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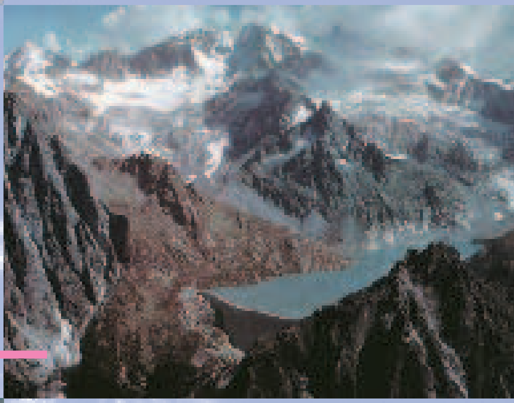
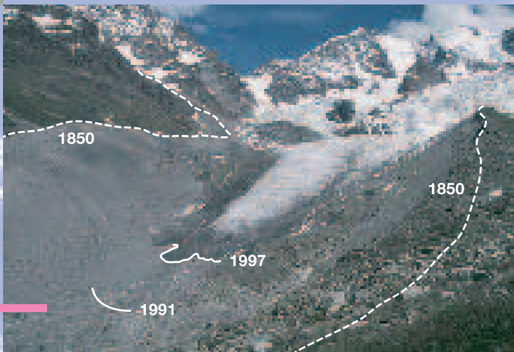
Alpine Waters – Fragile Diversity in Peril





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Alpine Waters in Peril

Lead Article

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In Brief

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Phone +41-1-823 55 11
Fax +41-1-823 53 75
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Editor Martina Bauchrowitz, EAWAG

Translations Norbert Swoboda, USA

Linguistic revision Helen Bruegger-Clarke, Zurich

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Behind the Alpine Scenery

Bernhard Wehrli,
Head of the department
"Surface Waters"

The solitude of mountain lakes and wild glacial streams adorns many postcards and travel brochures. The fact that human activity changes the character of these alpine habitats often does not fit into this idyllic picture. For at least 4000 years, alpine forests have been cleared and the open areas used for pastures. Pollen of flowering plants, embedded in sediments of alpine lakes, can document this fact. In light of the current transformation of Alpine valleys into European transportation corridors, the protection of these routes and of the villages from floods and landslides is becoming ever more urgent. Steps, weirs and levies keep our wild alpine streams in bounds. For over 100 years, we have used hydropower – the white gold of the Alps. Relative to its surface area, Switzerland today is the world leader in the production of hydroelectric power. Many streams are diverted via pipes and tunnels at an elevation of 2000 m into reservoirs. Down in the valley, warning signs alert the hiker to the possibility of sudden water surges, in case the power plants bring their turbines on-line. In addition, the use of fossil fuels also impacts alpine streams: global climate change causes not only accelerated recession of our glaciers, but also changes precipitation and discharge regimes.

The UN declared 2002 to be the "Year of the Mountains". On this occasion, EAWAG held its Info Day under the heading of "Alpine Streams – Fragile Diversity in Peril". Presentations summarized the most recent findings on the functioning of alpine streams and their inhabitants and presented information about the effects of anthropogenic change. In order to apply scientific results to everyday life, we need close cooperation between institutions at home and across national borders. Exactly because the Alps are a major obstacle for North-South transit, intense cultural exchange between different Alpine regions has taken place for a long time. An outgrowth of this cooperation on the political level is the Convention for the Protection of the Alps. Its primary goal is the sustainable development of this sensitive region in the heart of Europe. With regard to alpine streams, we are charged with the duty to shape power generation, flood protection and tourist development such that the ecological viability of these sensitive ecosystems is guaranteed in the long term.

This is why about one year ago, EAWAG joined efforts with the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Federal Office for Water and Geology (BWG, FOWG) and various institutes of ETH Zurich and Lausanne in developing the "Rhone-Thur" project. Its goal is to develop methods and criteria to assess the success of revitalization projects.

This issue of the EAWAG news complements the previous issue, which had an emphasis on the ecology of alpine streams. Both issues are intended as summaries of the current state-of-the-art rather than final reports. As environmental changes are rapidly sweeping through the region of the Alps, so too is research on Alpine streams rapidly discovering new scientific perspectives.

BWehrli

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[1] A summary of the presentation by Michael Monaghan can be found in EAWAG news 54.

Sights Set on Alpine Water Treasure

Water plays a determining role in the Alpine region: it represents untouched nature, sensitive ecosystems, and a resource that can be used in many different ways. These natural and utilitarian values are being threatened or destroyed by one-sided and intensive use. The alpine regions are, therefore, challenged to manage their water resources in a sustainable manner. At the same time, it is essential that interests are coordinated across national boundaries. Millions of people live along European rivers and depend on these alpine water resources. In light of predicted global warming, international cooperation is becoming ever more important.

The Swiss Alps are rich in streams and rivers and represent a "treasure chest" of water for vast areas of western Europe. These water resources are intensively used for electric power generation and, in an effort to both protect against Nature's forces and reclaim land, many streams and rivers have been corrected. Utilization and protection interests are often in acute conflict with the values of sensitive aquatic ecosystems and natural landscapes. What is needed is a balanced consideration of the various interests, with the goal of protecting valuable natural characteristics while also securing important uses. This requires comprehensive management approaches that are effective at different levels and that must have a solid scientific basis.

The Living Space Alps

The Alps comprise an area of roughly 190 000 km^2 divided among eight countries – France, Italy, Monaco, Switzerland, Germany, Liechtenstein, Austria and Slovenia (Fig. 1). Switzerland's share of the Alps covers 25 000 km^2, which corresponds to 60 % of Switzerland's total area. The lowest point of the Swiss Alps (Fig. 2 and 3) is on Lago Maggiore with an elevation of 193 m a.s.l.; the highest point is the Dufour peak at 4634 m. Within very short distances, we find enormous climatic differences: dry intermountain areas, Mediterranean zones, and every possible transition zone all the way to polar zones. Average annual precipitation ranges from 500 to 4000 mm. The huge variability in natural conditions, as well as agricultural practices that are often still near-natural, gives rise to a wide spectrum of habitats for fauna and flora. This is why areas of high species diversity, so-called "hotspots", are found primarily in the Alpine region in Switzerland. An abundance of relics allow us to reconstruct the historical development of the Alps since the last ice age.

The population density in the Alps is generally low. The entire area of the Alps is inhabited by almost 14 million people. Of the Swiss population, only about 1.6 million people, or 22 %, live in the Alpine zone [1]. With 26 people per km^2 and many unpopulated high mountain areas, the Canton of Grisons has a particularly low population density; in contrast, it can reach 400 people per km^2 in some of the larger valleys. Valley bottoms are not only used intensively for agriculture, but are also populated by industrial activity. At the same time, they are the main corridors for roads and trains which also play an important role in international transportation.

Agriculture was the dominant economic factor in most alpine areas as little as 100 years ago. Since then its importance has dropped dramatically, and the population living from agriculture only accounts for a few percent. Depending on the elevation, the dominant cultivation includes fruit trees, crop farming or grass production and grazing. In large areas, particularly in Ticino, Valais and the Grisons, land is becoming increasingly abandoned. The tourism and leisure activity sectors, on the other hand, have gained enormously. Today, between 10 % and over 20 % of the jobs in mountain regions are related to these sectors.

A Treasure Chest of Water

The Swiss Alps are the source for the large rivers Rhine and Rhone as well as the Inn and the Ticino, which are important tributaries of the Danube and the Po. Average rainfall in this area is 2000 mm with some 1175 mm of this precipitation, or approximately 28 km^3 or 900 m^3/s, running off into neighboring areas. Some 24 % of the water the Rhine releases into the North Sea originates in the Swiss Alps. For other rivers, this proportion amounts to only 1–10 % (Tab. 1), nevertheless discharge from the Alps plays a major quantitative role in long sections of many rivers.

Fig. 1: The Bow of the Alps.

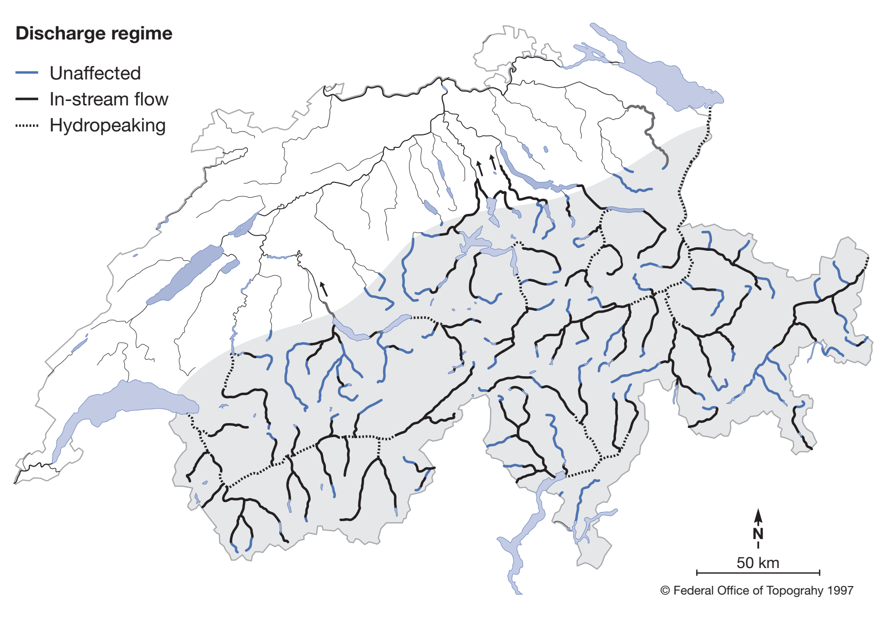

Fig. 2: Alpine streams and rivers affected by hydroelectric power generation. Adapted from [14].

The Alps also represent an enormous water reservoir. Approximately 74 km^3 water are stored in Swiss glaciers at the present time; in 1901, the volume still was 95 km^3 [2]. Natural lakes, including lakes along the periphery of the Alps (counting only the Swiss portion in the case of lakes crossing national borders), hold approximately 100 km^3, while artificial storage lakes add just under 4 km^3. Snow is another water reserve, although it is accumulated and released on an annual basis. Very large but hardly assessable water reserves are located in various underground systems, such as in recent gravel deposits in valley bottoms or in pores and fractures in rock.

Water – Pivotal for Alpine Nature

The Swiss Alps contain 30 000 km of streams and rivers as well as 17 natural and 47 artificial lakes with a surface area of more than 0.5 km^2, not to mention innumerable smaller mountain lakes. Glaciers currently cover an area of 1300 km^2, which corresponds to roughly 5 % of the alpine zone.

Alpine streams have many different faces: not only quiet springs, mellow lake outlets, steep whitewater streams, meandering networks of stream channels in flood plains, roaring waterfalls, glacier streams that rage at certain times and are calm at others, but also streams flowing over artificial steps, confined by hard banks or even stream channels suffering from total withdrawal of water. Streams are classified according to the origin of the water: glacial melt water, ground water, rain or snowmelt water. The various types of streams represent different habitats and are characterized by their hydrology, morphology, physical appearance and chemical composition. Climatic and topographic barriers lead to fragmentation, creating an array of habitats and biotic communities [3] (see article by M. Hieber on p. 9).

High alpine lakes are extreme ecosystems that are shaped by their harsh climatic conditions, scarceness of nutrients and low salinity. They are not, however, too remote to receive input of anthropogenic chemicals. Pollutants are transported via the atmosphere and deposited in high alpine areas (see article by R. Psenner on p. 12). Dominant elements of both the landscape and hydrologic system are the large lakes on the periphery of the Alps: Lake Geneva, Lake Constance, Lake Lucerne, Zugersee, Walensee, Brienzersee, Thunersee, Lago di Lugano and Lago Maggiore.

Alpine streams, as well as high mountain lakes, are very sensitive to both climatic changes and anthropogenic impacts (see article by M. Sturm on p. 15).

Human Society Benefits from Abundance of Water

In the Swiss Alps, one use dominates the interest in our water resources: energy production. Almost 60 % of Switzerland's electricity requirements are being met by hydroelectric power generation. The majority of this power is produced in the Alps whereas their usable potential is largely realized. Other important uses of our streams and rivers are the supply of drinking and process water for towns, tourist centers and industry, and the disposal of waste water where streams and rivers act as receiving media and transport vehicles.

Irrigation in agriculture has a long tradition, particularly in the dry valleys of the intermountain region. The best known example is probably the irrigation system in the

Rivers Swiss Alps	Main river	River mouth	Discharge from		Portion of Swiss Alps at	
			Swiss Alps	entire WS	entire WS of main river	annual discharge at river mouth
Rhine-Aare WS*	Rhine	North Sea	1238 mm/Jahr 530 m^3/s	309 mm/year 2200 m^3/s	6 %	24 %
Rhone	Rhone	Mediterranean	1100 mm/Jahr 182 m^3/s	611 mm/year 1900 m^3/s	5 %	10 %
Ticino WS**	Po	Adriatic (Mediterranean)	1239 mm/Jahr 134 m^3/s	657 mm/year 1460 m^3/s	5 %	9 %
Inn	Danube	Black Sea	876 mm/Jahr 54 m^3/s	253 mm/year 6450 m^3/s	0.2 %	1 %

* Rhine, Thur, Linth, Aare, Emme, Reuss, etc. / ** Ticino, Maggia, Tresa, etc.

Tab. 1: Hydrological relevance of the Swiss Alps. Rivers originating in the Swiss alpine region [15]. WS = Watershed.

Valais, where irrigation canals have been used for several hundred years. The water is usually caught high up in the mountains and piped across extremely difficult terrain down to fields and pastures along the valley floor. Ditches and pipes in the Valais total some 1500–2000 km and irrigate an area of 140–200 km^2 [4]. One use of our streams that is no longer practiced is the drifting or floating of logs, although it was common well into the 20th Century. This often required hydrologic engineering, such as retaining basins or sluices for directing the logs [4].

In addition, streams offer a multitude of opportunities for recreational and sporting activities. They enrich the landscape, are essential for human well being, and are often the source of strong emotions. A diverse landscape and intact streams increase the recreational value of a region. On the other side of the coin, however, increased recreational use places increasingly higher demands on the streams [5]. Streams, or water in general, can cause floods and landslides, thus posing a serious threat to human life and economic values.

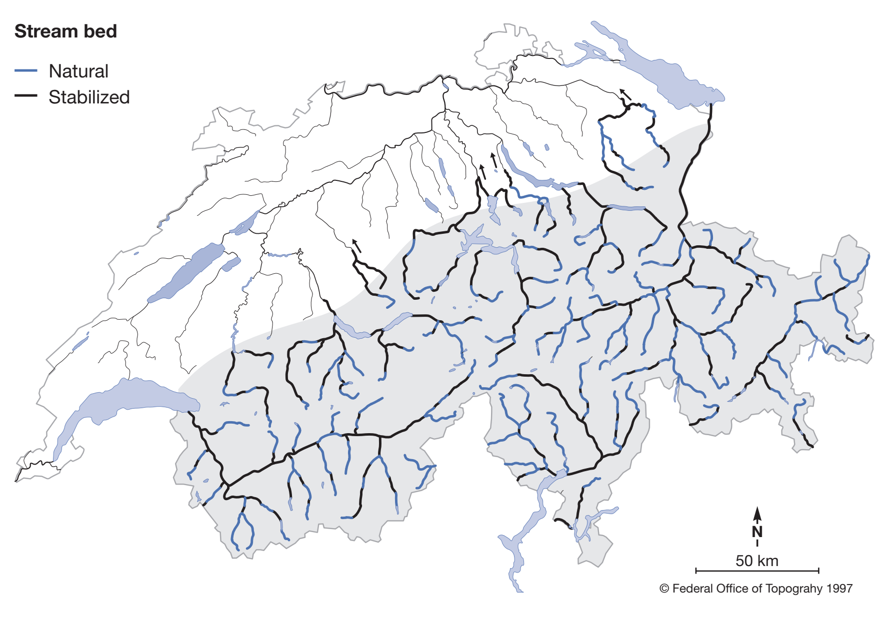

Fig. 3: Alpine streams with corrected stream bed. Adapted from [14].

Utilization Impacts Water Bodies

The production of hydroelectric power requires a number of different production and storage structures [6], resulting in operational and structural impacts that affect streams in a variety of ways (Tab. 2). Often, both infiltration and exfiltration zones are affected, which translates into changes in the groundwater regime.

Storage basins often receive water from areas which do not belong to the natural drainage area. Water is transferred within a river watershed or even between watersheds of different river systems. The Ticino, for example receives water from the areas of the Rhine, the Reuss (Aare) and the Rhone. In some cases, water is diverted across national borders; in the case of the Inn, for example, a water volume corresponding to 55 mm of precipitation in its Swiss watershed is exported to Italy [2].

In the Swiss Alps, virtually all larger and many smaller streams are affected by water withdrawal and hydropeaking (Fig. 2). The operation of storage basins can also lead to dramatic shifts in summer and winter patterns of discharge volume. This is true in the case of the Rhone and the anterior Rhine [2, 6].

Many wild streams and most of the larger rivers have been corrected (Fig. 3) for the protection of settlements from natural disasters as well as for the reclamation and safeguard of farm land. River corrections are often accompanied by the drainage of large tracts of land adjacent to the rivers. In the Swiss Alps, only a few relics of the formerly widespread flood plains remain.

The effects of hydroelectric power generation and river corrections can be felt far downstream. Most noticeable are changes in discharge patterns, particle and nutrient concentrations, and temperature regimes (see article by A. Wüest on p. 18).

Effects of Climate Change

Water regime along the rivers will be affected by climate change in different ways. Changes taking place in the Alps will be felt along the entire course of the Rhine, all the way to its mouth at the North Sea, and they will be superimposed on regional effects [7]. An increase in snow levels, larger flood events during the winter, lower discharge volumes during the summer, more dynamic discharge patterns, increased evapotranspiration, and a rise in sea level resulting in increased salinity in near-shore ground water will take place. These effects together with the changes in land use by settlements and agriculture will require modifications in

Physical and chemical effects of hydropower utilization	**Type of intervention:**				
	Water withdrawal	Removal of sand (sand flushing)	Water return	Water storage	Structural interventions
Changes in discharge regime	P	(P)	P		
Changes in flow patterns	S		S		P
Changes in suspended solids loads	S	P	S	P	(S)
Shrinking and/or structural changes in habitat	S	S	S		P
Changes in chemistry and temperature of water and sediments	S		S	P	

Tab. 2: Primary (P) and secondary (S) effects of hydroelectric power generation on streams. S is a consequence of P.

stream management, and furthermore in all human activities related to water (see article by B. Schädler on p. 24).

Conflicts of Interest

Local and regional water interests within the Alps can get in each other's way. Often power generation and river correction are in sharp conflict with the desire for an intact, natural landscape, recreation and tourism. What concerns downstream regions, is that they depend on electricity and water for their people and industries from the Alpine regions. On the other hand, upstream manipulations can affect uses and conservation objectives along the downstream river stretches, examples include improvement of river habitat, flood protection, navigation and water supplies.

Downstream water users are becoming more sensitized to these issues, especially as they are considering the possible consequences of global climate change. The longer the more, water management in the Alps will be confronted with problems and demands of the downstream regions. However, these regions also have some responsibilities of their own. The farther they move from the sustainable use of their own water resources, the more they will depend on the importation of water as, for example, from the Alpine regions [8]. All of this demonstrates rather clearly how the different interests regarding water resources are intertwined, from the Alps all the way to the sea.

Premises for Water Management

The water of the Alps serves both Nature and society. One-sided utilization priorities – disregarding the value of a natural Alpine environment or interests of other regions – must be rejected. Much needs to be accomplished at the local, regional and international levels.

All the different interests and problems must be analyzed and evaluated at all levels – considered from the broadest possible viewpoint and then integrated into management concepts. This will require consistent political directives that can then be implemented at different levels in a step-by-step approach. This process has to provide incentives and opportunities for all participants and affected parties [9].

The Water Framework Directive of the EU regulates the integrated management of water resources in the context of large watersheds [10]. The directive is not adequate, however, to preserve the invaluable ecological resources of the Alpine region. There are a number of voices advocating that the Convention for the Protection of the Alps be supplemented by a Water Protocol. The intent is to balance the various demands that are put on our water resources and to guarantee sustainable protection and utilization (see article by M. Broggi on p. 7).

Examples of Actions

The development of a Swiss certification process for the labeling and promotion of environmentally-friendly electricity is a prime example of successful environmental optimization of a specific water use with direct involvement of the stakeholders. Ecological and economic concerns were brought together and addressed in an approach that was beneficial for all the different interest groups involved [11].

Constraints for the Third Rhone Correction in Canton Valais are given by the multiple purposes the correction is to fulfill. A balance has to be found between flood protection, improvement of the ecological viability of the river, the creation of recreational value, and economic and social demands (see article by M. Fette on p. 21).

In the case of the Rhone, the management of storage reservoirs plays an important role. In combination with retention structures, these storage reservoirs can be used to significantly reduce hydropeaking, contribute to flood protection and mitigate negative ecological effects. The ecological optimization of reservoir management is generally one of the key issues of Alpine water management in the near future.

Support by Science

Integrated approaches require contributions from a wide range of areas; physicists, chemists, biologists, hydrologists, civil and hydraulic engineers, economists and social scientists, but also energy managers, regional politicians and affected interest groups have to join in the search for and realization of viable solutions. Their actions depend on support from science. First, we need basic knowledge about the ecology of Alpine water [12] and about the effects of direct and indirect interventions. Results on these topics are presented in this issue. Secondly, science needs to aid in the development and testing of integrated management approaches where relevant political, legal, economic, institutional, social and cultural aspects are considered [13]. Scientists are challenged to wield not only their professional expertise but also their personal engagement in support of the sustainable development of our Alpine water resources.

Ulrich Bundi is a member of the EAWAG directorate and deals with questions of water management and environmental politics.

I would like to thank Rudolf Koblet (EAWAG) for contributing substantially to this manuscript.

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Does the Convention for the Protection of the Alps Preserve Its Water Resources?

Alpine streams are in jeopardy: the space allotted to streams and rivers is often inadequate, water quality is poor, and discharge is too low. Since the Alps are of primary importance to Europe's water supply, it is urgent that we take action. As early as 1991, the European Union and countries that share parts of the Alps agreed on a Convention for the Protection of the Alps. In order to minimize the risk to streams and rivers and to increase awareness of the importance of our water resources, the convention will soon be extended into a water protection protocol.

The importance of the Alps as the water resource of Europe, where major rivers like the Rhine, Rhone, Drau, Durance, Inn and Po have their origins, is generally recognized. Despite this fact, alpine streams and rivers are not getting the attention they deserve. Of the 30 000 kilometers of streams in the Swiss Alps, 12 500 kilometers of medium and large rivers are in a condition that is far from their natural state. The majority of the corrections to these rivers were made in the last 200 years in response to ever increasing demands for flood protection and hydroelectricity. If one attempted to revitalize all of the "engineered" alpine streams using the current revitalization rate, it would require over a 1000 years [1]; therefore, we need to act immediately in order to protect streams that have not yet been altered and to revert manipulated streams back to more natural conditions. What is urgently needed are governmental regulations that transgress national boundaries.

Alpine Streams Perform a Number of Functions

The alpine region is shaped by anthropogenic influences, fragmented by roads, buildings, and water works. In this environment, streams are the only natural networks that are largely contiguous and cover the entire area. Economically speaking, streams and rivers are critically important for hydroelectric power generation, in supplying drinking water, and for tourism in cases where their unique beauty attracts people; however, with an annual discharge volume of over 200 billion m^3, streams and rivers are not just a positive element of the landscape. They represent a substantial, potential danger that shapes all areas in their immediate vicinity [2]; the devastation of various parts of Europe during this past summer's flooding demonstrates this rather clearly (Fig. 1).

Fig. 1: A trail of devastation after a flood event.

Acute Threats to Alpine Streams

There are a number of ways in which alpine streams are threatened. We would like to highlight some of them:

- Hydroelectric *power generation* is one of the more delicate problems. While electricity from hydroelectric power plants has been praised over the last 100 years for being "domestic", "clean" and "renewable", the ecological impacts of this form of energy generation turns out to be more severe than originally assumed. Hydroelectric power plants play a significant role in the finances of mountain villages, although this economic gain comes at an enormous environmental cost (see articles by A. Wüest on p. 18 and M. Fette on p. 21).
- The *sale and privatization* of springs and streams poses a new kind of threat. In Switzerland, little attention is given to this risk since most streams, as well as the water supply systems themselves, are in public hands. International companies like Nestlé, Coca Cola and Danone have secured their access to drinking water and established a strong position in the water market. We can only speculate what effects this may have on the environment.
- According to unofficial sources, the total number of buildings in Switzerland tripled between 1951 and 1991. *Settlements and the transportation infrastructure* move ever increasingly into the domain of streams and


W. Gerber, WSL

Fig. 2: Many mountain streams that were once roaring are today left with very low in-stream flows and all the consequent disadvantages.

rivers. Damage during flood events demonstrates that the buffer zone is often inadequate (Fig. 1).

- The impact of agriculture on streams continues to be a problem. In addition, it was recently determined that sewage treatment plants are unable to completely remove hormonally-active compounds, so-called endocrine substances. These compounds show effects on animals and humans even at very low concentrations.
- Even if *canalization* is virtually banned by the current Swiss legislation, we should not forget that over the last few decades, the annual loss of natural streams has been at the order of 50 kilometers per year [3].

Is the Convention for the Protection of the Alps Sufficient?

The Convention for the Protection of the Alps was signed in 1991 by the EU and by countries that partially lie in the Alps, namely Germany, France, Liechtenstein, Italy, Monaco, Austria, Switzerland and Slovenia. The framework convention, stating the basic principles for the protection of the Alps, has been in force since 1996. It is remarkable that the convention treats the entire region of the Alps as one entity, stating that it represents an extremely diverse and complex environment that is occupied by eight countries and 8500 communities, covers an area of 190 000 km^2 and is home to nearly 14 million people [4, 5]. The countries signing the convention have committed themselves to the "principles of prevention, polluter pays, and cooperation". The goal of the convention and its protocols (Tab. 1) are the institution of integrated policies for the preservation and protection of the Alps through prudent and sustainable use of the natural resources.

Protocol	Signed by Switzerland
Urban planning and sustainable development	16.10.1998
Nature protection and landscape conservation	16.10.1998
Mountain agriculture	16.10.1998
Mountain forests	16.10.1998
Soil conservation	16.10.1998
Tourism and leisure	16.10.1998
Energy	31.10.2000
Transportation	31.10.2000
Arbitration	31.10.2000
Monaco protocol	20.12.1994

Tab. 1: The ten protocols of the Convention for the Protection of the Alps [4].

Alpine streams and their sustainable use are mentioned in the convention. The *framework convention* explicitly demands that healthy water systems be preserved or that they be restored. Focus areas include stream protection, hydraulic structures that leave the stream as natural as possible, and the environmentally-friendly use of hydroelectric power. In addition, the preamble to the protocol on *Environmental Protection and Nature Conservancy* emphasizes the importance of streams for the preservation of species diversity. The Energy Protocol stresses that streams are of utmost importance to ecological diversity, for drinking water and for energy production; however, all these demands and declarations are not specific enough when it comes to their practical application. We need an independent water protocol that spells out the specific functions and needs of streams and rivers and clearly states the risks that are currently threatening our streams.

Expectations for a Water Protocol

In Switzerland, there is general consensus on the most important points that such a water protocol should address [1, 6–9]:

- **Preservation of natural streams:** The remaining natural streams must be completely protected. We need to prevent the speculative sale of streams (drinking water).
- **Adequate space for streams:** The basic requirement is an adequate stream cross-section such that flood events do not cause damage to adjacent areas. Furthermore, there has to be enough room for appropriate ecosystems to function and for linkages between these systems. This is the only way to reestablish natural aquatic, amphibian and terrestrial diversity. Recreational needs of humans should also be considered. Contamination by agricultural practices needs to be minimized by establishing adequate buffer zones.
- **Sufficient Discharge:** A balance needs to be found whereby in-stream flows are adequate for the preservation of aquatic habitats and the landscape, and where flow volumes are sufficient to approach natural flow volumes and allow for sediment transport (Fig. 2).
- **Adequate Water Quality:** Contamination of streams by solids and dissolved materials needs to be minimized. A temperature regime close to natural values must be guaranteed.

Since the need for a water protocol has not been recognized on a political level, there is much work to be done before it is realized. Only if the above demands are translated into political action, can we hope that our alpine streams will fulfill their diverse functions in the future.

Mario F. Broggi, Forestry Engineer (ETH), is director of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) as well as lecturer for applied landscape ecology and nature protection at the University of Vienna and at the University of Basel. 1983–1992 Mario Broggi was president of the CIPRA.

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Alpine Streams: Diverse and Sensitive Ecosystems

Who does not know them – babbling mountain brooks and roaring glacier streams? They are still the quintessence of raw beauty and untouched nature; or are they? Because of the prevailing harsh conditions and their inaccessibility, remarkably little is known about alpine streams and their inhabitants. A comprehensive project conducted at EAWAG has been able to show that alpine streams comprise of a wide variety of habitats. Their resident flora and fauna have numerous ways of adapting to the often extreme conditions, though even the smallest disturbances by anthropogenic impacts or climate change may irrevocably destroy these sensitive ecosystems.

Alpine streams can be found almost anywhere in the world – from the poles to the tropics [1]. They are situated between the tree line and the permanent snow line. In the European Alps, this corresponds approximately to the zone between 2000 and 3500 m a.s.l. Within a very small geographical area, alpine streams can accommodate very different habitats that are usually home to specific species. There are, however, a number of characteristics that are common to all alpine streams [2]:

- They are subject to extreme weather and climate conditions. This generally implies to low water temperatures and high solar radiation.
- The growing season for organisms is extremely short due to long, hard winters and usually restricted to the summer months; for glacial streams, however, optimum conditions prevail during spring and fall, i.e., in the short periods between snow cover and summer snow melt.
- Because of sparse vegetation along their banks, alpine streams receive very little organic material that, in turn, limits the nutrient base for many aquatic animals.
- Alpine regions regularly experience natural disturbances such as floods and landslides.

Quiet Headwaters and Roaring Glacier Streams

We can distinguish between three main types of alpine streams, according to their primary water source: (1) **kryal** streams, otherwise known as glacial streams since they are fed primarily by glacial meltwater; (2) **krenal** streams are spring-fed and, therefore, depend on ground water, while (3) **rhithral** streams are primarily fed by rainfall and snow melt [3]. The origin of the water is an important factor in determining habitat conditions in each of these stream types (Tab. 1).

Glacial melt and snow melt occur during a relatively short period and cause strong seasonal fluctuations in many environmental conditions. The discharge volume of the glacial stream "Ova da Roseg" (Engadin, Switzerland), for example, increases from calm 0.2 m^3/s to roaring 30 m^3/s during the summer melt period. During this time, the otherwise stable streambed is completely reshaped. At the same time, the stream carries so-called glacier milk; the stream is extremely turbid and resembles milk due to high concentrations of suspended solids from the glacier [4]. Rhithral streams are far less affected by seasonal fluctuations and generally experience more moderate environmental conditions. Of the three types of alpine streams, groundwater streams have the most constant and stable conditions, since they receive a steady supply of ground water [5].

Alpine Streams: Diverse Ecosystems

One of our major findings from the current project is that no two alpine streams are alike; heterogeneity is much greater than has been traditionally assumed. The presence or absence of waterfalls, lakes, hydrological connectivity among streams, slope, exposure and many other factors determine the habitat conditions of such systems.

Lake outlets, for example, represent a transition zone between standing and running water ecosystems. The lake outlet habitat

Channel type	Water source	Seasonality	Channel stability	Temperature (°C)	Turbidity
Main channel (M)	kryal	high	low	0–4	high
Lake outlet (O)	kryal	medium-high	low-medium	0–9	high
Side channel (S)	kryal	high-medium	low-medium	0–4	high
Intermittently-connected channel (I)	kryal	high	medium-low	0–5	high-medium
Mixed channel (X)	kryal-krenal	high-medium	medium	0–5	medium
Tributary (T)	kryal-rhithral	low	high	0–8	clear-medium
Groundwater channel (G)	krenal	low	high	3–5	clear

Tab. 1: Channel types within the first 11 kilometers of the Roseg (Engadin, CH) and their main environmental characteristics [2]. See also Figure 1.

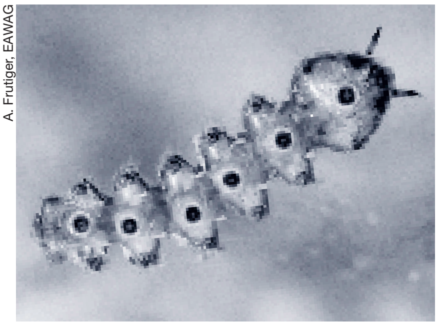
R. Zah, EAWAG

Fig. 1: Different stream types in the Val Roseg: O = lake outlet, M = main channel, G = groundwater channel, S = side channel, I = intermittently-connected channel, X = mixed channel, T = tributary.

is, therefore, significantly influenced by both adjacent ecosystems. In fact, both typical “lake” and typical “stream” organisms are found [6]. Flood plains, on the other hand, contain a number of very different habitats which, depending on discharge conditions, are either connected or isolated. They are subject to constantly changing conditions due to snow- and glacial melt. Our research showed that within the first 11 kilometers of the Roseg stream, we are able to distinguish seven different channel types (Fig. 1 and Tab. 1) [4]. Depending on seasonal discharge conditions, the degree of connectivity between channels varies, and with it the total stream length and origin of the water. While the total channel length is only about 5 km in winter, it expands to more than 20 km during summer. In winter, the network of channels is predominantly fed by ground water and is relatively homogeneous; in summer, however, the main water source is glacial meltwater and the channels are very heterogeneous [4].

Life in Extreme Habitats

How do aquatic organisms in these very diverse stream types deal with small-scale differences in habitat characteristics and extreme environmental conditions? As early as the beginning of the 20th Century, Steinmann [7] noted: *“The mountain stream offers its inhabitants an environment of such distinct character that this has to be reflected in the way these organisms live.”* In addition to the stream fauna, algae and higher plants have developed a wide range of adaptations to the distinct environmental conditions characteristic of alpine streams. The majority of organisms in alpine streams are benthic, i.e., closely associated with the substrate. This improves their chance for survival during frequent, high-flow velocities. Other adaptations to fast-moving water include the strong claws of some stonefly larvae (Plecoptera), the flattened body shape of many mayfly larvae (Ephemeroptera), the ventral suction cups of the blephariceridlarvae *(Liponeura)* (Fig. 2), life in self-made cases constructed from a range of materials, such as stones (caddisfly larvae, Trichoptera), or the formation of gelatinous crusts of many algae. Characteristic diatoms and insect families typically dominate algae and invertebrate communities found in alpine streams. Organisms in kryal streams experience particularly extreme habitat conditions and fluctuations resulting in communities that are very similar worldwide (cosmopolitan), but are restricted to a relatively short longitudinal zone of the stream (stenozonal). In contrast, inhabitants of rhithral streams are rather moderately cosmopolitan, but are distributed over longer sections of the stream (euryzonal) [3]. Due to their extreme environment, kryal streams typically harbor biotic communities that are rather species poor compared to communities in rhithral and krenal streams (Fig. 3).



A. Frutiger, EAWAG

Fig. 2: The ventral suction cups of the blephariceridlarvae *Liponeura* allow survival in fast moving water.

The effect of upstream lakes varies with the source of the water: more species were found in kryal lake outlets than in kryal streams, but fewer were found in rhithral lake outlets than in rhithral streams. The individual stream types differ not only in the number of species, but also in the community composition and in the dominance of different taxa. Kryal and rhithral streams are mostly colonized by insects, while we also find many non-insect species such as oligochaets and benthic crustaceans such as copepods and ostracods in the more stable and homogenous spring-fed streams and rhithral lake outlets (Fig. 3).

Alpine Streams: Sensitive Ecosystems

How do alpine streams respond to anthropogenic impacts and changes in climate? Some effects of anthropogenic disturbances are quite obvious: water diversions may result in the drying up of entire streams, dams change the discharge regime (see also article by A. Wüest on p. 18 and M.Fette on p. 21), and flood protection structures force mountain streams into solid, impermeable stream beds. The effects of climatic change, on the other hand, are more difficult to predict. Scientists predict a general increase in temperature as well as changes in precipitation patterns: it appears likely that there will be more precipitation during the winter months, while summer months could become drier (see article by B. Schädler on p. 24). All around the world, glaciers have continually retreated over the last 150 years (Fig. 4) and extreme prognosis predict that glaciers may completely disappear from the Engadin within the next 50 years [8].

What does this mean for alpine stream organisms? Retreat and disappearance of glaciers entail the loss of a unique habitat – the discharge regime shifts from a pattern dominated by glacial melt and snow melt to one that is shaped by rainfall and snow melt, extreme habitats disappear and habitat conditions become more homogeneous. This gives exotic species and organisms that occupy habitats further downstream the opportunity to colonize these previously unattractive locations and to displace the original species. Specific indicator organisms and glacial species will disappear since there are no higher and colder areas to which they may retreat.

Ecological Stream Management – a Contradiction in Terms?

It is obvious that the sustainable management of alpine streams is only possible if we understand the interactions between environmental conditions and biota. We, therefore, need to press on with basic research in order to better characterize these ecosystems. At the same time, we need to investigate more applied aspects. EAWAG is analyzing questions like these: how much in-stream flow is needed below dams in order to preserve near-natural conditions [9]? Is it feasible to preserve natural communities in such stream sections by artificially inducing flood events [10]? What form does the revitalization of a corrected section of a stream have to take in order to allow a natural biotic community to become re-established (see article by M. Fette on p. 21)? These and similar projects give us some hope that our alpine streams will be as enthralling in the future as they are now.

Mäggi Hieber, biologist, has recently completed her thesis on alpine streams, with an emphasis on the ecology of alpine lake outlets, in the Limnology department at EAWAG. Since then she is project leader at the Center for Applied Ecology Schattweid.

Coauthors:
Peter Burgherr, Urs Uehlinger, Klement Tockner

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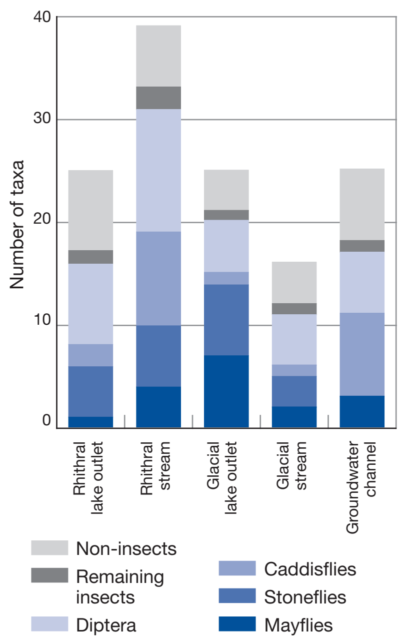

Fig. 3: The composition of invertebrate communities in different alpine stream types.

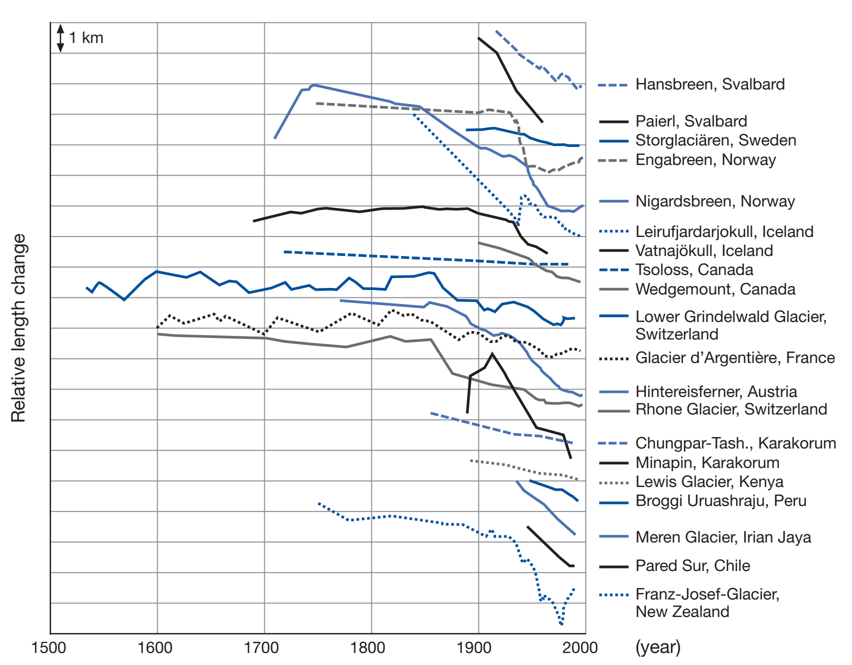

Fig. 4: Retreat of glaciers over the last 500 years. Adapted from [8]. 1 unit = 1 km.

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.

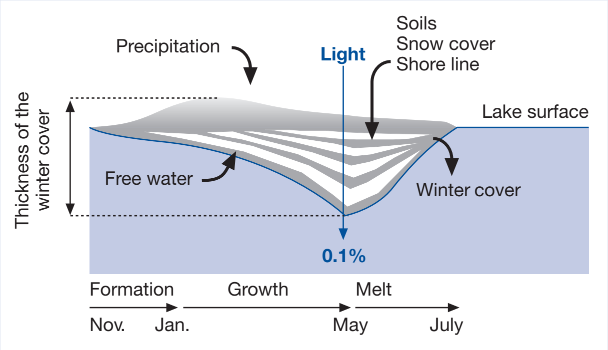

Fig. 1: Formation, growth and melting of the snow cover on alpine lakes. A centimeter thick layer of clear ice is overlain by a several meter thick structure of slushy snow (white) and opaque ice (grey). Origin and transport of microorganisms are indicated by arrows. Adapted from [3].

… 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. 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

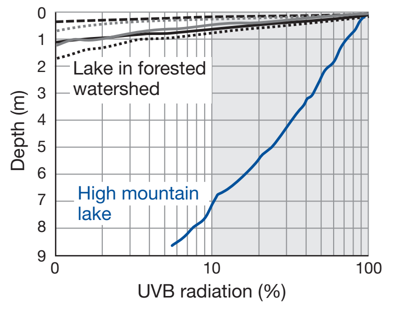

Fig. 2: Penetration depth of UVB radiation (wavelength = 305 nm) in lakes with high and low concentrations of dissolved organic compounds or humic acids. Adapted from [4].

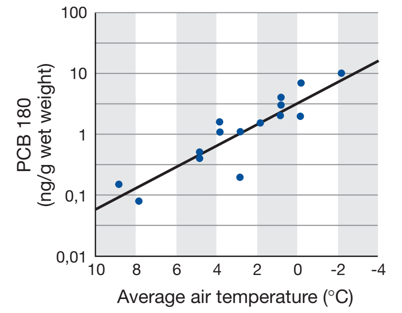

Fig. 4: Accumulation of polychlorinated biphenyl 180 (PCB-180) in fish from different European mountain lakes. Average air temperatures span a range of approximately 10 °C, which leads to a 100-fold increase in accumulation. Adapted from [9].

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.

R. Psenner, University of Innsbruck

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.

Roland Psenner is Professor of Limnology at the University of Innsbruck. He is particularly interested in high alpine lakes, the effects of global change on alpine watersheds, biogeochemical cycling of nutrients and pollutants, as well as the microbial ecology of water, ice and snow.

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Archives in the Depths of High Mountain Lakes

Humans began settling remote mountain regions of the Swiss Alps over 4000 years ago. So what were the Alps like in earlier times? Downturns in climatic conditions forced humans to repeatedly abandon these areas, but as soon as conditions improved, they returned. We can decipher these fluctuations in human settlement from the sediment record that is stored in mountain lakes. These archives allow us to assess the effect of human impacts on the background of natural climatic changes.

The Alps are commonly referred to as the "water treasure chest of Europe". The preservation and sustainable use of this resource is one of the most important tasks that the Convention for the Protection of the Alps is facing (see article by M. Broggi on p. 7). The Convention presumes that Alpine regions are still largely unaffected by human activities. But is this really true? EAWAG has gone further into that question. By analyzing the sediments of high mountain lakes, it is possible to reconstruct several thousand years of history of these lakes and their watersheds. Specifically, we would like to know, if, since when, and to what extent these mountain regions have undergone changes, and whether it is possible to separate anthropogenic impacts from naturally occurring changes.

Historical Archives in the High Mountains?

As long as historic documentation or long-term monitoring data are available, we may answer such questions directly. Changes in land use patterns in the Canton of Grisons, for example, are clearly documented in the Swiss Land Use Statistics database (Tab. 1). But if we want to look at changes in earlier epochs, it becomes more difficult as we often do not have instrumental data, records or reliable historical sources. In these cases, we must relay on indirect data sources, archives of so-called environmental proxy. Lake sediments are among the most important of such archives and are used to interpret former environmental conditions. Sediments can reveal geobiochemical and physical processes that have occurred in a lake and its watershed with high temporal resolution (seasonal, annual) and over long periods of time (10^6 years) [1]. Because high mountain lakes are ecologically in a marginal situation, they react faster to changes in their environment than lakes at lower elevations. For this reason, there have recently been a series of studies in the Swiss Alps that have made use of sediment records in mountain lakes [2–4].

Sägistalsee – a High Mountain Lake in the Bernese Oberland

One high mountain lake that has been studied in detail is the Sägistalsee, which is situated at 1935 m a.s.l. in the Bernese Oberland between Grindelwald and Brienzersee (Fig. 1). As part of the interdisciplinary research project AQUAREAL funded by the Swiss National Science Foundation, a 13.5 m long sediment core was collected from Sägistalsee in 1996. This core represents an archive of the last 9000 years, i.e., for almost the entire Holocene. Layer by

	% of total area (as of 1992/1997)		**% change** (since 1979/1985)	
	GR	**CH**	**GR**	**CH**
Forest	26.7	30.8	+3.9	+1.9
«Unproductive areas»	41.7	25.5	No data	
Agriculture	29.8	36.9	−3.1	−3.1
Settlements	1.8	6.8	+12.9	+13.3

Tab 1: Land use statistics for the Canton of Grisons (GR) and Switzerland as a whole (CH); Swiss Federal Statistical Office (2002).

M. Zeh, Laboratory for Water and Soil Protection, Canton Berne

Fig. 1: Sägistalsee in Canton Bern, Switzerland viewed from the west. Clearly visible are the hard ridges of the Upper Jura limestones and the soft troughs of marls and schists in the Lower Cretaceous formations [5].

Measured parameter	Indicators of past environmental conditions
Organic carbon (C_{org})	Biological productivity in the lake
Calcite/quartz ratio	Soil formation in the catchment
Mean grain size	Mineral weathering in the catchment
Manganese/iron ratio (Mn/Fe)	Oxygen conditions in deep lake water
Benthic midge larvae (Chironomidae)	Oxygen conditions in deep lake water
Pollen of trees, shrubs, grasses	Vegetation in the catchment
Charcoal remnants	Forest fires and human activities in the catchment

Tab. 2: Environmental proxy parameters determined in a sediment core from Sägistalsee functioning as indicators for environmental conditions in the past.

layer, this core has been analyzed for various parameters (Tab. 2) allowing the reconstruction of past environmental conditions and human activities in the region.

Natural Changes in the Environment

The global warming trend since the end of the last ice age led to increased nutrient input into Sägitalsee, resulting in increased biological productivity until about 6000 years ago (Fig. 2A). During this same period, soil formation increased (Fig. 2B) and mineral weathering decreased (Fig. 2C). At the deepest locations in the lake, anoxic conditions developed (Fig. 2D) allowing for the survival of only a few benthic organisms living at the sediment/water interface (Fig. 2E). During the next 2000 years, until approximately 4000 years before present, the previously sparse forest of pine and spruce grew denser and was then dominated by fir *(Abies alba)*. As a consequence, the forest floor became more stable (Fig. 2B), and the oxygen supply to deep layers of the lake improved (Fig. 2D). This, in turn, led to an increase in the occurrence of midge larvae (Chironomidae) in the sediment (Fig. 2E).

Humans Begin to Change the Environment

The first signs of human settlements are evident at approximately 4000 years before the present. At this time, the Neolithic-Bronze Age civilization began to cut down the forests and use the cleared areas as pastures. This development is indicated by an increase in grass pollen (Fig. 2F), the emergence of pasture indicators (Fig. 2G), and the more frequent occurrence of charcoal remnants (Fig. 2H). In the deep-water of the lake, oxygenation decreased dramatically, and benthic organisms disappeared almost completely (Figs. 2D and 2E).

These early impacts of human activity in the Sägistalsee watershed can be followed for several centuries until about 3500 years ago, when the climate worldwide deteriorated significantly [6]. The records in the sediment archive of Sägistalsee indicate clearly that human settlements in the Alps suffered severely under these conditions. Within less than 100 years, the pastures within the watershed of Sägistalsee disappeared (Fig. 2G), forests filled in again (Fig. 2F) and mineral weathering increased (Figs. 2B and 2C). In the lake itself, the deteriorating climate led to a significant decrease in biological productivity (Fig. 2A) and, therefore, to higher oxygen concentrations in the deep-water, which in turn result once again in an increase of sediment biota (Figs. 2D and 2E).

Up and Down of Settlement and Reforestation

In the subsequent period of the Holocene, anthropogenic signals in the Sägistalsee sediments become more frequent and begin to overlay the climate signal. During the Iron Age, approximately 3000 years before the present, climatic conditions improved

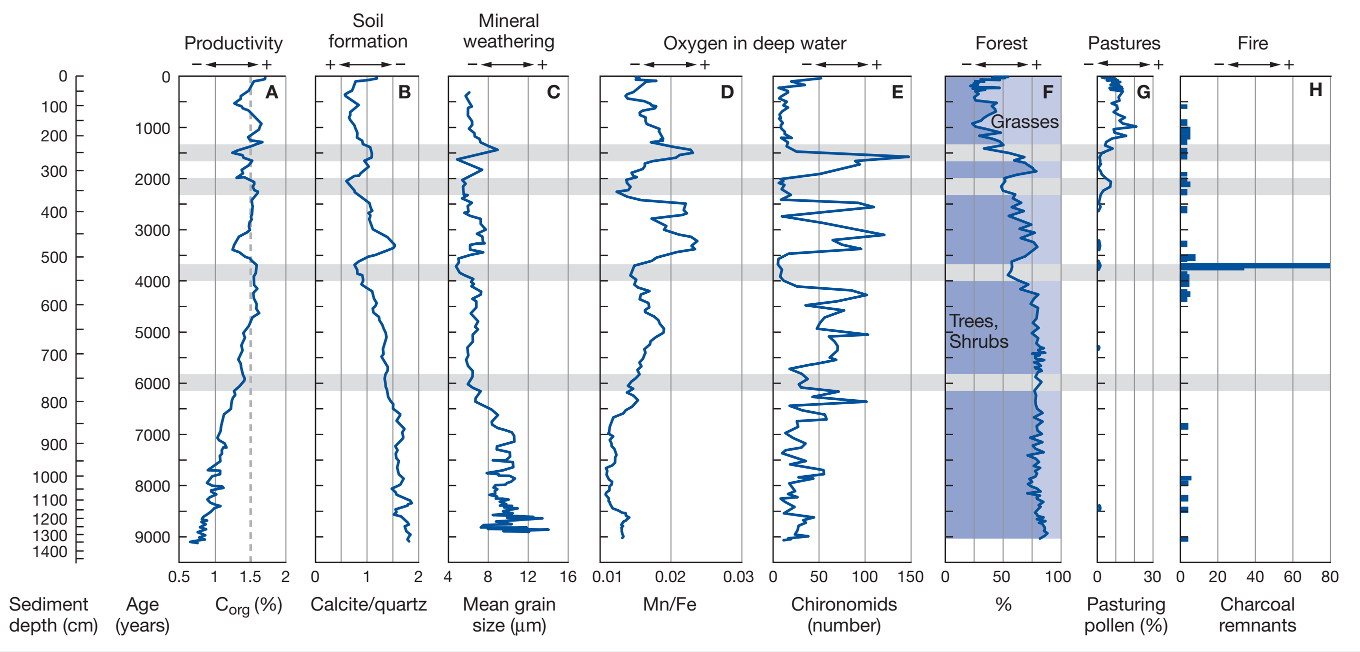

Fig. 2: Environmental parameters (see Tab. 2) as a function of time as determined in a sediment core from Sägistalsee [8–10]. Age = given in calibrated ^{14}C-years before the present. Grey bars indicate periods of drastic change.

again, allowing for continuous use of the watershed by humans until the present day. The forest was once more replaced by open areas (Fig. 2F). The alpine pastures were used intensively particularly during the time of the Roman Empire, approximately 2000 years ago (Fig. 2G). The deep-water of the lake again became anoxic and was almost depleted of organisms (Figs. 2D and 2E).

The early Middle Ages, about 1500 years ago, saw a sharp decline in anthropogenic land use, induced by changing climatic conditions. Forested areas grew (Fig. 2F) while consolidation of the soils decreased (Fig. 2B). Dramatically larger grain sizes of minerals in the lake sediment (Fig. 2C) suggest increased mineral weathering in the watershed. Oxygen was present throughout the water body, and the numbers of midge larvae increased significantly (Fig. 2E).

The renewed improvement of the climate some 1200 years ago, during the high Middle Ages, gave rise to increased agricultural use of the watershed. This level of utilization has remained high through to the present day and was not disrupted during the cold period of the little ice age, which lasted approximately from the middle of the 13th until the middle of the 19th centuries.

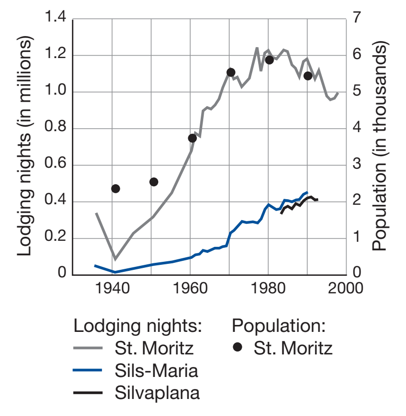

Fig. 3: Growth of the population of St. Moritz (solid circles) and lodging nights in St. Moritz (grey), Sils-Maria (dark blue) and Silvaplana (black) over the last 60 years. Source: Tourist Office St. Moritz, Sils-Maria and Silvaplana.

Sägistalsee is not an Isolated Case

Results from Sägistalsee demonstrate how quickly and how sensitively high mountain lakes respond to rapid climatic change, such as during the deterioration of the climate 3500 years ago. At the same time, they illustrate that human settlement and land use – even in remote mountain areas – began much earlier than had previously been assumed; it appears now that humans started to settle these areas as early as 4000 years ago. Human activities have left a lasting mark on the lake and its watershed. But is this also true for other mountain regions?

Studies of sediment cores from the larger lakes of the Upper Engadin revealed that these lakes, situated at 1800 m a.s.l., react rather sensitively to climatic changes like Sägistalsee. Traces of settlement and agricultural activities are evident around the same time, i.e., about 4000 years before the present. Again, we can use the sediment archive to decipher a record of alternating periods of clearing and regrowth of forests with intermittent evidence of pastures [7].

Are High Mountain Regions Really Remote?

The assumption that remote mountain regions or high mountain lakes are beyond the reach of anthropogenic impacts is clearly invalidated by our results. Although environmental changes are basically caused by natural processes (climate changes), the influence of human activities in the mountain regions of the Alps is evident as early as 4000 years ago. “Remote” is, therefore, not synonymous with “untouched”. All the same, it may be said that in the past, high mountain areas have been used less intensively than the more densely settled areas in the lowlands.

Today, however, environmental change is increasingly caused by human activities; Figure 3 illustrates this trend. Within a short period, the tourism industry has transformed the region around St. Moritz from its original “remote” mountain quality to an “urban” area. Because high mountain areas react quickly and sensitively to environmental changes, increased anthropogenic pressure (e.g., vehicular traffic, ski slopes, hydroelectric power plants, filling in of new land areas) leads to far more dramatic changes of the environment than natural climate changes alone would allow. High mountain areas are, therefore, not only threatened by global warming, but also by a rapid increase in anthropogenic activities. The delicate treatment of our sensitive “resource Alps”, the “water treasure chest of Europe”, must be assigned the highest level of priority on European States’ agenda.

Michael Sturm is a geologist and head of the section “Sedimentology” in the department “Surface Waters”. Within his main areas of interest – paleolimnology and limnogeology – he has been working for years on the interpretation and reconstruction of environmental changes as they are recorded in the sediments of lakes and streams.

Coauthors:
Thomas Kulbe, Christian Ohlendorf (now University of Bremen)

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Alpine Hydroelectric Power Plants and their "Long-range Effects" on Downstream Waters

Alpine hydroelectric power plants not only affect the local waters, but also streams and lakes that lie far downstream. The transport of suspended solids, for example, is significantly reduced below reservoirs, which affects the oxygen content of lower lying lakes. Apart from suspended solids, reservoirs also retain nutrients. The collapse of landlocked salmon populations in the Canadian Columbia River, for example, appears to be caused by the construction of several dams, which reduced the nutrient concentrations in downstream lakes. Hydroelectric power generation also changes the temperature regime of downstream waters.

Hydroelectric power is of enormous importance to our economy and to society in general. With an annual production of 38 TWh, Switzerland's hydroelectric power plants provide 58 % of the domestic electricity production; approximately 60 % of this production is generated in the Alps. Over the last 50 years, 130 reservoirs have been built. With a total volume of 4 km^3, they can retain a quarter of the annual discharge from our alpine watersheds (Rhone, Ticino, Rhine, Reuss and Aare).

Downstream Export of Ecological Deficits

Such intensive utilization cannot be without ecological impacts on streams (see box). In addition to the well-known local effects, there are impacts that can be felt in distant, lower-lying stream sections, lakes and coastal waters [1]. The worldwide criticism of hydropower [2], therefore, calls for the differentiated assessment of these frequently neglected impacts. It is the purpose of this article to discuss some of these ecological deficits that are being exported, together with the electricity, to the lowlands (see also article by M. Fette on p. 21).

Reservoirs as Particle Traps

Since construction of the roughly 50 dams in the Rhone watershed, the annual suspended solid load carried into Lake Geneva has dropped by almost 50 % to approximately 1.5 million tons [3]. Because the main demand for electricity is during the winter months, most of the water is stored in the reservoirs for more than half a year before it is sent through the turbines. During this time, most of the suspended solids settle to the bottom of the reservoirs. As an additional consequence, the frequency of flooding in the Rhone has dropped significantly. Before construction of the dams, discharge volumes exceeding 500 m^3/s were observed on 23 days per year, whereas today such high discharge takes only place at an average of five days [3].

The reduced suspended solid load and flooding frequency also change the hydraulic regime of most lower lying alpine lakes. The reason is that the water density depends in part on temperature and dissolved solids, but even more on the concentration of suspended solids. When the concentration of suspended solids exceeds approximately 0.5 g/l (Tab. 1), the stream water becomes heavier than lake water and sinks to the deep regions of the lake. This effect is

Lake (river/sampling location)	Annual suspended solid load[1] (million tons/year)	Average suspended solid concentration in summer[2] (g/l)
Lake Constance (Rhine, Diepoldsau)	3.6	0.91
Lake Geneva (Rhone, Porte du Scex)	1.9	0.52
Brienzersee (Lütschine, Gsteig)	0.16	0.39
Walensee (Linth, Mollis)	0.11	0.18
Brienzersee (Aare, Brienzwiler)	0.11	0.14
Lago Maggiore (Ticino, Bellinzona)	0.47	0.12
Urnersee (Reuss, Seedorf)	0.05	0.047

[1] Annual average between 1979 and 1993 [LHG Berne]. (Biweekly measurement of suspended solids).

[2] Averaged solid concentrations in summer (June to August).

Tab. 1: Input of suspended solids into prealpine Swiss lakes (data: BWG/LHG, Berne).

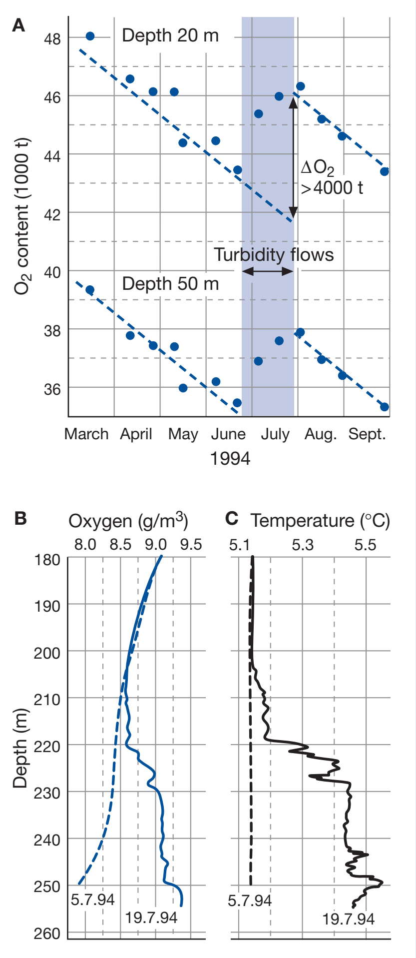

Fig. 1: Oxygen budget in deep water of Brienzersee in the summer of 1994: in July, several warm and particle-loaden flows from the Aare and the Lütschine – induced by thunderstorms – transported approximately 4000 tons of oxygen into the deep water layers within only a few hours (A). Oxygen (B) and heat (C) input between July 5 and 19 occurred primarily in the bottom 50 m.

particularly pronounced in the case of high water events that are caused by thunderstorms, since they tend to carry high loads of suspended solids. The result is an increase in the oxygen content of the deep water.

This increase in oxygen concentrations is directly caused by the sinking stream water transporting large amounts of oxygen to the bottom of the lake. An EAWAG report [4] documented that in July of 1994 several of such flows of dense stream water carried approximately 4000 tons of oxygen into the deep water of Brienzersee (Fig. 1A). This caused a dramatic increase in oxygen concentrations (Fig. 1B) especially in the deepest layers. By comparison, artificial aeration of lakes on the Swiss plateau introduces less than 500 tons of oxygen per year.

There is also an indirect mechanism for introducing oxygen. The stream water is not only denser but also warmer than the deep lake water, so each episode of stream water intrusion causes a slight warming of the deep water (Fig. 1C). Over a period of years, the temperature of deep water gradually increases – as, for example, in Lake Geneva where the temperature has increased by 1.5 °C [5]. As a result, the density gradient in the deep parts of the lake becomes smaller, which prepares the lake for efficient, deep mixing. Such a complete turnover event occurs sporadically, approximately every 5–10 years, and also brings a lot of oxygen-rich water to the deepest parts of the lake.

Flash-floodings that carry high suspended solid loads, therefore, have an important ecological function in the large prealpine lakes (Tab. 1). The direct and indirect supply of oxygen has in the past contributed substantially to the fact that these lakes (with the exception of Lake Lugano) had relatively favourable oxygen conditions, even in times of high nutrient loading. The less frequently such sinking stream surges occur, the more the oxygen conditions near the lake bottom will deteriorate. From the viewpoint of lake ecology, any further reduction in particle-rich flood events is highly undesirable.

Reservoirs as Nutrient Traps

Along with suspended solids, reservoirs also retain nutrients. While this is a positive side effect in our over-fertilized Swiss watersheds, it can lead to detrimental changes in the fauna and flora of nutrient-poor regions. We became painfully aware of this fact in the late 1980s, when the populations of a unique landlocked salmon, the “Kokanee”, in Lake Kootenay and in the Arrow Lakes of British Columbia (Canada) collapsed in a disturbing way (Fig. 2). These lakes are on the Kootenay and Columbia Rivers, both of which have seen the construction of two major dams. Since their construction, the annual phosphorus input to the downstream lakes has dropped by approximately 50 tons [6].

For the lack of other convincing arguments, nutrient retention by the upstream dams/reservoirs was identified as the most likely cause for the “Kokanee crisis”. In response, the lakes (Kootenay Lake since 1992 and the Arrow Lakes since 1999) are being fertilized with 50 tons of phosphorus and 200 tons of nitrogen annually (see photo on p. 20). Whether this highly controversial emergency measure was effective – it was feared that these salmon populations were going to be lost entirely – cannot be concluded with any certainty at this point; however, the number of spawners appears to have stabilized to that of previous levels (Fig. 2) [6]. EAWAG asked the question about whether other factors might not have contributed to the decline in Kokanee populations [7]. These studies revealed that the additional damming of the Arrow Lakes themselves, and the depth of the outlet in particular, had a critical effect on the flushing of biomass from the lake system.

Dissolved nutrients may also be retained selectively, depending on the conditions of individual reservoirs. If the retention time is long enough, diatoms can effectively remove silicic acid [8]. For example, rivers in

Impacts of reservoirs on downstream rivers and lakes in a global context [2]

Impacts marked in *cursive* are relevant in an alpine environment.

Hydrology:
Seasonal shift in the discharge pattern, fewer flood events, hydro peaking, in-stream flow, changes in groundwater levels, changes in the internal hydraulic processes of downstream lakes, **water loss.**

River morphology and suspended solids:
Retention of suspended solids, temporal shift in turbidity and particle/nutrient transport, clogging, stagnant river morphology, erosion, **delta and shore recession.**

Geochemical cycles:
Primary productivity, modification of water quality, ***self-purification and nutrient retention in reservoirs,*** **anoxic reservoir runoff, release of reduced compounds and metals, methane production.**

River and floodplain ecology:
Shift in composition of biotic communities, disruption of connectivity, loss of flooded wetlands, flood plains, and stream-land transitional zones, **new wetlands in root dam zones.**

Fish ecology:
Interference with migration and fragmentation of populations, shift from stream species to lake species, flooding of spawning grounds, changes in thermal regime, reduction of habitat quality in sections with low residual flow or hydro peaking, **gas bubble disease, anoxic reservoir runoff.**

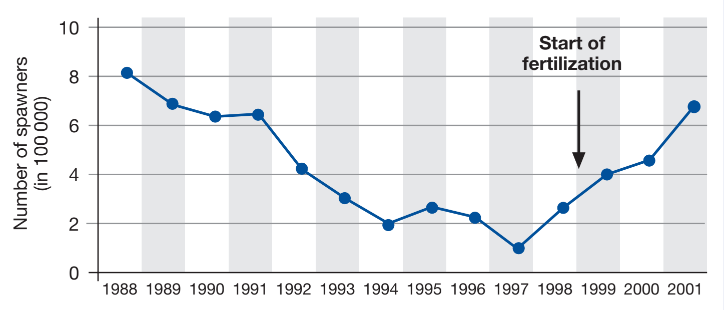

Fig. 2: Collapse and recovery of the population of the landlocked salmon Kokanee in the Arrow Lakes [6].

K. Ashley, Canada

Barge with nutrient tanks on Kootenay Lake, which has received 50 tons of phosphorus fertilizer annually since 1992 [6].

the mountains of northern Sweden that are dammed, carry up to 60% less silicic acid to the Baltic Sea than rivers from watersheds that are not dammed [9]. There are concerns that the diatoms in the Baltic Sea will gradually be replaced by other species, which could lead to changes in the composition of both zooplankton and fish communities. A similar downstream effect is currently being investigated in an EAWAG project concerning the “Iron Gate” dam on the system of the Danube and the Black Sea.

Reservoirs as Modulators of River Temperature

The utilization of hydropower affects not only particle and nutrient transport, but also the temperature regime of downstream lakes and streams. When water drives turbines in a power plant, potential energy is converted to electricity. Under natural discharge conditions, this energy is dissipated via friction into heat, thus warming the stream water. Operation of a turbine, therefore, causes cooling of the stream. For the Swiss Alps as a whole, the average temperature drop is 1.1 °C, and this in streams that are normally rather cool. The effect is most significant on the Rhone where the temperature drop is 1.6 °C.

When taking annual and diurnal cycles into account, however, this estimate paints a rather incomplete picture since several indirect effects need to be considered as well. An enormous amount of heat energy is absorbed through the surface of the reservoirs during the summer months (ca. 14 km^2 in the case of the Rhone watershed) and partially carried over to the winter. Water sent through the turbines is taken from the bottom of the three large reservoirs (Mauvoisin, Grand Dixence and Cleuson) and has an even temperature of 4–5 °C over the entire year. In winter, when the discharge of the Rhone is low, the return water typically warms the river by 0.5 °C. During summer, water retention in the reservoirs reduces flow downstream, which leads to an increase in water temperatures. When turbine water is returned to the river, the cooler water abruptly lowers the temperature of the river. These temperature changes can amount to several °C (Fig. 3A and B).

Studies that are currently being conducted in the context of the revitalization project “Rhone/Thur” (see article by M. Fette on p. 21) are intended to investigate the effects of hydroelectric power generation on the thermal regime of the Rhone and to describe consequences for its inhabitants.

Current Swiss Problems

Since the 1980s, the fishermen on Brienzersee have warned about potential ecological changes caused by the hydroelectric power generation in the Grimsel area. As a result, EAWAG has conducted several studies investigating the potential effect on turbidity, which shows a different seasonal pattern due to the reservoirs [4]. After a massive collapse of fish yields and *Daphnia* populations in Brienzersee in 1999, the Canton of Bern decided to investigate the ecological mechanisms in Brienzersee and their potential changes in more detail. Nine hypotheses were formulated; they will be tested in a number of research projects over the coming years. EAWAG will participate both indirectly in a consulting function, and directly by conducting research projects (fish, biological production, stratification, suspended solids, etc.). It is a rather complex and far-reaching task to document which of the large number of factors are the key “long-range effects“ impacting Brienzersee.

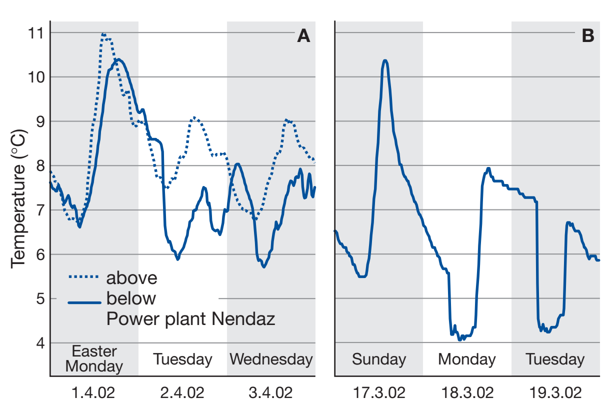

Fig. 3: (A) Temperature as a function of time in the Rhone above (dotted line) and below (solid line) the power plant outlet of Nendaz April 1–3, 2002. While on Easter Sunday (plant not operating) the temperature rose to over 10 °C at noon, the cold water of the Grande Dixence cooled the Rhone to below 6 °C on work days.
(B) Temperature as a function of time in the Lonza (tributary of the Rhone) below the power plant outlet of Lötschen on March 17–19, 2002. For the same reasons as discussed above, the temperature varies by more than 6 °C between Sunday and Monday.

Alfred Wüest, physicist in the department “Applied Aquatic Ecology”. Titular-professor for aquatic physics at ETH Zurich. Research interests: Mixing and transport process in lakes and reservoirs, anthropogenic impacts on aquatic nutrient cycling.

Coauthors:
Lorenz Moosmann, Gabriela Friedl

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The Third Rhone Correction: Rehabilitation Despite Operation of a Power Plant?

In contrast to past corrections of the Rhone, the Third Correction, which is currently in the planning stage, will return some of the space that has been "taken" from the river. The river corridor will be widened in a number of places, which will both improve flood protection and the river's ecological viability. The current situation is, however, rather complex. Over the past 50 years, several new hydroelectric power plants have been built in the alpine headwaters of the Rhone, which cause pronounced periodic changes in the water level of the river. EAWAG is currently investigating how the proposed broadening of the river corridor – and continuing fluctuations in water level – will affect groundwater levels and whether or not a natural ecosystem will be able to become re-established under these conditions.

"On se représente sans peine l'attitude des hommes devant le fleuve: ses grandes crues assez fréquentes devaient leur donner l'impression que le Rhone est une force contre laquelle l'homme ne peut rien." For centuries, inhabitants of the Rhone valley have been at the mercy of a river that has produced massive flood events and caused great human loss and material damage [1]. After the dramatic flood of 1860, it was decided to force the river into a rigid structure, which was realized by the First (1863–1928) and Second (1930–1960) Rhone Correction; however, recent floods have pointed out some new deficiencies, which have led to a proposed Third Correction of the Rhone.

Third Rhone Correction

At the time of the First and the Second Rhone Correction, "hard" flood protection was the preferred method of controlling a river. Today, river management emphasizes integrated planning, giving consideration not only to economic, social and political concerns, but also to ecological values [2]. Goals for the Third Rhone Correction include flood protection as well as measures for improving the ecological function of the river. Restoration, i.e., "reverting the river back to a natural, or at least near-natural, state" [3], will, to a large extent, remain wishful thinking. Instead, the Third Rhone Correction will rehabilitate selected stretches of the river, where a widening of the river corridor is expected to allow for improved ecological function.

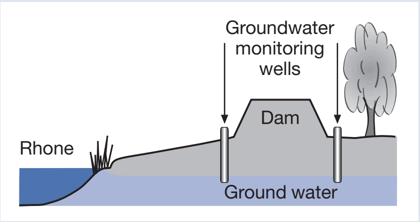

Fig. 1: Cross-section of the Rhone with dam and groundwater monitoring sites.

Utilization of Hydroelectric Power Has Problems

The Valais is ideally suited for the operation of hydroelectric power plants due of its topographical characteristics. Over the last century, several impressive projects were realized, one of them the largest hydroelectric power plant in Switzerland, Cleuson-Dixence, with a total power production equivalent to that of a nuclear power plant. The plants produce electricity only when there is demand and are, therefore, brought on-line almost exclusively during periods of peak consumption. Water from high alpine lakes is piped to turbines situated several hundred meters lower in the valley. One consequent problem results when the water is discharged into the Rhone where it causes transient increases in water level. This phenomenon of hydropeaking can cause the water level to vary by as much as one meter in some locations. For engineers of the Third Rhone Correction, this adds a difficult and demanding aspect to the overall problem of flood protection.

Consequences of Broadening of the River

The upcoming rehabilitation will create large riverbank zones that raise some planning questions:

- Will relocating the dam cause disturbances in groundwater levels?
- How will hydropeaking affect the ecological equilibrium of the revitalized stretches?

Two EAWAG projects are currently investigating these questions; some of our preliminary findings are presented in this article.

The Third Rhone Correction

has a budget of approximately 900 million Swiss Francs, spread over a 30-year period, and has the following goals: improved flood protection and enhancement of the ecological and esthetic aspects of the river corridor. In addition to the cantonal project, there is an ongoing interdisciplinary research project focusing on several specific questions, where EAWAG is also a participant. Results from these projects will give us valuable know-how for similar waterwork projects in Switzerland and abroad.

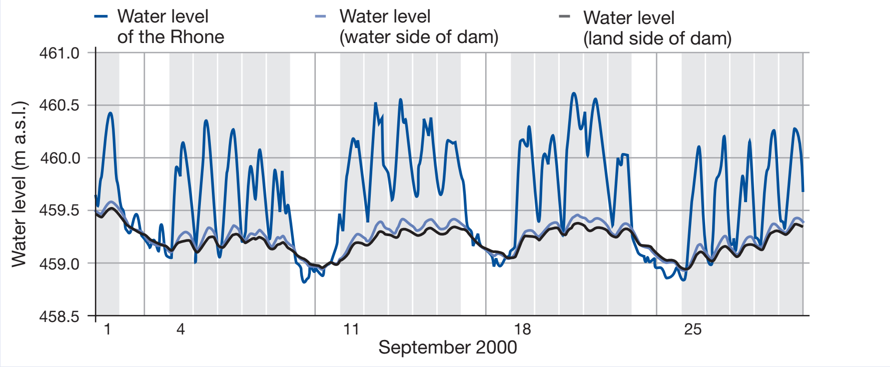

Fig. 2: Groundwater levels in the vicinity of the left Rhone dam near Martigny in comparison to water levels in the Rhone (raw data: Canton Valais/office BEG). Grey area: Monday through Friday; white area: Saturday and Sunday.

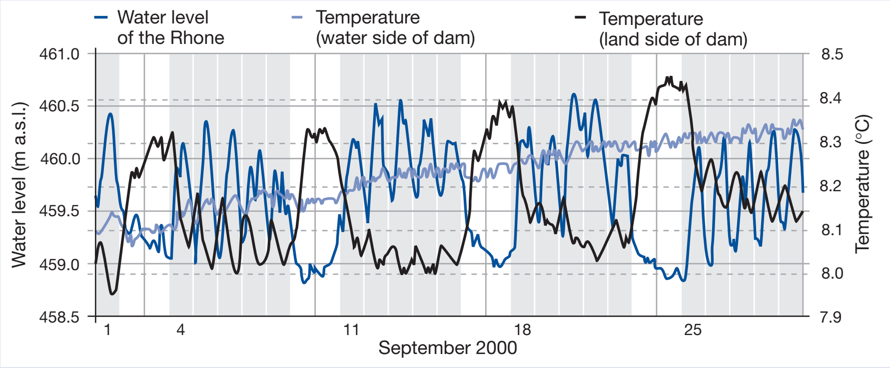

Fig. 3: Temperature profile of ground water in the vicinity of the left Rhone dam near Martigny in comparison to water levels in the Rhone (raw data: Canton Valais/office BEG). Grey area: Monday through Friday; white area: Saturday and Sunday.

How Hydropeaking Affect Groundwater Levels

In an effort to answer the question about relocation of the dam disturbing groundwater levels, water level and temperature were assessed in groundwater wells both on the water and on the land side of the dam (Fig. 1). Figure 2 clearly shows that the water level of the Rhone reflects the cycles of hydropeaking caused by operation of the power plants: Monday through Friday, this results in a daily fluctuation in water level of approximately one meter (dark blue line). The same behavior is observed in wells on either side of the dam, although the amplitude is dampened, and there is a slight time lag (light blue and black line). When the turbines are turned off on Friday evening, the groundwater level stabilizes as does the water level of the Rhone itself.

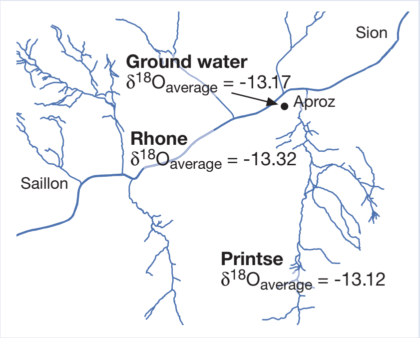

Fig. 4: Isotope data from the study area.

The temperature profile on the water side of the dam (Figure 3, light blue line) does not exhibit any detectable variations. On the land side of the dam, however, a pattern corresponding to hydropeaks in the Rhone is observed (black line). Daily temperature fluctuations are 0.1–0.2 °C, and on weekends, the temperature can rise by as much as 0.4 °C. Wells located more than 100 m from the dam do not show any effects of hydropeaking. In this dam then, we can assume that the observed water level fluctuations are the result of pressure waves; however, other results (see isotope data discussed below) suggest that some water exchange is also taking place. Since it appears that there is no hydraulic connection across the footing of the dam, we maintain that water exchange occurs only below the dam.

Isotope Chemistry Yields Further Insights

Further insight into water exchange processes in the Rhone can be gained from isotope chemistry. Isotopes are atoms of the same element that differ in their total mass. The oxygen atom in water, for example, can be the ^{16}O isotope with a mass of 16, or the ^{18}O isotope with a mass of 18.

The water cycle causes these isotopes to be released into the atmosphere and then to be re-precipitated as rain or snow. Fractionation processes in the atmosphere cause precipitation that falls at high elevations to be “lighter”, i.e., lower in ^{18}O, than precipitation that falls in the valley. The relative amount of the ^{18}O isotope is normally given with respect to the $^{18}O/^{16}O$ ratio of a reference material, the difference being reported in ‰ and denoted as $\delta^{18}O$. Streams at different elevations, therefore, have different $\delta^{18}O$ values. This “altitude memory” can be used to determine the origin of the water.

Using average $\delta^{18}O$ values (Fig. 4) of Rhone water (-14.30), of the nearby ground water (-13.71) and of the Rhone tributary Printse (-13.12), we are able to estimate whether the groundwater body is primarily being fed by Rhone water or by water originating from higher elevations. Due to a lack of data, we neglected the contributions of precipitation and of ground water located upstream of the study area. Our calculations indicate that the ground water is made up of approximately equal portions of Rhone water and high elevation water.

Reduced Diversity Due to Hydropeaking Effects

A second EAWAG project deals with the second question: how does hydropeaking affect the ecological equilibrium of a rehabilitated stretch of the river? In this project, the diversity of aquatic and terrestrial invertebrates along the banks of various streams are being monitored for several years.

Both sides of the actual stream bank are being sampled, i.e., both the flooded and the dry areas. Twelve different stream sections have been selected for this study, representing a range of hydrological and morphological conditions.

Results from the first sampling campaign are summarized in Figure 5. As expected, the hydropeaks exert a negative influence on diversity. The number of aquatic invertebrates in streams that are subject to hydropeaking is obviously lower than in streams with natural flow regimes. The same trend is observed, although is less pronounced, for terrestrial invertebrates (Fig. 5A). Species diversity of terrestrial invertebrates is, however, strongly dependent on the morphology of the stream bank; along artificially straightened sections of streams, the number of species is approximately 50% lower compared to stretches with natural morphology (Fig. 5B).

These results indicate that the broadening of the river corridor may improve the terrestrial fauna along the riverbank, but in order to create better conditions for natural aquatic communities, it appears that we need to adapt the hydropeaking regime.

Back to the Question…

Does this mean that rehabilitation and operation of hydroelectric power plants are mutually exclusive? According to what we know so far in the case of the Rhone, we have to answer this question with a tentative "no". In order to secure the valley bottom, flood protection dams will be needed, even if the river corridor is broadened. According to our current assessment, replacing old dams with modern structures should not have any negative impacts on the hydrological status quo of the ground water.


M. Fette, EAWAG

Discharge water from the turbines of one of the power plants of the Grande Dixence.

Engineering Alternatives for the Third Rhone Correction [4]

- **Updating of the current flood protection system by reinforcing and raising existing dam structures.**
- **Broadening of the river corridor and creation of a natural riverbank zone.**
- **Construction of a second channel, which is not immediately adjacent to the Rhone, for the absorption of high water swells.**

From a biological perspective, it is becoming clear that hydropeaking will prevent the establishment of natural biotic communities even when the river corridor is widened. Additional measures, such as relief basins or diversion channels, will have to be considered. The success of the proposed correction will, therefore, depend on a combination of "hard" technical and "soft" ecological measures.

Two boundary conditions are already quite obvious: the Rhone is already heavily impacted by hydraulic structures and is intensively used for power generation, so it is unrealistic to expect that the lower reaches of the Rhone will revert to an idyllic landscape rich in fauna and flora. *"Le Rhône (…) symbole d'une force inflexible, toujours jeune et triomphante, qui descend vers le soleil, il suscite dans notre exprit des pensées vivantes"* [1] – these poetic images remain an ambitious goal.

Markus Fette, engineer and doctoral student in the department "Surface Waters". The studies presented here are part of the Rhone Project being conducted by EAWAG and WSL.

Coauthors:
Bernhard Wehrli, Achim Pätzold, Klement Tockner

More information: www.rhone-thur.eawag.ch

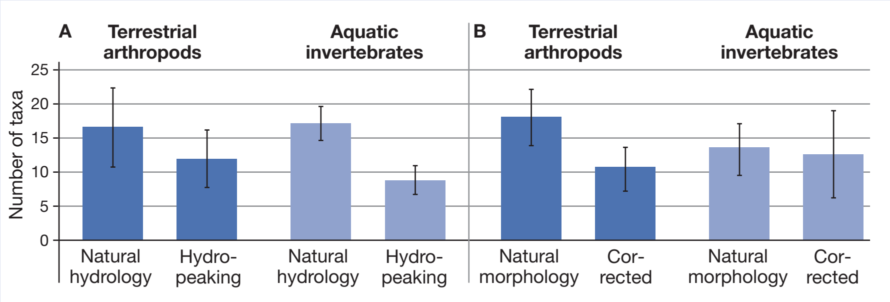

Fig. 5: Diversity of aquatic invertebrates in rivers subjected to hydropeaking and in rivers with a natural discharge regime (A). Diversity of terrestrial invertebrates along corrected river sections and along stretches with natural morphology (B).

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Effects of Global Climate Change on Alpine Aquatic Systems

Global climate change has a direct effect on the alpine aquatic cycle. The last decade was probably the warmest period of the last 1000 years. If this trend continues, there will be significant consequences for the water cycle in Switzerland. Predictions are that summers will be drier, while winters will see more precipitation. Snow lines will increase but glaciers will recede dramatically or disappear altogether. What consequences would these changes have for the streams and rivers in the alpine region?

Alpine aquatic systems – streams, rivers, small and large lakes, ground water, water in pores and fractures of the soil – are part of the global water cycle. Through evaporation and precipitation, this cycle links atmospheric, soil, vegetation and aquatic systems. The water cycle is affected by climate and weather, but climate is also a function of the water cycle – an enormously complex system of feed-back loops. Additionally, humans interfere with these loops and cycles through water management, e.g., water is retained in reservoirs or diverted to different watersheds; large tracts of agricultural land are irrigated; wetlands are drained; and groundwater levels are raised and lowered.

At our latitude and under conditions where global climate would not change, interactions between the aquatic cycle, climate and weather would be stable over a period of several hundred years; this would also be true for the alpine environment.

Changes in the Water Cycle – Yesterday and Before Yesterday

In order to assess the effect of future climate change, we have to consider the water cycle and precipitation patterns in particular. All regions of Switzerland have seen significant fluctuations in precipitation over the last 100 years (Fig. 1). For the Ticino watershed, for example, the extremes were 1084 mm in 1949 and 3038 mm in 1977, thus varying by a factor of three. Probst and Tardy [1] have analyzed discharge data for large rivers and shown that such fluctuations have been observed all over the world. They are due to changes in global circulation and general atmospheric conditions.

Discharge is indirectly coupled to precipitation. In the course of several years, discharge reflects precipitation patterns, provided evaporation is relatively constant; however, precipitation does not necessarily run off directly. It can be stored and retained in many different ways: in snow, glaciers, soil, ground water, natural or artificial lakes, just to name a few. The release of water from these storages affects discharge in the short-term. We can distinguish different discharge types depending on the degree of glaciation and snow cover. They differ in their annual discharge pattern. Figure 2 shows a selection of different discharge types. The largest fluctuations are observed for the type "a-glaciaire", i.e., streams that are primarily fed by glaciers and snow melt. In these streams, discharge between summer and winter can easily vary by a factor of 30. The smallest degree of fluctuation is associated with streams of the type "pluvial supérieur" which depend mostly on rainfall.

With respect to extremes in discharge volume between dry and flood conditions, the differences are even more dramatic. In the Rappengraben, a stream with a very small watershed, extremes of less than 0.1 l/s to over 2300 l/s have been observed. For the Rhine, a river with a very large watershed (only including the portion down to Basel), the extremes were 205 m^3/s in the year 1858 and 5700 m^3/s in 1876.

A problem arises when water management circles and society as a whole, consider the extremes that have been observed in the last 100 years to be representative of the range of values we can expect. If we go back more than 100 years, however, we realize that our "representative" range considerably underestimates the true variability. Pfister [2] has analyzed climatic variations over the last 500 years and notes that the 20th Century was a rather atypically "benign" century. Frozen lakes and dry, cold winters were nothing unusual for people of the 18th Century. At the same time, the record shows that summers were exceptionally dry; before 1730, this occurred

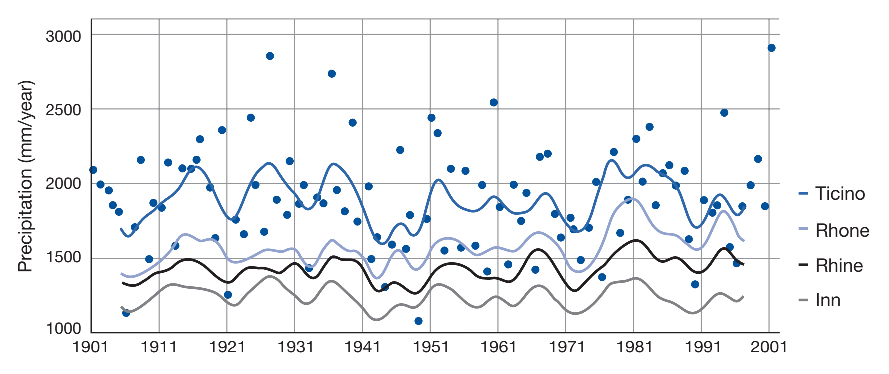


Fig. 1: Temporal pattern of annual precipitation (mm/year) in the watersheds of the Ticino (to Bellinzona), the Rhone (to Lake Geneva), the Rhine (to Basel, Swiss portion of watershed only), and the Inn (to border with Austria). The time series of the annual averages were smoothed with a Gaussian low pass filter over nine-year intervals. For the Ticino, values for individual years are shown as solid circles [7].

every 12 to 15 years. After that time, the interval was roughly every 50 years, and in the 20th century the only such year was 1947. A high incidence of cold and wet summers was recorded between 1576 and 1635, causing glaciers to advance. Since then, such extreme summers have become rather rare.

The frequency of floods has changed accordingly: in the mountain cantons of Valais, Uri, Ticino and the Grisons, the periods of 1550–1580 and 1827–1875 saw an especially high occurrence of floods. Floods were a rather rare event in the years 1641–1706 and 1927–1975. In the 20th Century, flooding has occurred more often since about 1977. It is not a surprise then that Schmidli et al. [3] have noted an increase in winter precipitation, while Frei and Schär [4] have observed increased intensity of individual precipitation events for the same time period.

The Water Cycle Tomorrow and After Tomorrow

The 1990s was probably the warmest decade of the last 1000 years. The third report of the "Intergovernmental Panel on Climate Change" (IPCC) is the first document to state this very clearly [5]. At the same time, the report noted that the largest part of the temperature increase of the latest 50 years was probably due to human activity. With regard to Switzerland, the "Advisory Body on Climate Change" ("Organe consultatif sur les Changements Climatiques", OcCC) [6] has summarized the most important conclusions from the IPCC reports. Assuming temperatures continue to rise, which is a likely scenario, the consequences for the water cycle in Switzerland within the next 50 years would be as follows:

- decreasing precipitation in summer, increasing precipitation in winter, larger fluctuations in annual rainfall;
- more frequent heavy precipitation events in winter (see Fig. 3);
- less precipitation in the form of snow;
- snow lines increasing by 200 m;
- complete melting of a large number of glaciers;
- an increase in discharge volume north of the Alps by 10 %, a decrease by 10 % south of the Alps;
- shift in the discharge regime by one regime level (see Fig. 2);
- increased frequency and severity of floods, especially in the winter months in the middle and lower regions;
- increasing dry periods during the summer, especially in the lower reaches;
- larger fluctuations in discharge dynamics;


WSL

A debris flow in action.

- increased occurrence of debris flows in steep zones of rock and gravel debris that become exposed after the melting of permafrost areas and recession of glaciers.

We have to emphasize, however, that the predicted changes for our region still are somewhat uncertain. This is primarily due to the fact that global climate models cannot reliably calculate regional scenarios.

Consequences for Water Resource Management

Progressive global climate change may lead to situations whereby elements of the water


B. Schädler, BWG

The result. More debris flows due to global warming?

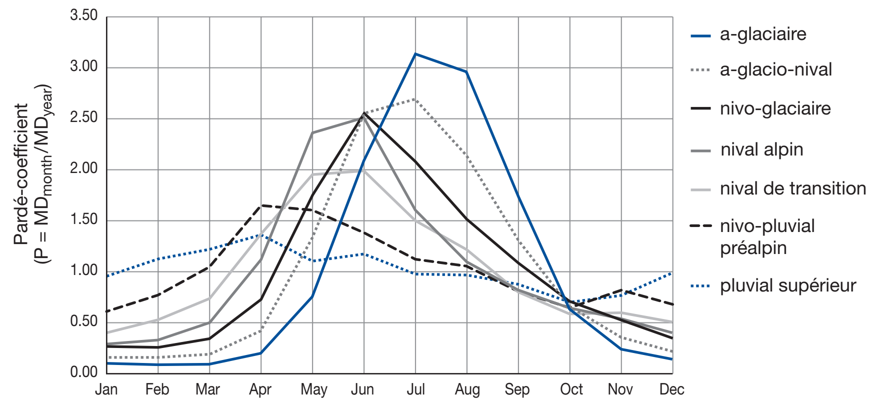


Fig. 2: Average discharge pattern for Swiss watersheds at varying elevation, ranging from "pluvial supérieur" (average elevation 800 m a. s. l.) to "a-glaciaire" (2700 m a. s. l.) [after 8]. MD = mean discharge.

cycle assume values that exceed current experimental values; therefore, we need to anticipate the consequences of various aspects of water resource management:

- Due to a reduction in precipitation during the summer months, lakes and streams will carry less water. At the same time, agricultural crops will have to be irrigated, leading to an even more pronounced water shortage. A water shortage would, in turn, have consequences for water quality; pollutants would no longer be diluted, and water temperatures would increase. Normally, water temperatures change in concert with air temperatures (Fig. 4). When discharge volumes are reduced, however, we have to assume that water temperatures will rise more than proportionally, especially in smaller streams.
- We cannot preclude that there would not be some impact on the ground water near streams since infiltration of rain and stream water would be reduced, and evaporation would be expected to increase.
- The management of all larger lakes in Switzerland (with the exceptions of Lake Constance and Walensee) is based on experimental values established in the 20th Century that balance the interests of all lake users. Increased precipitation during the winter could lead to more demand for flood protection. This could create a need for different operational procedures or even new structural measures. Since such changes require a long lead time for planning and implementation, we have to move quickly to develop scenarios for these problems.
- The temporal pattern for recharge flow to reservoirs and demand for electricity are expected to change. There could be, however, new demands on reservoir operators in terms of water retention during high water periods. Substantial political, legislative and technical groundwork would have to be laid before our reservoirs could be operated as multi-purpose installations.
- If the increased number of flood events translates to more flooding in downstream countries, we have to expect a demand for more retention of water in our Swiss reservoirs and lakes during those periods. This would definitely add a very strong political dimension to the two issues discussed above.
- Finally, navigation of the Rhine could be affected: we would anticipate very low water levels all the way to The Netherlands, especially during the summer and fall, while we would expect high water surges to move through the system in the winter. As a result, barges would reach Switzerland only partially loaded or not at all, which would result in increased prices for high volume goods such as oil.

The water resource management field is accustomed to reacting to extreme situations and to finding workable solutions. The predicted climate changes, however, are a type of challenge where we can and should take proactive measures before major problems arise, following the principle of "no regret". These are measures that will minimize the effects of global climate change and are, at the same time, desirable for other reasons, such as changes in land use politics or a more flexible management of our large lakes.

Bruno Schädler holds a doctorate in atmospheric science and hydrology. He is at the Federal Office for Water and Geology in Bern-Ittigen, where he heads the department "Water Resource Management". He is an expert consultant for water and climate in the "Advisory Body on Climate Change" (OcCC).

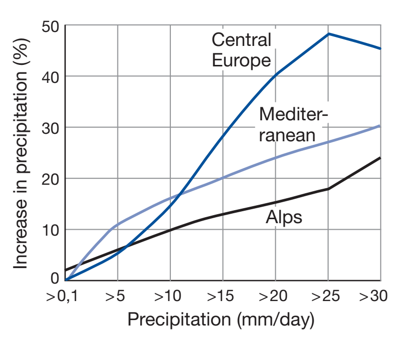
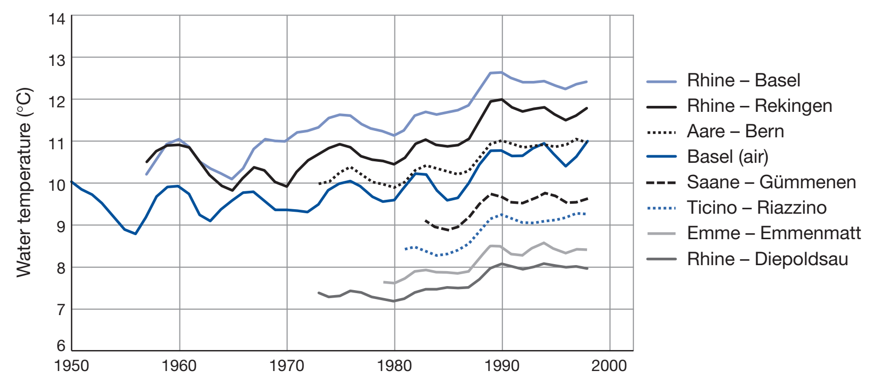


Fig. 3: Calculated increase in winter precipitation for three mid-European regions assuming an atmosphere that is 2 °C warmer and 15% more humid than the current atmosphere [after 9].



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IN BRIEF

International Water Management Course (IWMC)

The world's water resources are increasingly stressed, as populations are growing and the demand for food and material goods is rising. While many of the most serious water resource problems are to be found in arid regions of the developing world, the industrialized countries are also heavily drawing on their own water resources. These countries have an important role to play in developing strategies that ensure the quality and existence of this precious resource for future generation. Therefore, aiming at providing profound knowledge on the global and regional water situations, especially those faced by the industrialized countries, EAWAG will hold the "International Water Management Course" jointly with Swiss Re.

The course will take place from 5–12 July and is directed towards decision makers and professionals in the water management and urban infrastructure fields (executives from water supply and treatment facilities, industry, government agencies, NGO's and consultants).

Further information: www.iwmc.eawag.ch

International Conference on Environmental Future (ICEF)

On the occasion of the International Freshwater Year 2003, EAWAG and the "Foundation for Environmental Conservation" (FEC) are jointly organizing a conference on the topic "Environmental Future of Aquatic Ecosystems".

Given the particular vulnerability of many aquatic habitats, EAWAG and FEC have called this landmark meeting to promote well-informed international debate about what the next quarter century might hold in store for all the water-based ecosystems of the earth. Directly following the World Day for Water in the International Year of Freshwater, declared by the United Nations General Assembly, the 5th ICEF will assess threats to resilience and likely changes in the 21 major aquatic systems over a time horizon of the next 25 years. For this purpose, FEC and EAWAG have engaged leading scientists from around the world to review each of the major marine and freshwater systems.

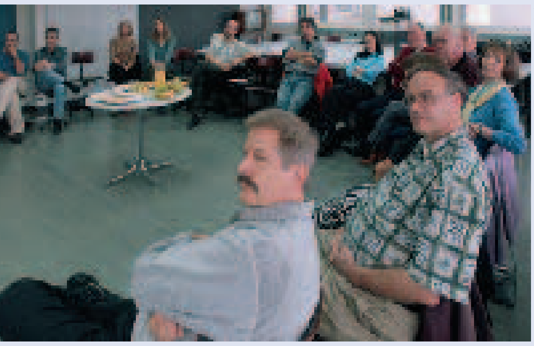
The conference will be held at ETH Zurich on March 23–27.

Further information: www.icef.eawag.ch

Results from the Round Table

"Things will never be like they were before. I have been sensitized once and for all for the responsible use of drinking water", summarizes a citizen who participated in the discussions. "I expected this to be easier, but we have come far enough to understand each other and to come away with something from the other's side", states an EAWAG scientist. The dialogue between lay persons and scientists has made some progress. This conclusion was drawn by the participants of the pilot project "Round Table – Science et Cité" at their last meeting on October 4–5, 2002. The project lasted three years. For a total of 12 days, citizens and scientists from EAWAG met periodically to discuss research projects and questions around the topic "water". The final report (in German) summarizes experiences and guidelines for future dialogue projects.

Further information:
www.eawag.ch/news/science_et_cite

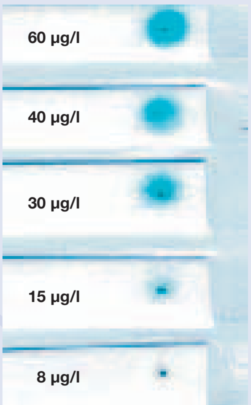


T. Kawara, Zurich

New Biosensor for the Detection of Arsenic in Water

Worldwide, arsenic is one of the most important inorganic pollutants in drinking water. Particularly alarming is the situation in Bangladesh: arsenic concentrations as high as 1000 µg/l drinking water have been found; the WHO recommends a maximum concentration of 10 µg/l. More than one million people are already suffering from arsenic poisoning (see EAWAG news 53). In order to test each one of the roughly 9 million private drinking water wells, we need an inexpensive, reliable and sensitive field method. For this reason, an EAWAG team has developed a new biosensor for arsenic. The paper strip test uses genetically modified bacteria that produce blue coloration even at low arsenic concentrations. EAWAG has applied for a patent for this sensor.

Further information: www.eawag.ch/news_e/arsenic



J.R. van der Meer, EAWAG

Test strips with color reaction.