Alpine Lakes: Extreme Ecosystems under the Pressures of Global Change

Cold temperatures, lack of nutrients, intensive UV radiation or darkness for months make high mountain lakes extraordinary habitats. The organisms they harbor must be experts in adaptation; however, even these remote lakes are no longer untouched. Anthropogenic influences add to natural factors and affect these ecosystems. Since high mountain lakes are particularly sensitive to environmental change, they are used as early warning systems. It remains to be seen, however, what direction these changes will take.

Alpine lakes are extreme ecosystems and, at first glance, appear to be hostile environments. They are characterized by highly acidic or alkaline, hot or cold conditions, are subject to high pressure or intense radiation (particularly UV radiation), and/or by unusually high or low salinity. Alpine lakes are often extreme with respect to more than just one parameter and, over the course of a year, different extremes may rapidly succeed one another.

In addition, alpine lakes are increasingly affected by anthropogenic influences. Global climate change is not the only factor; the atmosphere transports organic chemicals to these remote locations and deposits them into the lakes. Another problem is that humans can, intentionally or unintentionally, introduce organisms, some of which may not naturally occur in high mountain lakes. High mountain lakes are very sensitive to environmental changes and have been used since the 1980s as early warning systems (see box).

Naturally Extreme …

The snow cover on an alpine lake can grow to several meters and can block all light from the lake (Fig. 1). In the 10 m deep Gossenköllesee, for example, the ice and snow cover amounts to one third of the total lake volume at the time of maximum snow cover [1]. Without light, photosynthesis is no longer possible, and the entire water body turns into a heterotrophic system that is completely cut off from its surroundings for 6 to 8 months. It was only recently discovered that during this period, a mostly microbial community can develop, containing aquatic as well as terrestrial and atmospheric elements [2, 3].

After the long darkness of winter, alpine lakes make the transition to extremely bright conditions within a very short period of time. This takes place at the end of June or in early July when solar radiation reaches its maximum, and the ice breaks up. The higher the lake is situated, the stronger the shortwave UV radiation (UVB, 280–320 nm wavelength). At an elevation of 3000 m, UVB radiation is approximately 50% higher than it is at sea level. In addition, due to changes in the ozone content of the stratosphere, UVB radiation has increased by roughly 10% since 1970.

Because of the lack of humic acids and other dissolved organic compounds, UV radiation penetrates high mountain lakes to depths of 20 m (Fig. 2). On a sunny day, there is no safe depth at which an organism would be protected from UV radiation [4]. One adaptation to this extreme condition is the embedding of mycosporine-like amino acids, the so-called MAAs, into small crustaceans [5]. These MAAs are taken up with the algae they eat and absorb harmful UV radiation in the range between 310 and 340 nm.

… but not Extremely Natural

Naturally-occurring extreme conditions are increasingly superimposed on by the effects of anthropogenic activities. One of the most dramatic impacts on natural waters is the introduction of alien species [6]. Fish do not naturally occur in high mountain lakes. When lakes are stocked with fish, other species can be wiped out, such as rare species of daphnia; in extreme cases, this can lead to the complete destruction of the ecosystem, not to mention the fact that fish are poorly adapted to life in a nutrient poor, low salinity mountain lake [7]. One curiosity is the survival of a river trout from the Danube that was used to stock high mountain lakes on the orders of Emperor Maximilian I over 500 years ago. An interesting

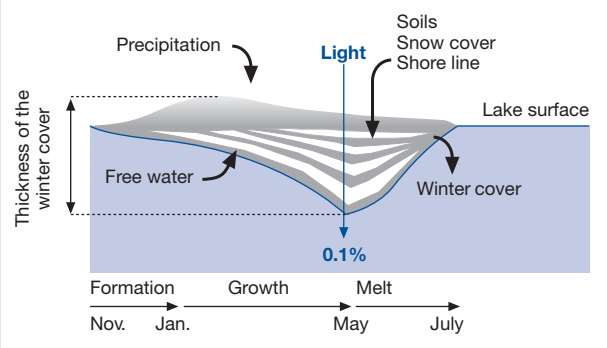

Fig. 1: Formation, growth and melting of the snow cover on alpine lakes. A centimeter thick layer of clear ice is overlain by a several meter thick structure of slushy snow (white) and opaque ice (grey). Origin and transport of microorganisms are indicated by arrows. Adapted from [3].

Fig. 3: From hunting and fishing chronicles of Emperor Maximilian I. He had high mountain lakes in Tyrolia stocked with trout and char around the year 1500.

sub-species of this trout has survived in two alpine lakes in Austria (Fig. 3).

Even anthropogenic pollutants like polychlorinated biphenyls (PCBs), DDT and their degradation products find their way into alpine lakes. The location of their use or their release is of little importance; the atmosphere transports these pollutants around the globe [8]. Where these contaminants accumulate, however, is controlled by temperature. Highly volatile compounds, such as hexachlorobenzene, accumulate only in the polar regions. Less volatile compounds, such as PCB-153, PCB-180 and DDT, accumulate in the cold areas of lower latitudes, as for example, at high elevations in the Alps. For this reason, fish from alpine lakes contain up to 1000 times more PCB (Fig. 4) and DDT than fish from lakes at lower elevations [9].

Global Warming and its Consequences

Open for discussion is the question of how alpine lakes will change in response to global warming [10]. Schwarzsee (Fig. 5), for example, was under ice year-round during the early 1900s; at that time the average temperature in the Alps was almost 2 °C lower than it is today. Its watershed, small in size and barely reaching 3000 m, had a permanent snowfield until the 1980s. In addition, it can be assumed that the ground was in permafrost. Since 1985, there has been a strong warming trend, with the result that Schwarzsee is ice-free from July until September, and that the snow fields melt out completely in late summer. The lake has changed dramatically in response to these climatic changes: the pH has increased dramatically while conductivity and dissolved silicate have doubled. Furthermore, Schwarzsee is now warmer and more productive – properties that counteract the increased acidity in precipitation [11]. Climate change has, therefore, led to a decrease in some of the extreme conditions; however, under water UV radiation has increased due to the longer ice-free period, thus making conditions from this perspective more extreme for organisms.

High Mountain Lakes as Indicators

Five properties make high mountain lakes ideal indicators of global climate change:

Uniform: Depending on the elevation, we find alpine lakes in all latitudes, from the equator to the poles; they are comparable

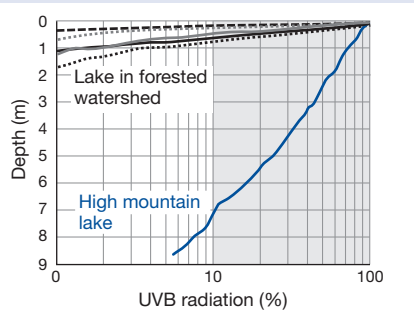

Fig. 2: Penetration depth of UVB radiation (wavelength = 305 nm) in lakes with high and low concentrations of dissolved organic compounds or humic acids. Adapted from [4].

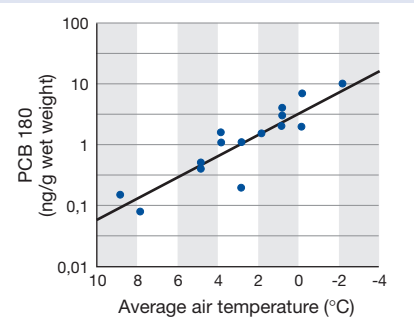

Fig. 4: Accumulation of polychlorinated biphenyl 180 (PCB-180) in fish from different European mountain lakes. Average air temperatures span a range of approximately 10 °C, which leads to a 100-fold increase in accumulation. Adapted from [9].

The central hypothesis

The condition of a lake depends essentially on three factors, with these factors linked in a hierarchical sequence: factor 1 influences factors 2 and 3; factor 2 influences factor 3; and factor 3 results in the expression of specific characteristics of a particular lake.

- **Factor 1: *The climate and atmospheric depositions …***
  … create the spatial and temporal gradients governing the driving forces.
- **Factor 2: *The geology, the soils and the vegetation in the watershed …***
  … determine the sensitivity of a lake towards external influences.
- **Factor 3: *The internal dynamics of the lake (organisms, chemical cycles) …***
  … determine the response of the individual lake to stress.

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Fig. 5: 100 years ago, Schwarzsee, situated at 2800 m a.s.l. above Sölden in the Ötztal Alps of Austria, was ice-covered year-round.

worldwide and have many common characteristics.

Remote: Thanks to their distance from human settlements and activities, alpine lakes are affected only by global impacts, such as air pollution or climate change; that is, if there are no local disturbances, such as roads, ski areas or mountain huts.

Simple: High mountain lakes are usually small, not very deep, species poor, and characterized by a simple food web; they are, therefore, generally easier to understand than other ecosystems.

Extreme: Physico-chemical conditions, such as temperature, UV radiation, ice cover and nutrient status are usually more extreme than in lakes at lower elevations; even small changes in these driving forces cause detectable responses.

Sensitive: Because of the extreme conditions and their immediate response to change, high mountain lakes are very much at risk from global impacts.

Minimize Anthropogenic Impacts

Despite that fact that cause and effect relationships are complex and that the future development of global environmental conditions cannot be predicted with any certainty, we can state some conclusions regarding the characteristics and fate of alpine lakes:

- Alpine lakes are both extreme and extremely sensitive to anthropogenic (and natural) changes. Some of these changes, for example, acidification and warming, cancel each other; some changes have such an impact that they completely obscure other changes that are taking place at the same time.
- Extreme conditions have induced interesting adaptations in organisms; however, several are living at the limit of their capabilities.
- Alpine lakes are remote, but not unaffected. There are no "natural" high mountain lakes in the strictest sense, since they all are affected by global processes. Despite this fact, alpine lakes are one of the last nearly natural types of ecosystems in a world increasingly altered by human activity.
- For this reason, we have to reduce all human impacts to an absolute minimum: this goes for local impacts (alien species, tourist developments) as well as global changes (emission of pollutants and greenhouse gases).

Over the last 2 years, we have learned a great deal about extreme environments, about alpine lakes and the complex interactions, but we should be ready for more surprises and revelations.

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