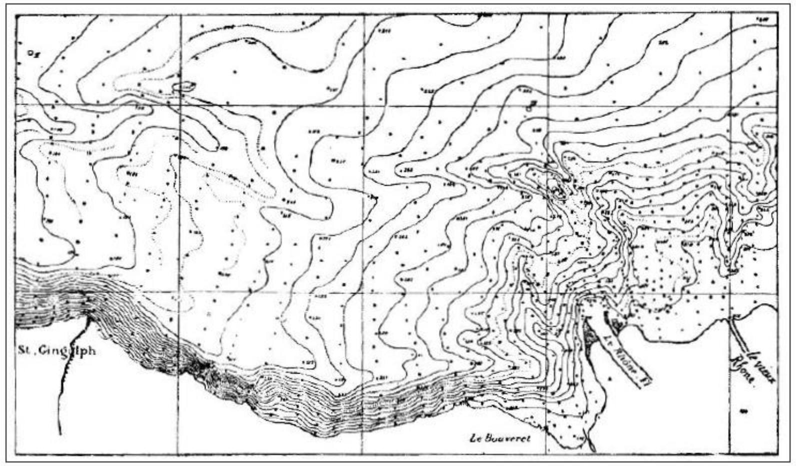
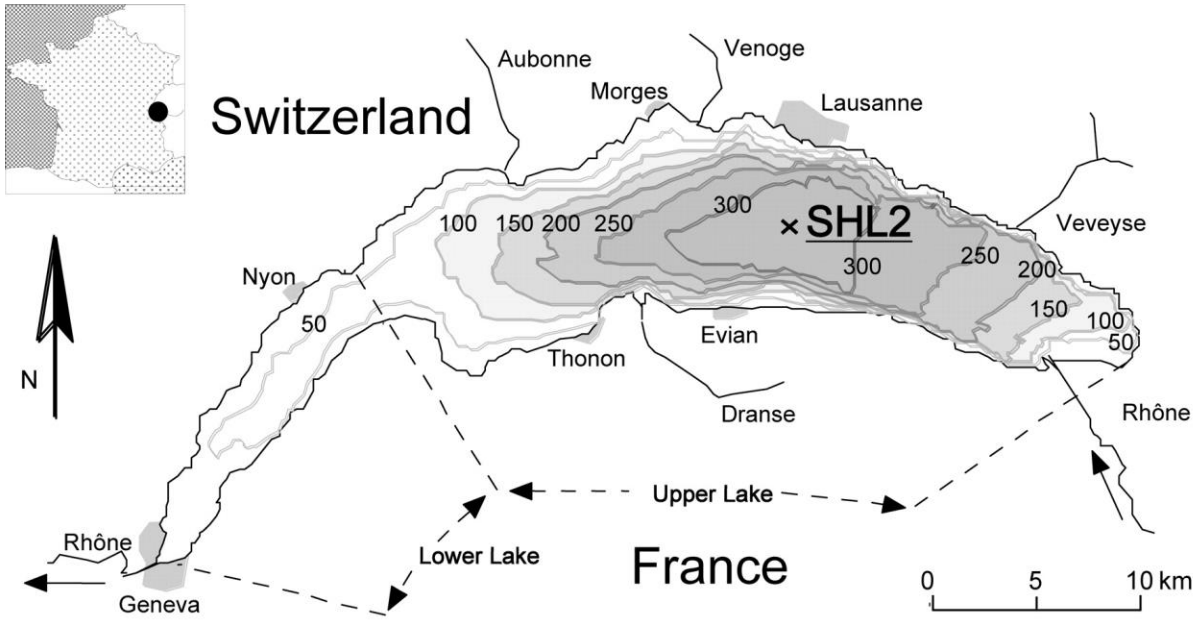


Fig. 1. Rhone channel bathymetry in Lake Geneva with 10 m contour line as drawn by J. Hörnlimann from manual soundings in 1885, and reproduced by Forel in his book Le Léman (p. 64, 1895).

Fig.2. Picture of François-Alphonse Forel, 46 years-old, in Lausanne (Photo Francis de Jongh 1887, © Musée historique de Lausanne).

Matters for:

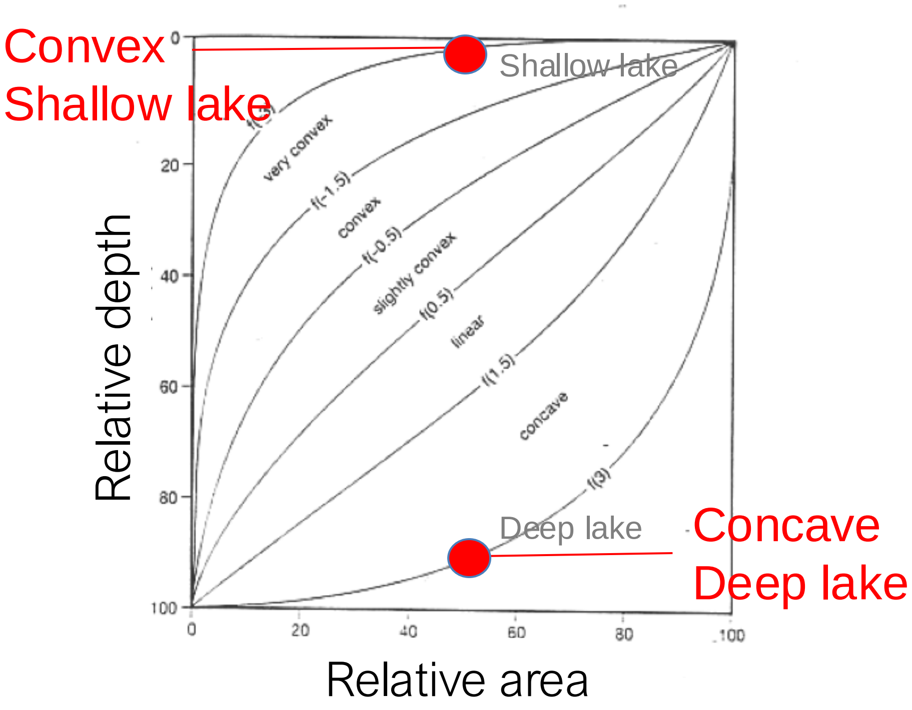
- Water storage
- Circulation and transportion processes



Lake bathymetry

Spatial distribution of water depth

Hypsographic curves
Relating depth to surface area



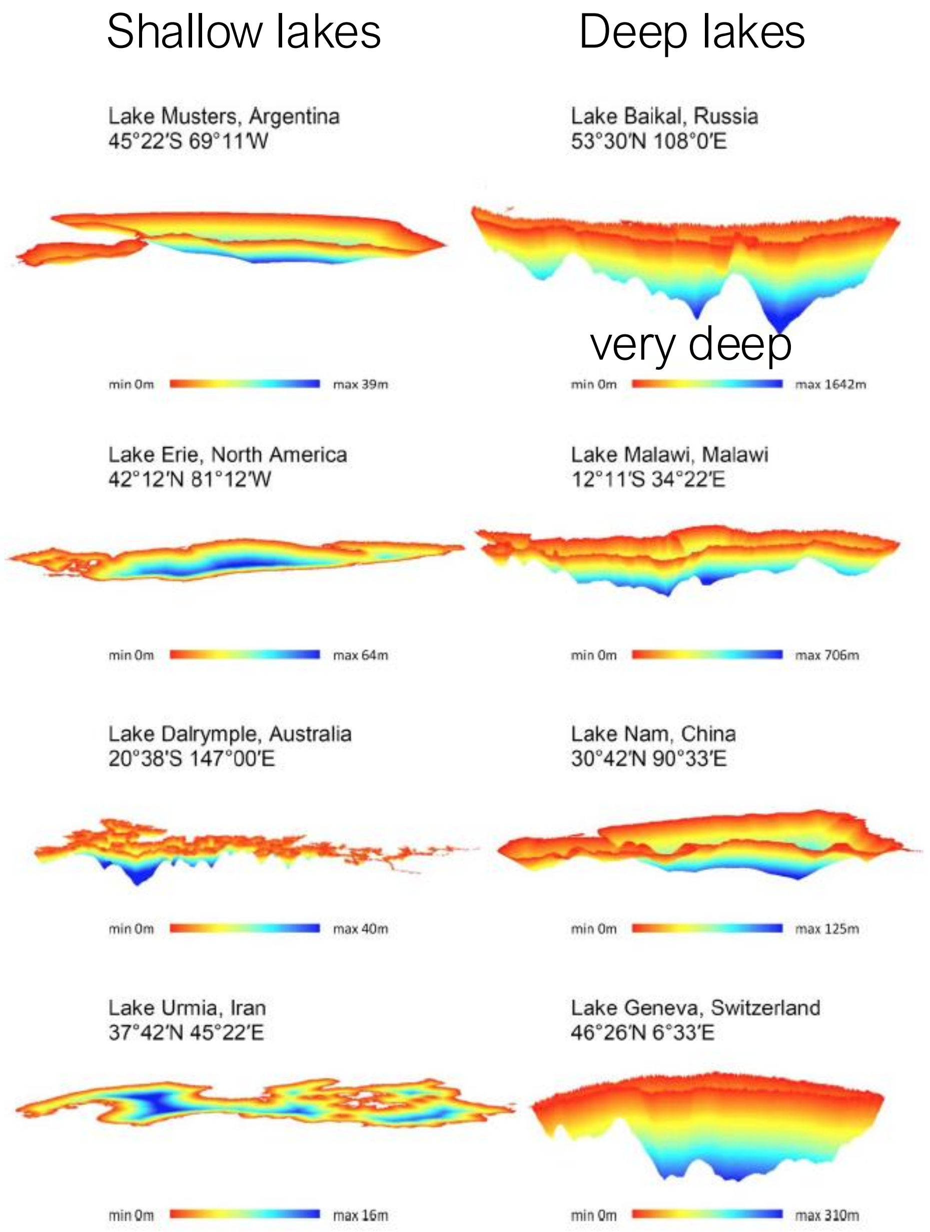


Fig. 2 Bathymetric maps for selected waterbodies in the GLOBathy dataset.

GLOBathy, the global lakes bathymetry dataset

Bahram Khazaei, Laura K. Read, Matthew Casali, Kevin M. Sampson & David N. Yates

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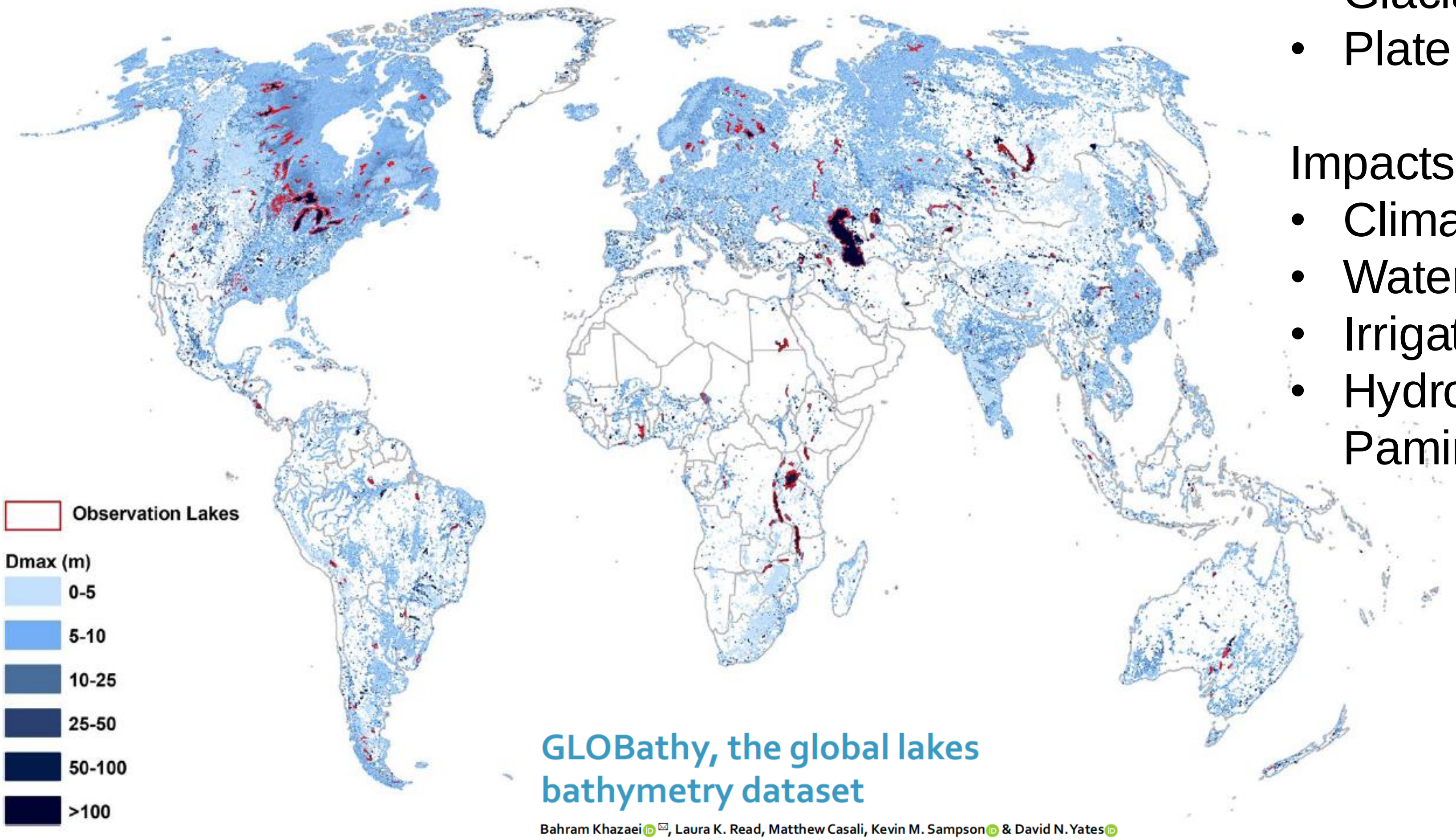
Lake bathymetry

Spatial distribution of lake depth

Global distribution of lake water depth (and volume)
- Glaciation
- Plate tectonics

Impacts for
- Climate
- Water resources
- Irrigation
- Hydrological cycle (e.g., see Pamir anomaly)



GLOBathy, the global lakes bathymetry dataset

Bahram Khazaei, Laura K. Read, Matthew Casali, Kevin M. Sampson & David N. Yates

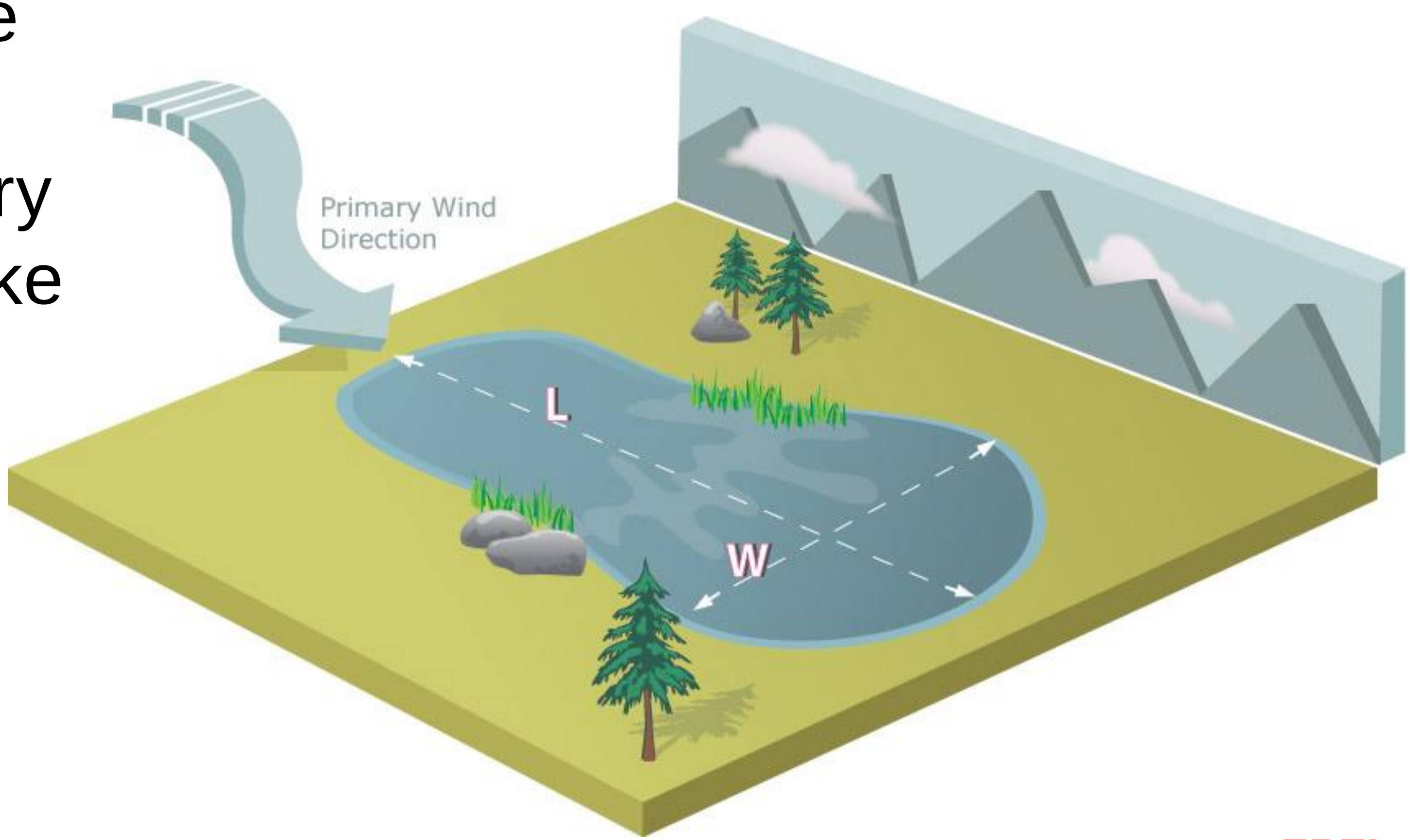
Fig. 1 Global waterbodies maximum depth (Dmax) distribution. Observational waterbodies are shown with red polygons.

Consequences of lake geomorphology: The wind fetch

The longest distance an air mass can travel across a lake

Depends on the lake geometry and the embedment of the lake in the landscape

- Lake mixing
- Energy exchange and balance (evaporation)



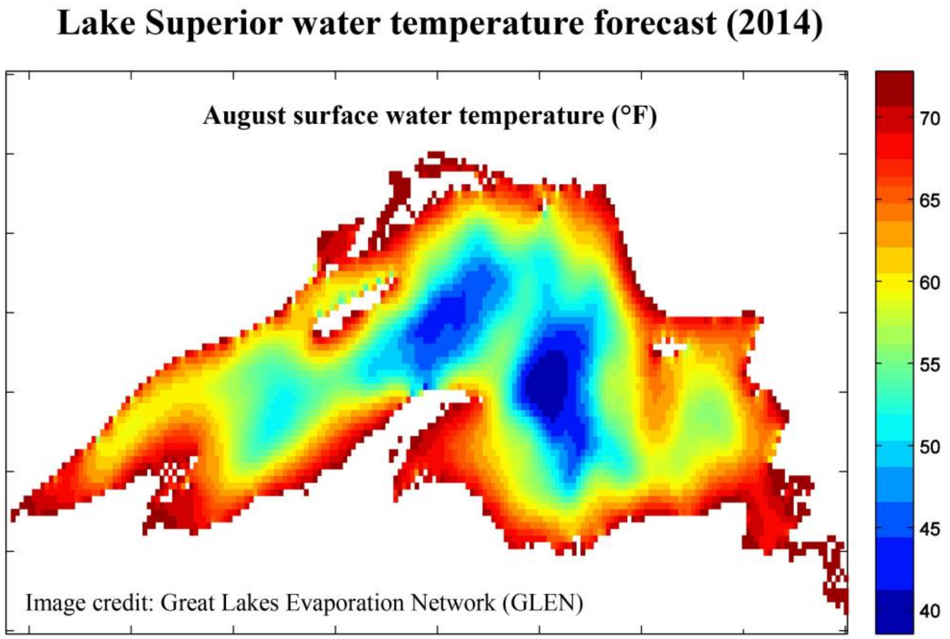
http://www.lakescientist.com/lake-shape/

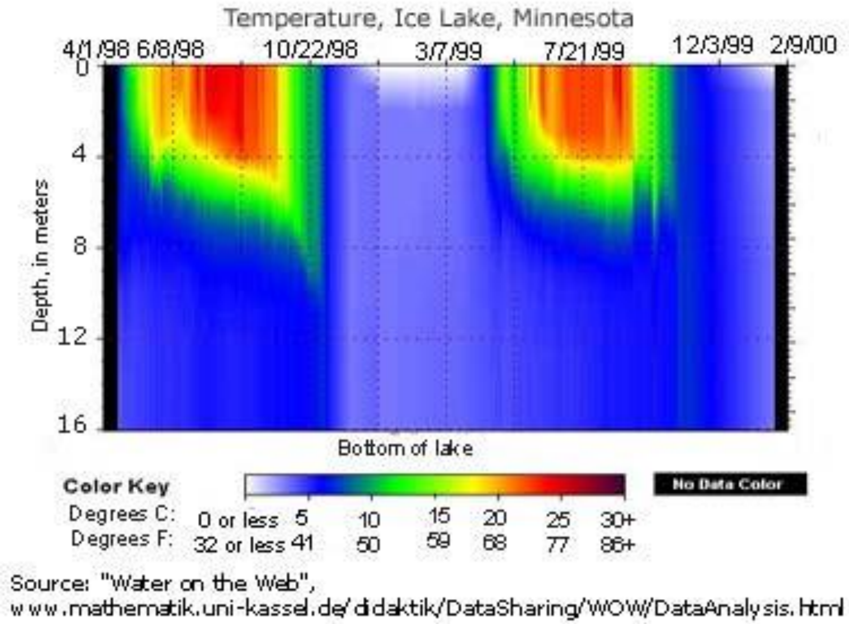
Consequences of lake geomorphology: Temperature and lig

Life, biogeochemical processes, gases, bathing

Horizontal

Vertical





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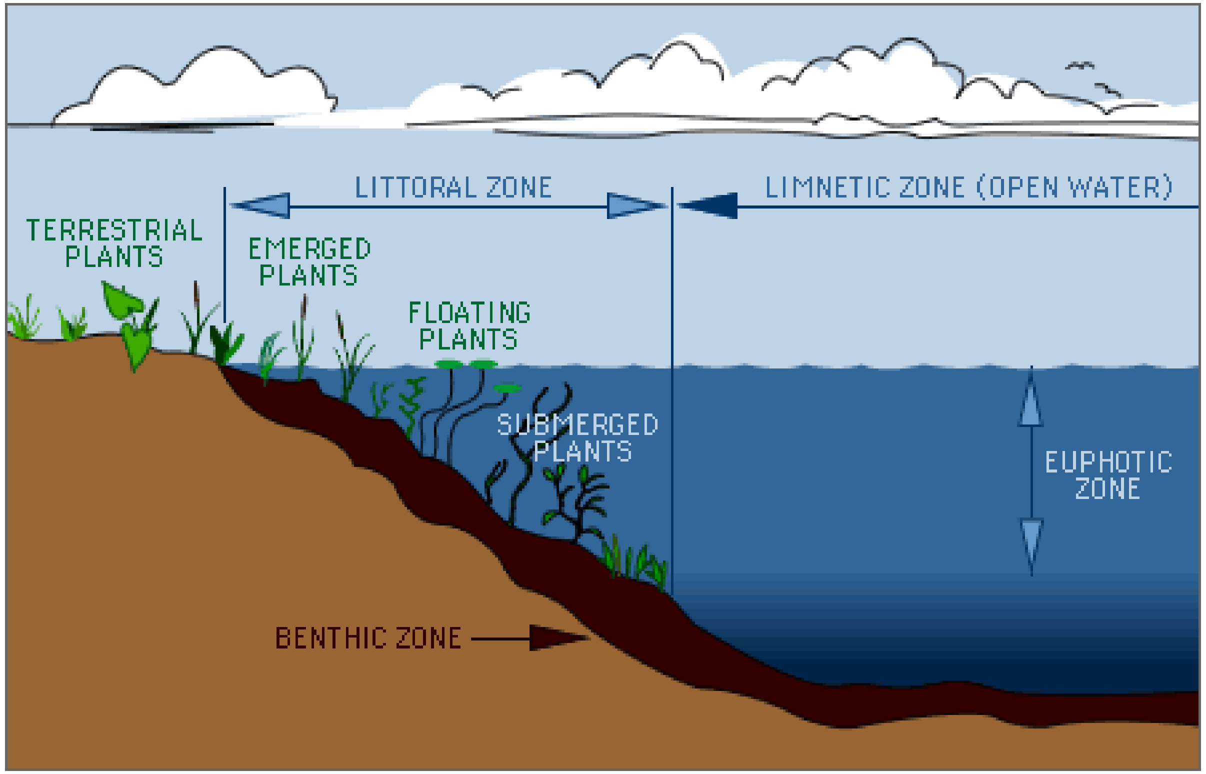
Consequences of lake geomorphology: Biodiversity

Depth distribution and perimeter translate into habitat zonation and heterogeneity, hence biodiversity

- Littoral zone
- Benthic zone
- Limnetic zone
- Euphotic zone
- Aphotic zone

Light regime



Light regime

- Thermal regime
- Photosynthesis

http://design.bi/natural-landscapes/

Light regime in aquatic ecosystems

Photons

Chemical energy

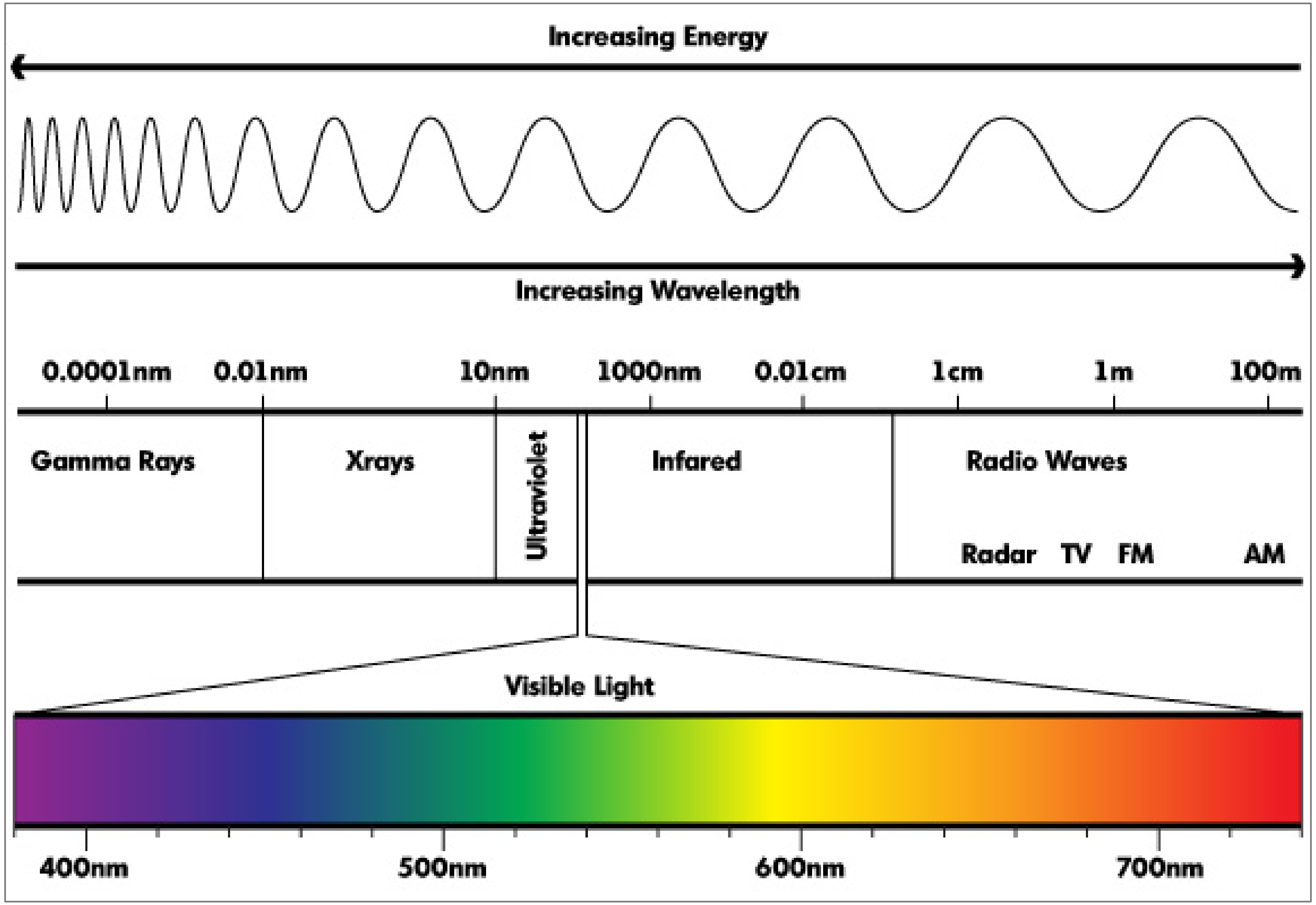
Thermal energy

Thermal energy: Heat transfer by electromagnetic waves or photons; absorption by dissolved molecules and suspended particles in the water.

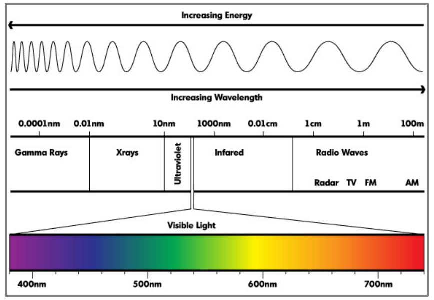
Chemical energy: Photosynthesis, primary production, organic carbon production, oxygen production, CO_2 assimilation.

How much energy a lake receives depends on its geomorphometry

Solar radiation

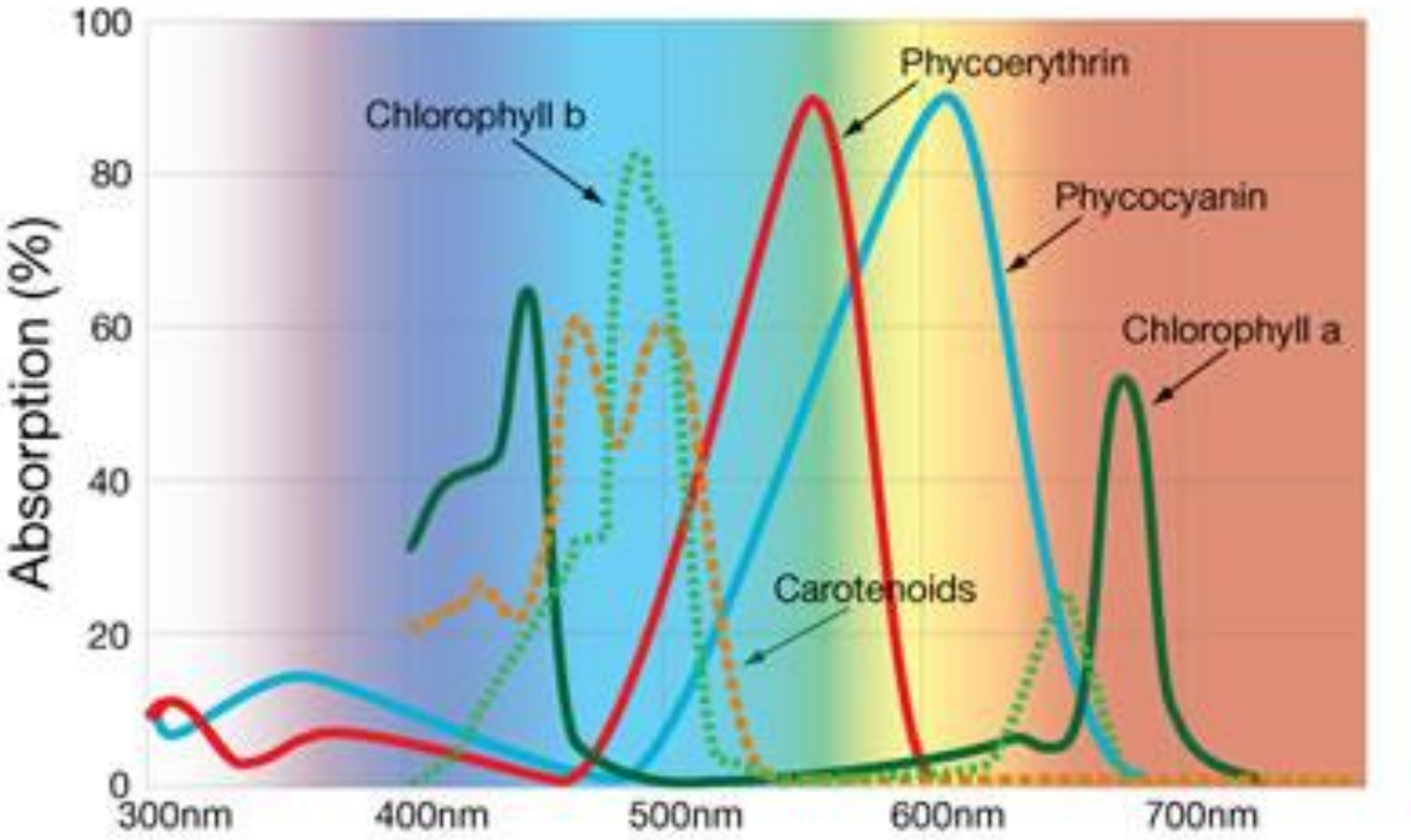


Solar radiation



Photosynthetic Active Radiation (PAR)

- Range of radiation wavelengths used for photosynthesis
- Major pigments capable to absorb various wavelengths
- Wavelengths changing with attenuation and depth
- Vertical stratification of niches



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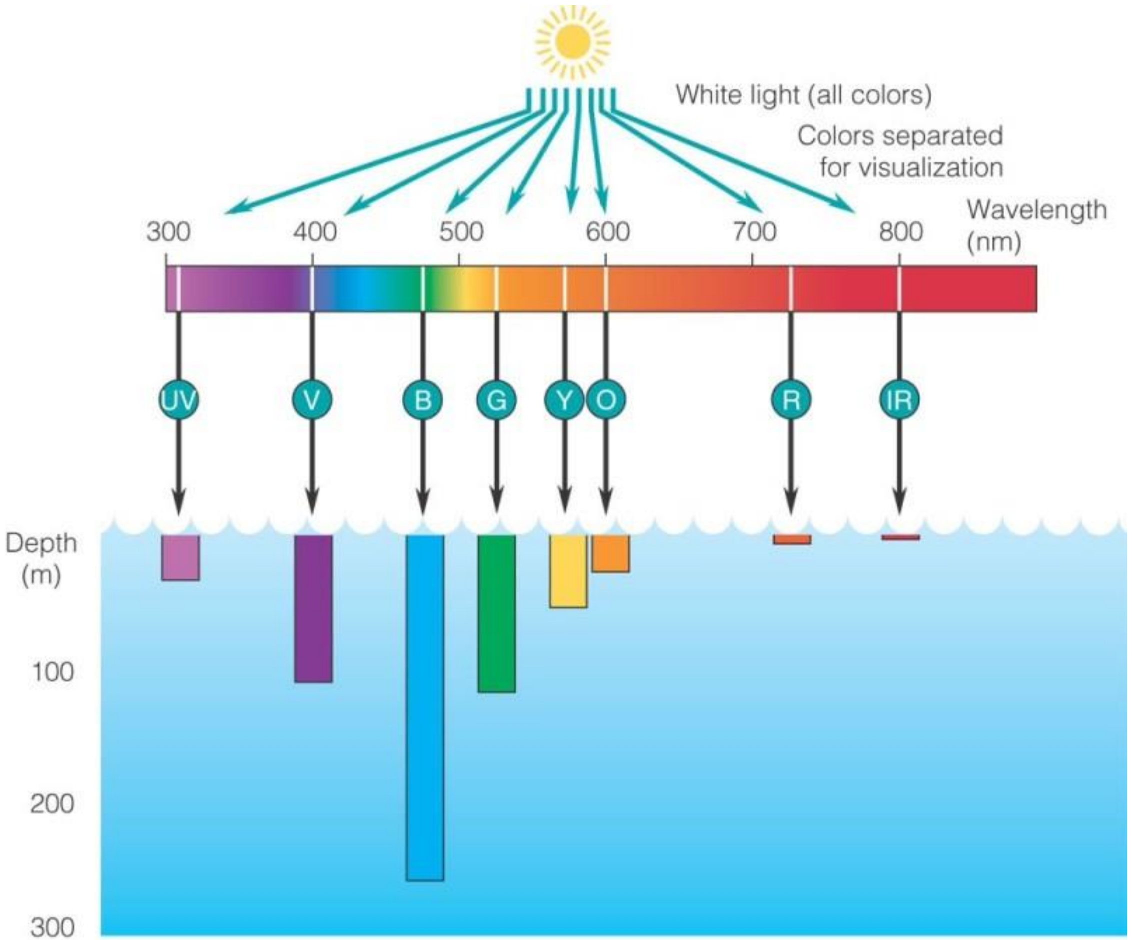
Light attenuation in a water body



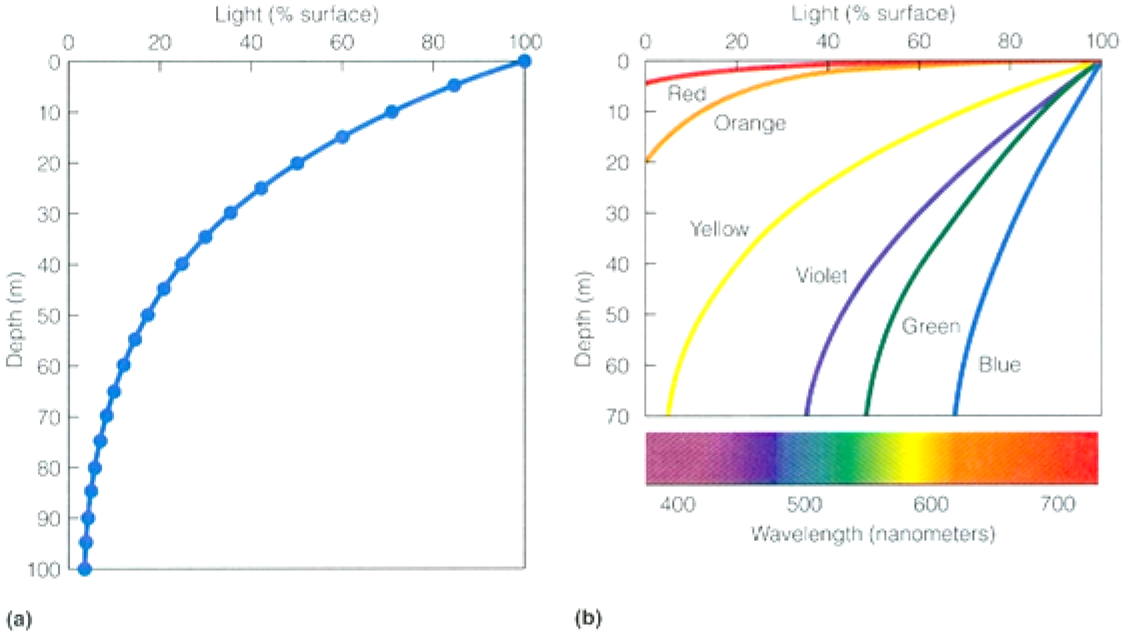
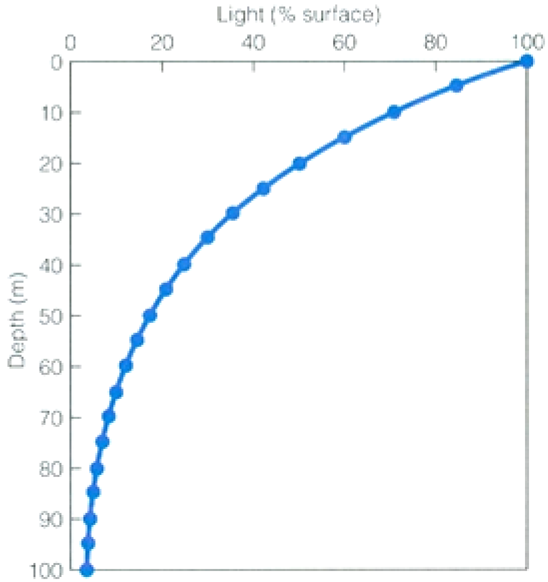


Figure 3.7 | (a) Attenuation of incident light with water depth (pure water), expressed as a percentage of light at the water surface. Estimates assume a light extinction coefficient of $k_w = 0.035$ (see Quantifying Ecology 4.1, pp. 63–64). (b) The passage of light through water reduces the quantity of light and modifies its spectral distribution (see Figure 2.4). Red wavelengths are attenuated more rapidly than green and blue wavelengths.

Vertical distribution of light intensity (I)



Reflection
Absorptio
n
Scattering

Attenuation, Transmission

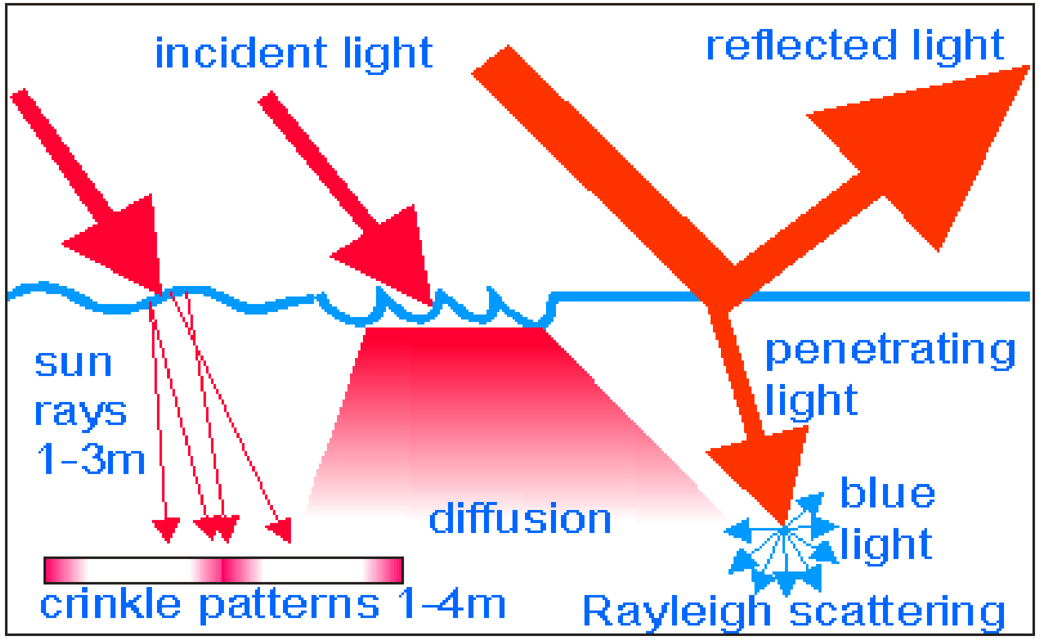
$$I_1 = I_o\, e^{-\varepsilon c d}$$

Lambert-Beer Law

I_1: Intensity of transmitted light ($W\ m^{-2}$)
I_0: Intensity of incipient light ($W\ m^{-2}$)
ε: Extinction coefficient ($m^2\ mol^{-1}$)
c: Molar concentration ($mol\ l^{-1}$)
d: Path length (depth) (m)

Light attenuation

Reflection (season, daytime, turbulence)



Reflection

- Time of the day
- Season (3% summer, 15% winter)
- Latitude
- Surface characteristics (waves, turbulence)

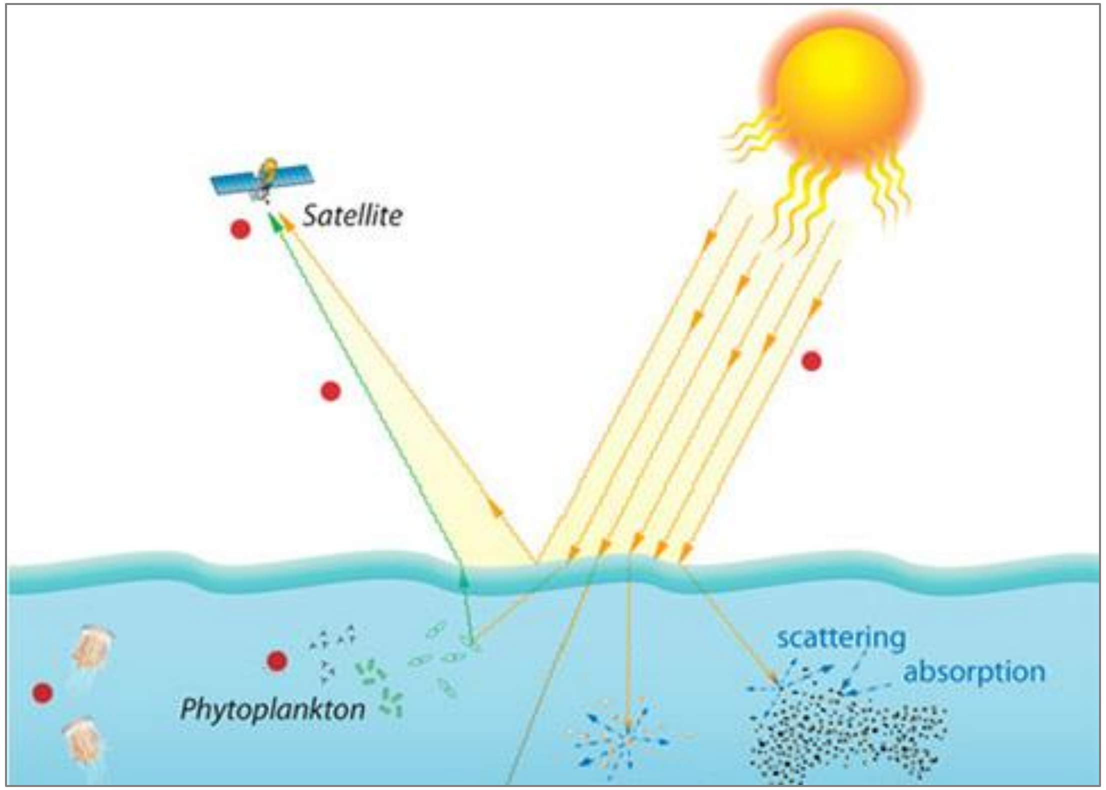
Light attenuation

Scattering:

Absorption (internal reflection) by molecules and particles

Depends on:

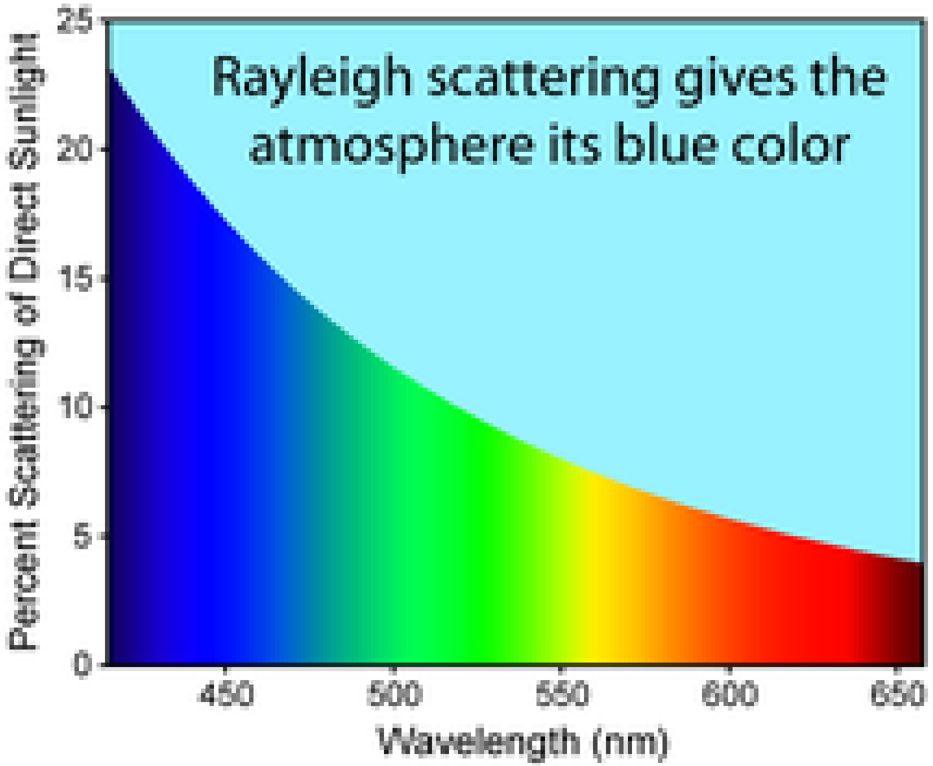
- Suspended particle composition and size
- Phytoplankton
- Dissolved organic matter concentration and composition



Light attenuation

Scattering:

Absorption (internal reflection) by molecules and particles

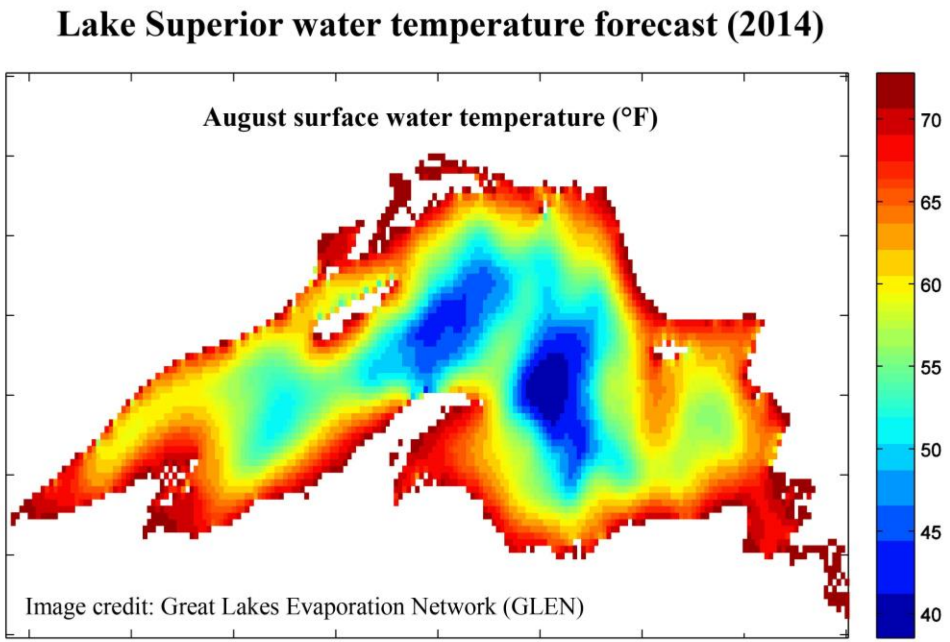


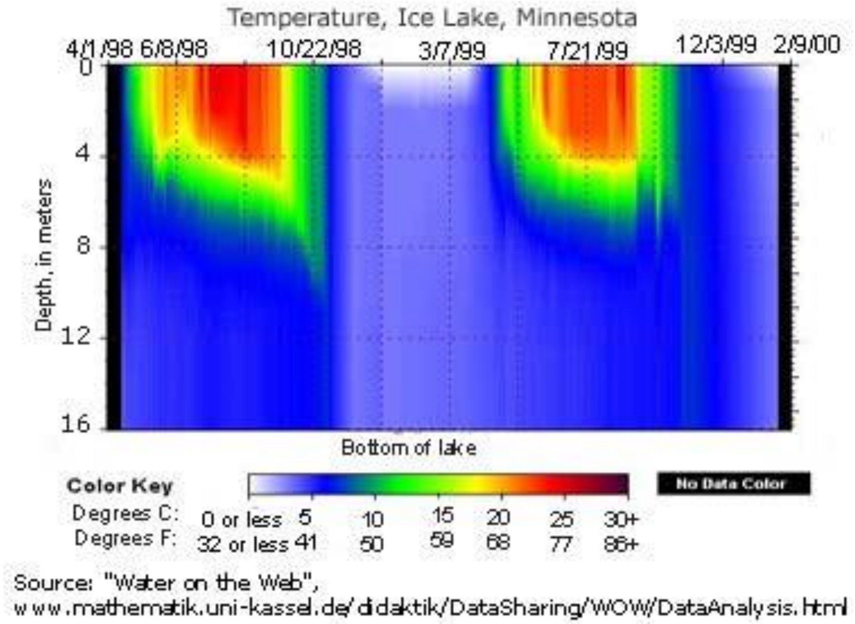
Scattering varies as a function of the ratio of the particle diameter to the wavelength of the radiation

The strong wavelength dependence of the scattering implies that shorter (e.g., blue) wavelengths are scattered more strongly than longer (e.g., red) wavelengths.

- Blue penetrates deepest into the water, while red, orange etc are absorbed in shallow layers.
- Strongest internal reflection of blue light; magnified by particles (e.g., calcite) in clear water.

The interplay between light and temperature





Light and Temperature

PERSPECTIVE www.rsc.org/pps | Photochemical & Photobiological Sciences

Differences in UV transparency and thermal structure between alpine and subalpine lakes: implications for organisms†

Kevin C. Rose,*[a] Craig E. Williamson,[a] Jasmine E. Saros,[b] Ruben Sommaruga[c] and Janet M. Fischer[d]

Received 20th March 2009, Accepted 1st July 2009
First published as an Advance Article on the web 3rd August 2009
DOI: 10.1039/b905616e

Turbid lake

Clear-water lake

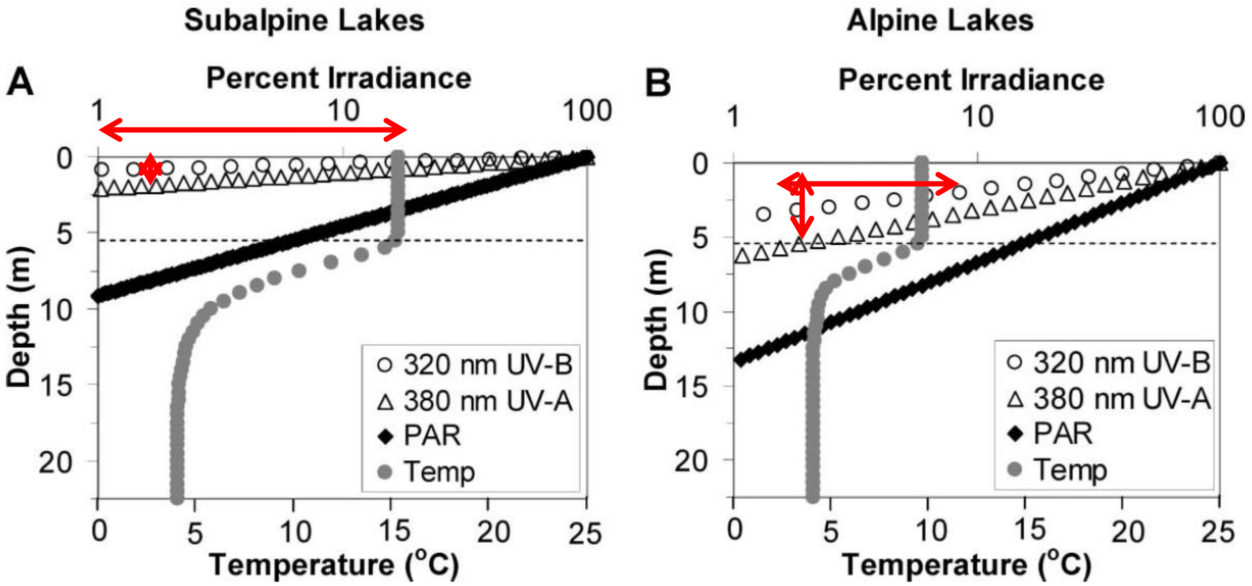


Fig. 1 Mean percent irradiance for 320 nm, 380 nm UV, and PAR and temperature data for subalpine (left, A) and alpine (right, B) lakes plotted *vs.* depth show that physical structure of subalpine, and alpine lakes differ in important ways. Transparency data are based on average epilimnetic diffuse attenuation coefficients and temperature data are based on surface temperatures, mixing depths, and hypolimnetic temperatures of lakes in Table 1.

- Strong attenuation of UV and visible light
- Elevated warming of the shallow waters

- Weak attenuation of UV and visible light
- Reduced warming of the shallow waters

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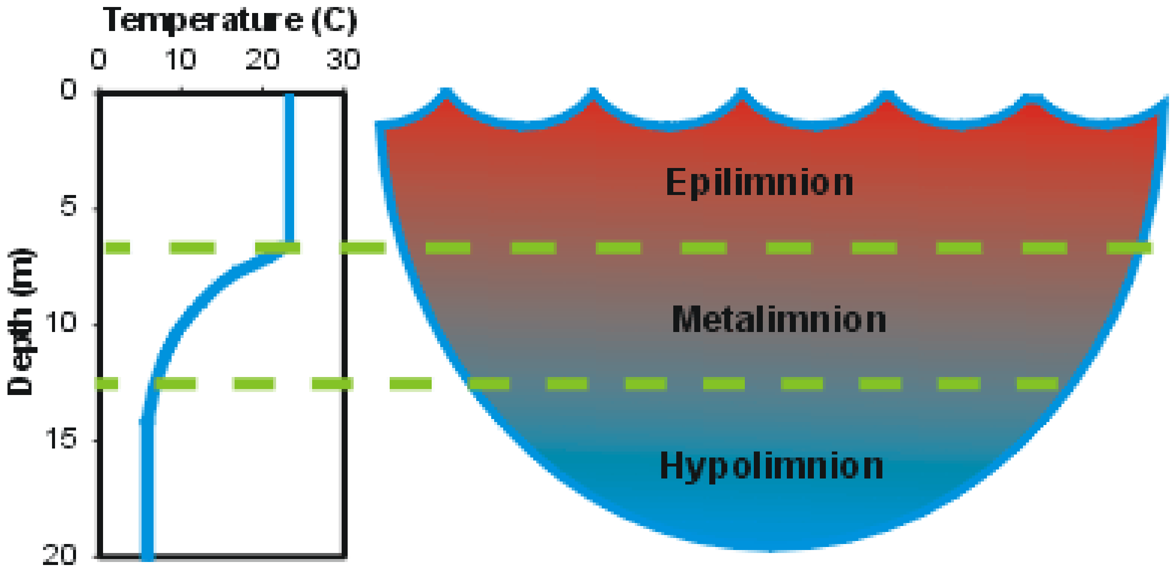
Vertical distribution of temperature in lakes



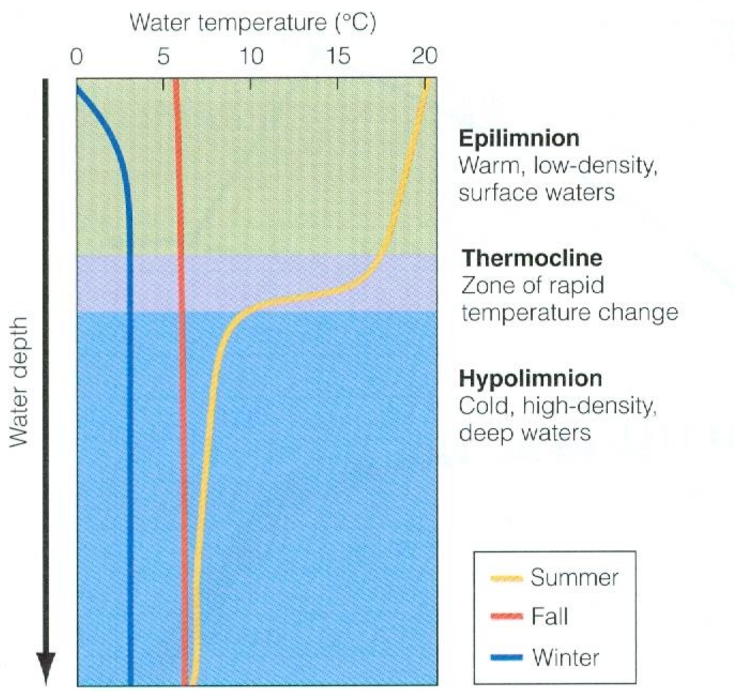


Figure 3.9 | Seasonal changes in the vertical temperature profile (with water depth) for an open body of water such as a lake or pond. As air temperatures decline during the fall months, the surface water cools and sinks so that the temperature is uniform with depth. With the onset of winter, surface water further cools and ice may form on the surface. When spring arrives, the process reverses and the thermocline once again forms.

Vertical distribution of temperature in lakes

Lake stratification and recirculation

Mixis patterns and magnitude depend on numerous factors:

- Geometry and wind fetch
- Energy balance
- …

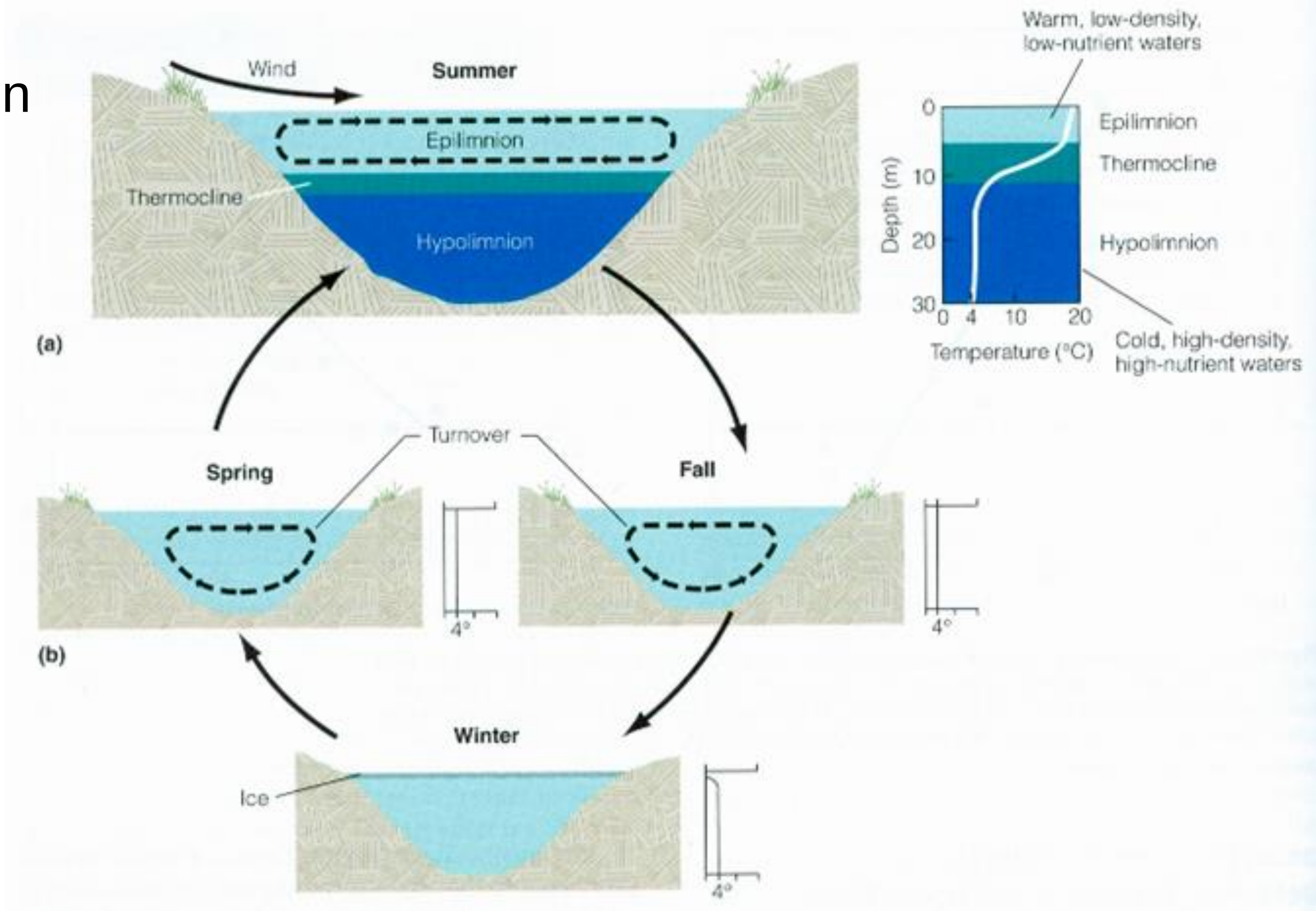
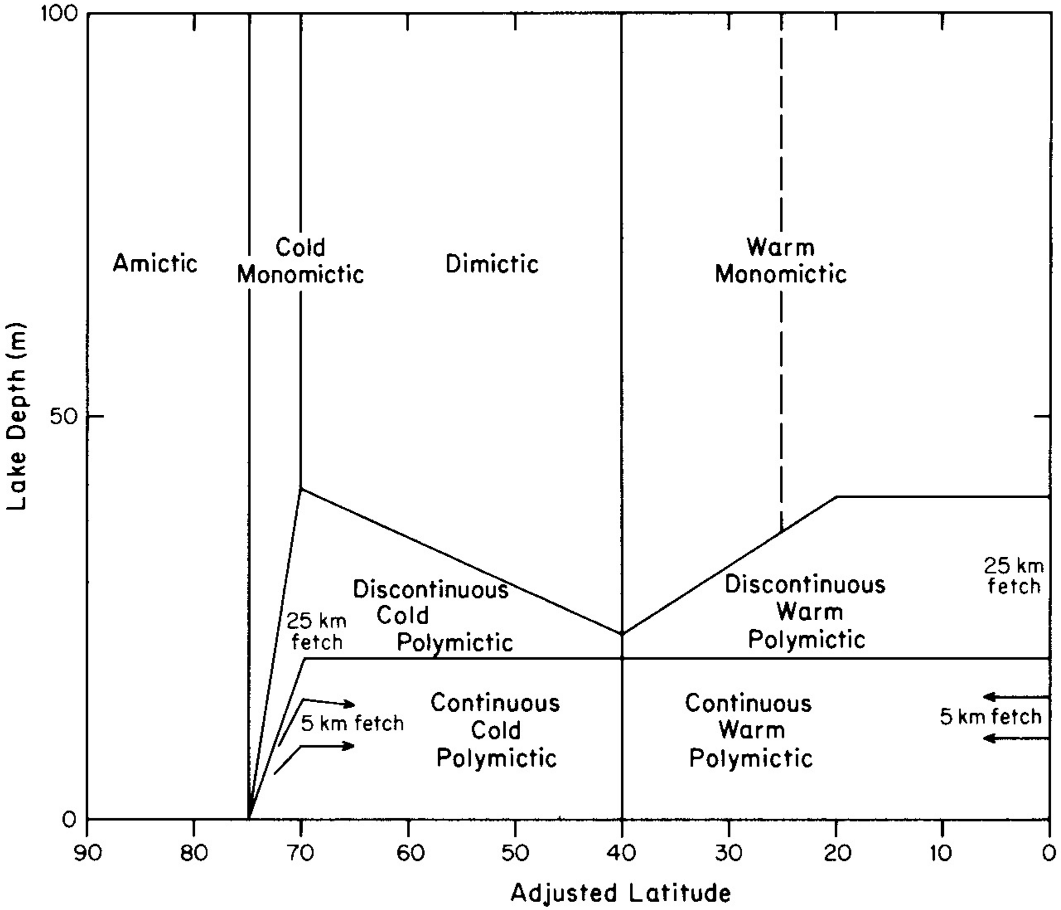


Figure 21.23 | Seasonal dynamics in the vertical structure of an open-water aquatic ecosystem in the temperate zone. Solid arrows track seasonal changes, and dashed arrows show the circulation of waters. Winds mix the waters within the epilimnion during the summer **(a)**, but the thermocline isolates this mixing to the surface waters. With the breakdown of the thermocline during the fall and spring months, turnover occurs, allowing the entire water column to become mixed **(b)**. This mixing allows nutrients in the epilimnion to be brought up to the surface waters.

Lake stratification and recirculation

Amictic: polar and alpine lakes with permanent ice cover
Cold monomictic: polar and subpolar lakes; summer circulation; winter stagnation
Dimictic: temperate lakes, recirculation in fall and spring
Warm monomictic: subtropical; winter circulation
Oligomictic: tropical; circulation unpredictable
Warm polymictic: tropical; circulation at night
Cold polymictic: tropical; high-elevation lakes

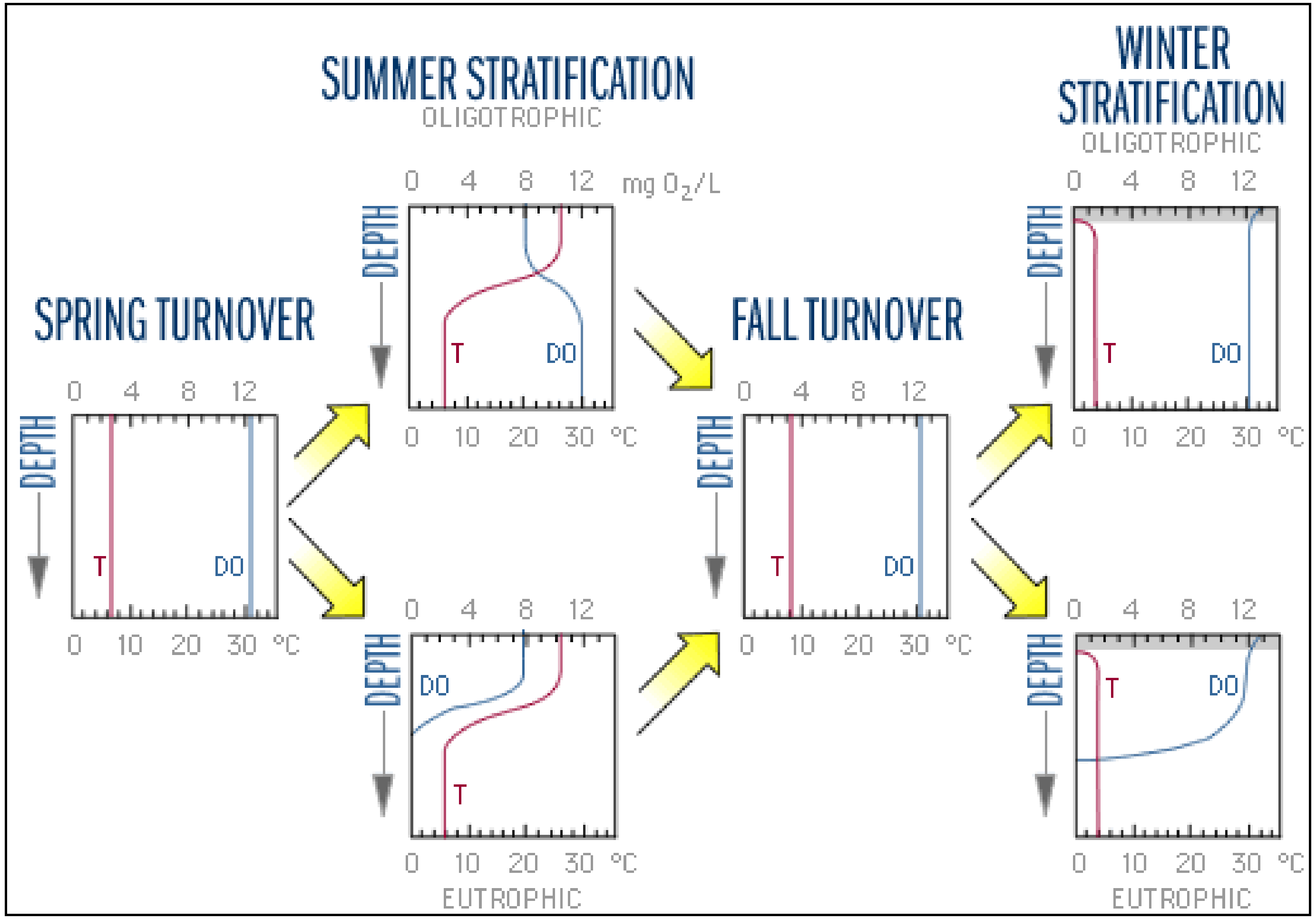


Modified from Hutchinson and Löffler 1956

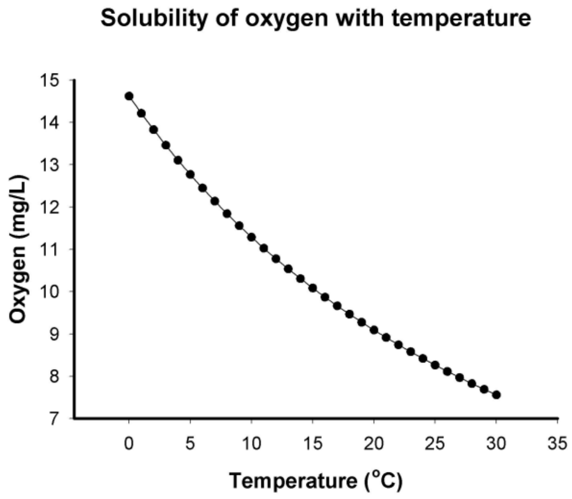
Lake stratification and recirculation

Temperature stratification affects oxygen distribution

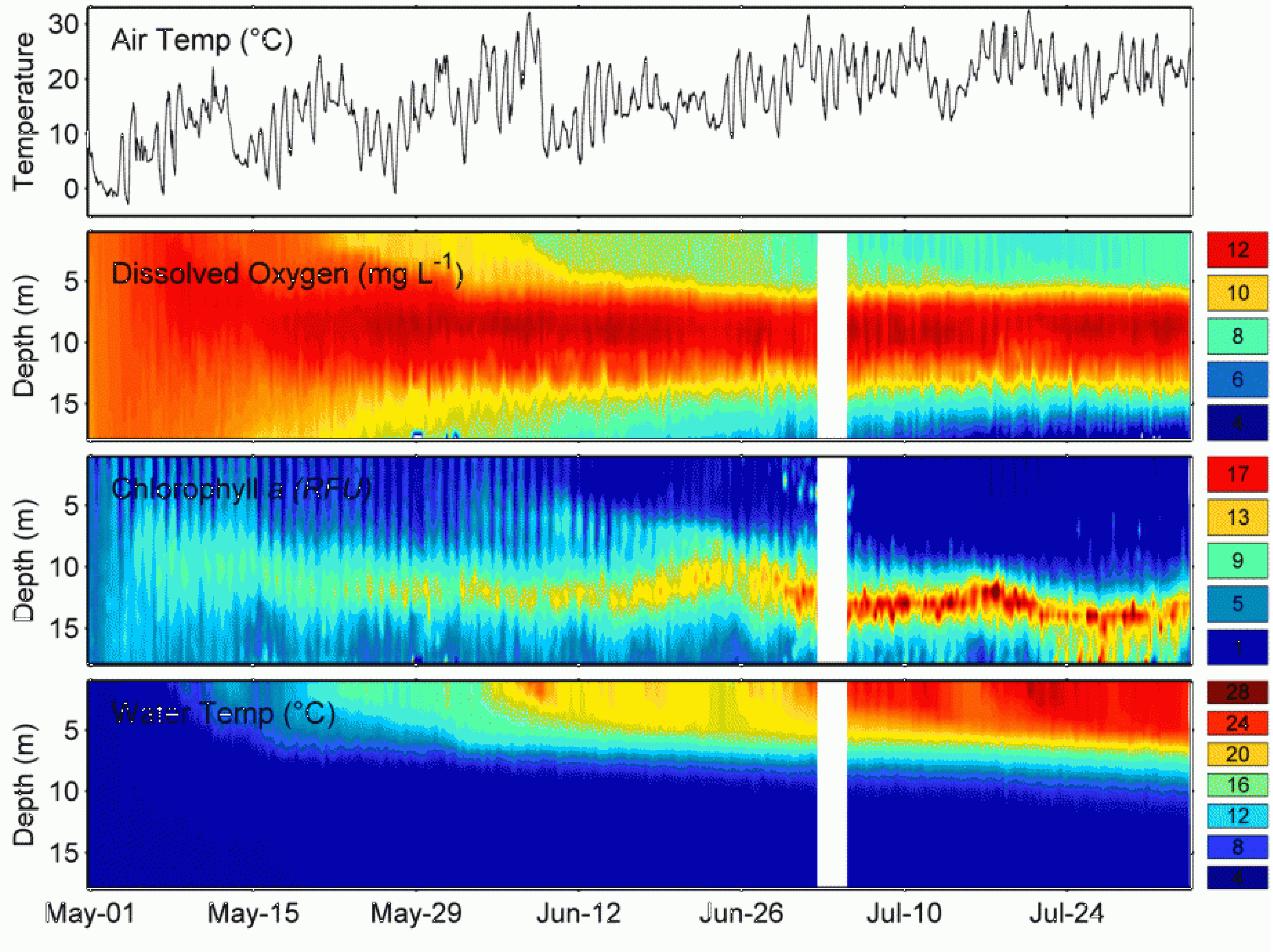
Critically important for the life in lakes



- Temperature affects O_2 solubility
- Temperature affects O_2 consumption and replenishment



Temperature stratification affects oxygen distribution



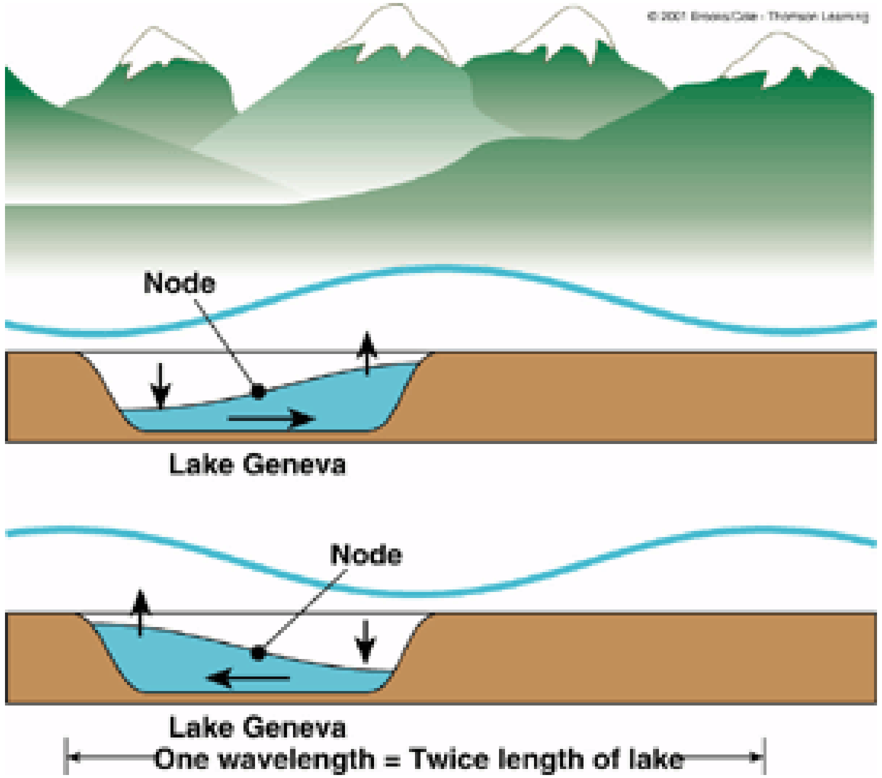
https://www.lternet.edu/research/keyfindings/real-world-solutions

- Temperature affects O_2 solubility, hence O_2 concentration
- Phytoplankton (chlorophyll a) in deeper layers produces O_2

EPFL

Erosion of lake stratification

Seiches – internal waves

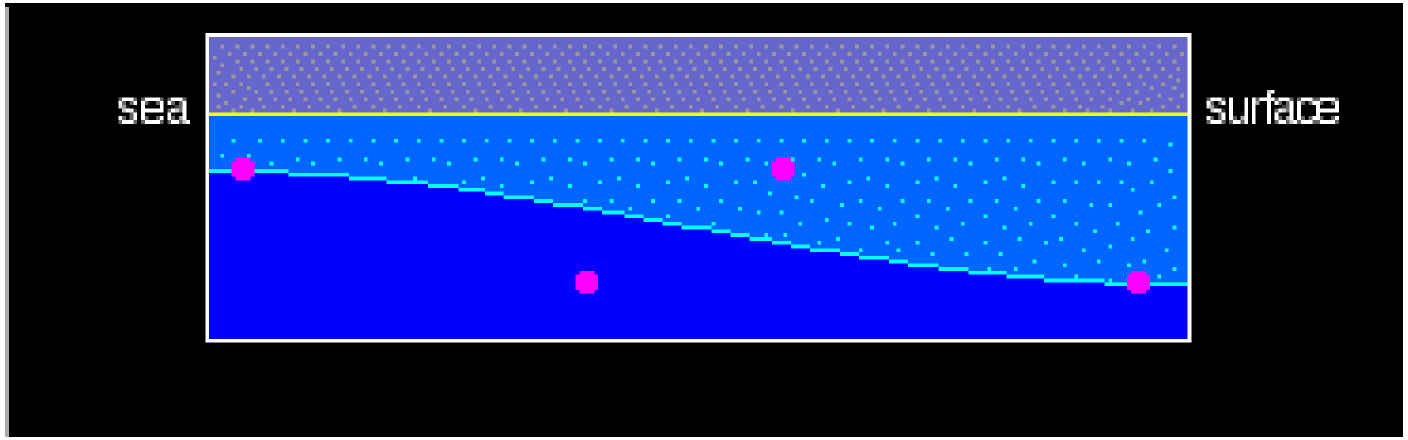


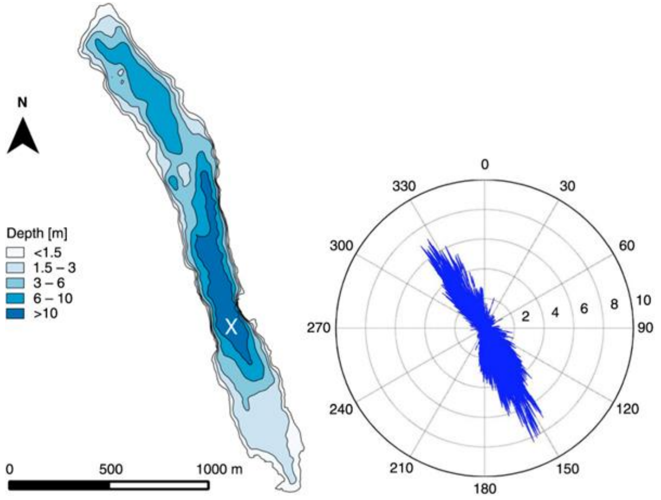
A seiche is a standing wave in an enclosed or partially enclosed body of water

First described by F.A. Forel for Lake Geneva ("to sway back and forth“).

Seiches – internal waves

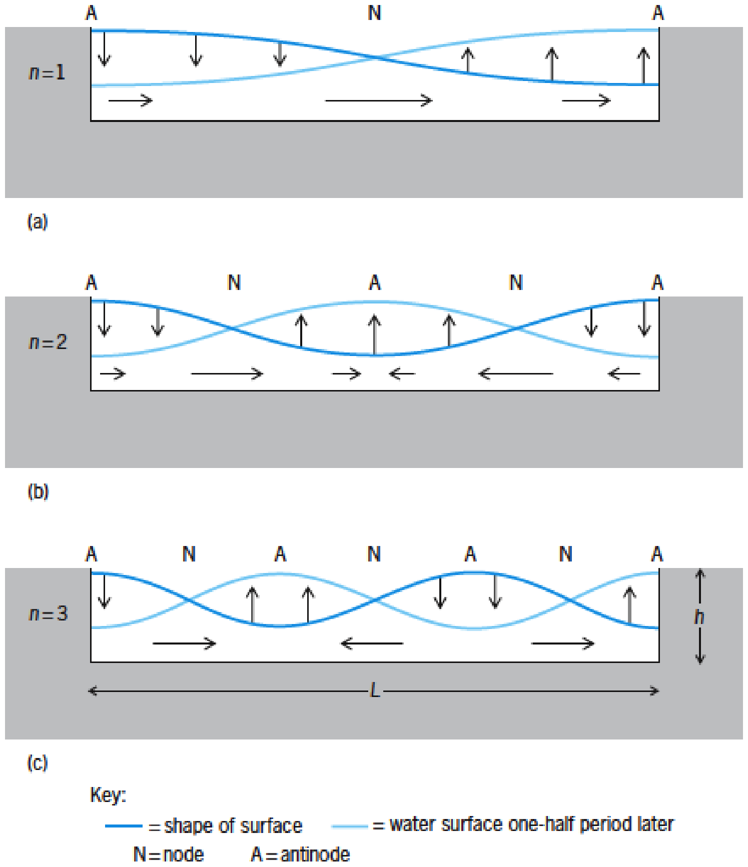
Facilitated by long wind fetch and continous wind





Eawag

Seiches – internal waves



Uni-nodal or poly-nodal seiches depending on lake geometry, size and wind action

Mixing and erosion of stratification

Seiches – internal waves

Seiches – internal waves

Loch Ness (A glacier lake)
Elongated geometry

Benoit Cushman-Roisin

Lakes

- Different origins
- Basin morphometry
- Radiation and temperature
- Oxygen
- Stratification and recirculation
- Seiches