The Hydrology of Switzerland

Selected aspects and results

M. Spreafico and R. Weingartner

Berichte des BWG, Serie Wasser – Rapports de l'OFEG, Série Eaux – Rapporti dell'UFAEG, Serie Acque – Reports of the FOWG, Water Series
No. 7 – Berne 2005

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Abbreviations

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FOWG	Federal Office for Water and Geology, Ittigen-Berne
CHYN	Centre of Hydrogeology, University of Neuchâtel
EPFL	Lausanne Federal Institute of Technology
ETHZ	Zurich Federal Institute of Technology
GIUB	Geographical Institute, University of Berne
GIUZ	Geographical Institute, University of Zurich
H – W	Hydrologie – Wasserbau, Urtenen-Schönbühl
IACETH	Institute for Atmospheric and Climate Science, ETHZ
MHNG	Museum of Natural History, Geneva
Nagra	National Cooperative for the Disposal of Radioactive Waste, Wettingen
SLF	Swiss Federal Institute for Snow and Avalanche Research, Davos
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf

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Preface

Water is Life

Knowledge of the quality and quantity as well as the spatial and temporal aspects of surface and subterranean water reserves is essential for the sustainable, ecologically optimal and economically feasible exploitation of water as a resource. Obtaining this knowledge, namely through measuring discharge and reserves, as well as analysing and researching the processes that govern them, is the task of hydrologists. For more than 150 years this basic hydrological information has been provided in Switzerland by the Swiss National Hydrological Survey, which involves federal offices, cantonal authorities, research institutions and private business as well as individuals.

The present publication covers selected aspects and results concerning current knowledge of surface water and groundwater in Switzerland. It focuses on the basic aspects of hydrology in Switzerland and provides an easy-to-read overview. It is a monograph drawn up by several scientists under the guidance of the Swiss National Hydrological Survey and the Hydrology Group of the Geographical Institute at the University of Berne. It is aimed at the general public, for which reason not every scientific detail is explained.

I should like to thank everyone who has helped to produce this work.

Federal Office for Water and Geology

The Director

Dr Ch. Furrer

Contents

1 Introduction

Introduction

Hydrology is the science that deals with water on and below the surface, its various forms, how it circulates, its spatial and temporal distribution, its biological, chemical and physical characteristics and its interaction with the environment.

Thanks to its mountainous terrain and the associated high-rainfall catchments, Switzerland is often called the "water tower of Europe". The justification of this description can be seen for example in the fact that Switzerland provides some 45% of the total discharge of the Rhine when it reaches the Netherlands, although it represents only 21% of the total catchment area.

This geographical predominance and the responsibility that it implies were already known to our ancestors. As early as the middle of the 19^{th} century, politicians, researchers and the authorities made efforts to record, measure and research the water reserves in order to be able to exploit and protect them as efficiently as possible.

Today Switzerland has hydrological measuring networks at its disposal that are dense and provide frequent information which ensures a basic knowledge of the quantity and quality of water reserves as well as the relevant hydrological processes. This information is also of service to the countries further downstream which use the water emanating from Switzerland. The experience gained in Switzerland is also leading to the development of other mountain areas where measuring networks are not so advanced. In this way Switzerland is helping countries in Central Asia to rebuild their hydrometeorological services, including discharge predictions and estimating available water resources. In addition, Switzerland contributes its wealth of specialised knowledge in the field of hydrology to many international bodies. Swiss research institutions carry out applied projects in many countries of the south and thus help to ensure the sustainable development of these regions.

The present publication provides an overview of the results and current knowledge concerning various aspects of hydrology in Switzerland. Its aim is to demonstrate the aspects mentioned in the above definition of hydrology in a clear and concise manner. The content is based on the "Hydrological Atlas of Switzerland" (HADES), which is regularly updated through contributions from the principal hydrological institutions in Switzerland. The present monograph is not a summary of the Atlas, which would tend to interest a scientific readership, but rather a discussion and brief account of selected aspects of hydrology in Switzerland that will appeal to the general public.

The publishers would like to thank the many helpers that have made this publication possible and look forward to working with them again in the future. Particular thanks are due to Tom Reist, who through his untiring efforts has made an important contribution towards the success of this work.

2 Precipitation

Statistics

Mean annual precipitation Switzerland (1961–1990)	1458 mm		Source: SCHÄDLER & WEINGARTNER 2002a
Min. mean annual precipitation (1951–1980)	522 mm	Ackersand (VS)	Source: KIRCHHOFER & SEVRUK 1992
Max. mean annual precipitation (1951–1980)	3142 mm	Mönchsgrat (VS/BE)	Source: KIRCHHOFER & SEVRUK 1992
Maximum annual precipitation	5910 mm	Mönchsgrat (VS/BE) 1939/40	Source: MeteoSwiss
Maximum daily precipitation	500 mm	Maggia (TI), 10.9.1983	Source: GEIGER et al. 1991
Maximum hourly precipitation	105 mm	Sternberg (ZH), 23.6.1930	Source: GEIGER et al. 1991
Maximum precipitation within 10 minutes	50 mm	Heiden (AR), 26.7.1895	Source: GEIGER et al. 1991
Longest drought	77 days	Lugano (TI), 6.12.1988–20.2.1989	Source: MeteoSwiss

2.1 Measuring precipitation

In principle precipitation can be recorded and measured everywhere using simple means. In reality, there are major problems involved in measuring precipitation, however. The knowledge of the interval during which the precipitation was measured is essential for the use of the data. Four measuring networks that cover the whole of Switzerland provide precipitation values for periods of one year, one day, half a day and 10 minutes.

2.1.1 Development of the measuring networks

In certain locations precipitation has been measured since the 18th century. It was only in 1863, however, that the Swiss Society for Research in the Natural Sciences first systematically recorded precipitation through an initial network of some 40 stations equipped with precipitation gauges. In 1881 the newly founded Meteorological Institute took over the existing stations. Over the following years the number of stations increased rapidly and around the turn of the century precipitation was being measured daily at 345 stations (see Fig. 2-1).

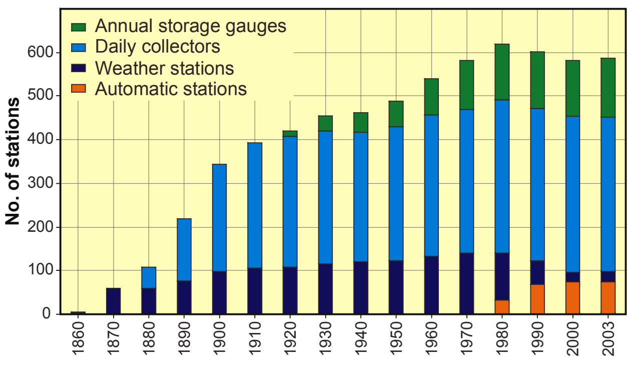


Fig. 2-1: Expansion of the Swiss network of precipitation measuring stations (from WEINGARTNER 1992; data from 1990: MeteoSwiss).

Measuring stations must be easily accessible if precipitation values are to be read off daily. This has led to a concentration of measuring points at lower altitudes and in areas with permanent resident populations. From 1914 on gaps in mountain areas were reduced through a network of annual storage gauges. Thanks to the expansion of the automatic measuring network (ANETZ) after 1978, precipitation data for shorter periods are now available for all regions of Switzerland. At the same time (1977) the first two meteorological radar stations were put into operation. Some of the automatic stations of the supplementary network (ENET) set up from 1995 on also measure precipitation. In addition to these national measuring networks there are also various cantonal, private and special (e.g. at airports) networks which will not be mentioned in more detail.

2.1.2 Precipitation measuring networks operated by MeteoSwiss

The MeteoSwiss networks that measure precipitation comprise around 600 stations (see Table 2-1). With a mean of 1 station per 70 km^2 for measuring annual precipitation, the measuring network is extremely dense by comparison with the world as a whole. The density of stations does vary from one region to another, however (see Fig. 2-2), there being fewer stations in mountain areas (see Fig. 2-3). This means that at higher altitudes, precipitation is not recorded in sufficient detail from a spatial point of view.

Measuring network	Time scale	Stations
Weather stations	Half-day totals	25
Precipitation (NIME)	Daily totals	351
Annual storage gauges	Annual totals	137
ANETZ	10-minute intensity	68
ENET	10-minute intensity	5
Total		586

Table 2-1: MeteoSwiss networks that measure precipitation (as at 2002/2003) (data: MeteoSwiss).

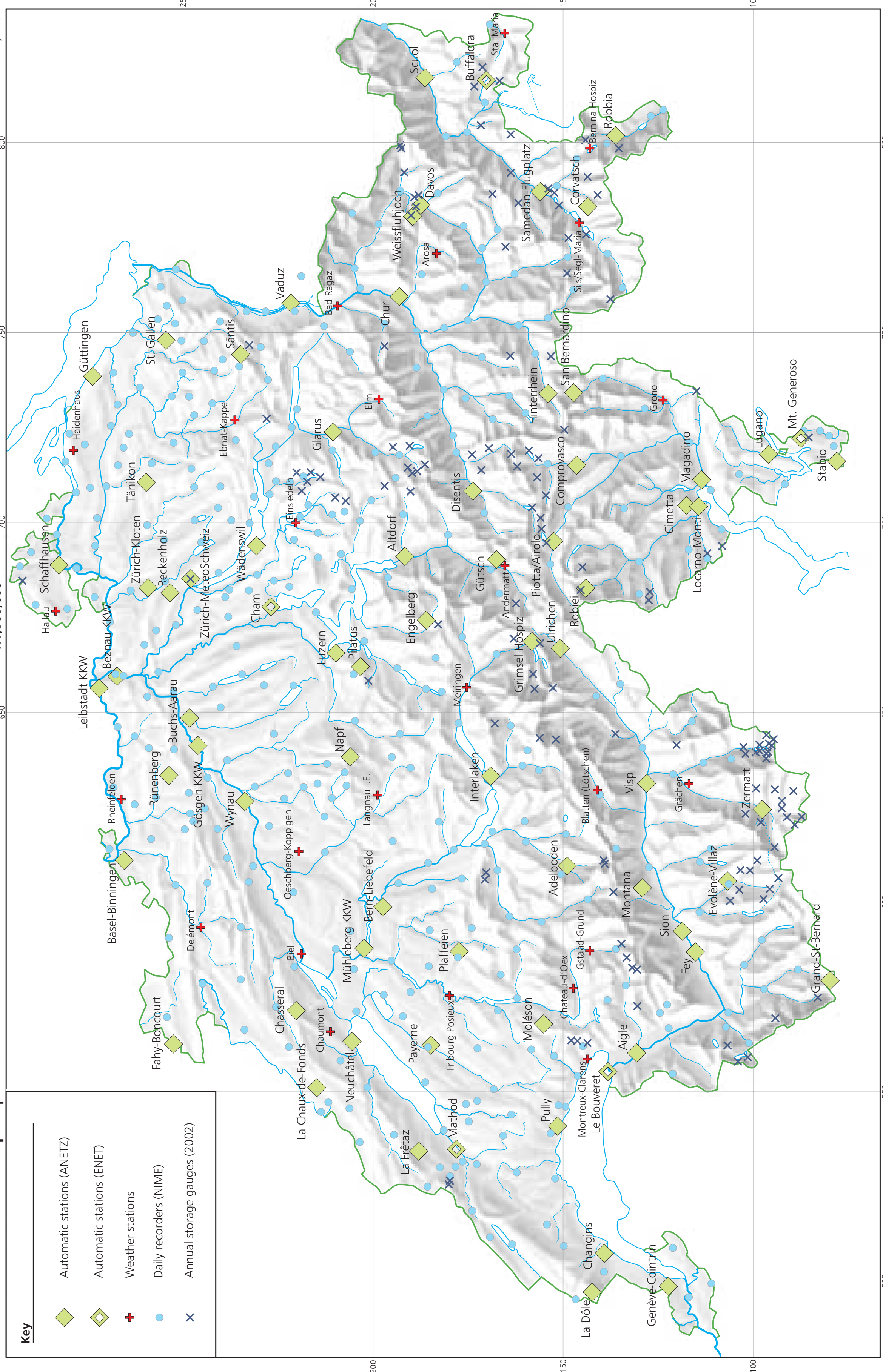


Fig. 2-2: Map of MeteoSwiss stations where precipitation is measured (as at 2002/2003) (data: MeteoSwiss).

For example, there are now only 9 stations that measure daily precipitation above 2000 m (1 station per 1073 km^2).

Figure 2-3 can be used to compare the altitude of the measuring networks for various time scales with surface altitude. If the distribution were optimal the curves would be identical. In reality, however, the altitude of the stations that measure precipitation at least once a day is hardly representative; 90% of all ANETZ and ENET stations and almost 100% of the weather stations and daily recorders are below 2000 m, whereas only 77% of the surface of Switzerland is below this altitude.

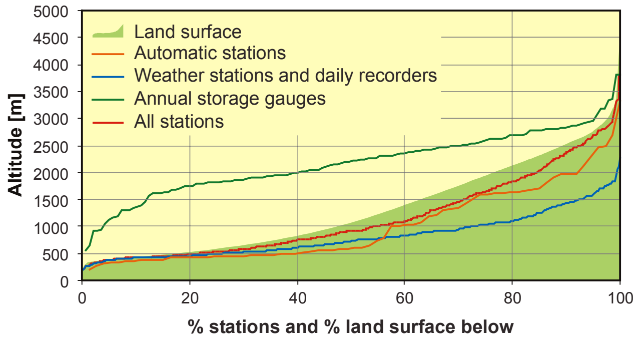


Fig. 2-3: Altitude of land surface and precipitation stations throughout Switzerland (data: MeteoSwiss).

2.1.3 Measuring apparatus and errors

The most precise measurements of precipitation are point measurements. A pluviometer collects the raindrops, hailstones and snowflakes that fall on its collecting surface (200 cm^2 for the Hellmann and Joss-Tognini pluviometers). Depending on the time scale, various measuring devices are used which differ mainly in the volume of precipitation that they can collect (see Figs. 2-4 and 2-5). In addition, pluviographs are fitted with a device by which they continually record precipitation in analogue or digital form (see Figs. 2-5 and 2-6). The gauges are set up at a height of 1.5 m above the ground (2 m in mountain areas and 4 m in the case of storage gauges) at a sufficient distance from trees and buildings. They are normally not placed in positions that are exposed to high winds or very sheltered. When temperatures are extremely low only heated gauges can operate.

Like any other object, a precipitation gauge will affect wind patterns in its immediate vicinity. Wind speed

Fig. 2-4: Pluviometer (Hellmann monthly storage gauge) on Gibel Alp (canton of Berne), Leissigen mountain torrent test zone operated by the Geographical Institute of the University of Berne.

Fig. 2-5: Precipitation gauges at the Rünenberg ANETZ station (canton of Basel-Land). Centre: pluviograph (Joss-Tognini tipping bucket system); right: Hellmann pluviometer.

Fig. 2-6: Precipitation gauges in the hydrological test zone operated by the Zurich Federal Institute of Technology (ETHZ) (Rietholzbach, canton of St. Gallen); from left to right: pluviograph (Joss-Tognini), pluviometer (Mougin annual storage gauge with windshield), pluviograph (Belfort scales, analogue recording), pluviograph (Belfort scales, digital recording).

and turbulence will increase and divert light raindrops and snowflakes in particular away from it. The resulting measurement error will rise with increasing wind speed, which is why special wind shields are used in particularly exposed locations (see Figs. 2-6 and 2-7). Other causes of error are splashing, evaporation from the collector and lack of precision in reading off values. Overall, errors are most marked in connection with snow and at high altitudes. On average throughout the year, it must be reckoned that point measurements will be up to 25% too low (see Fig. 2-8). In individual cases the rate of error can even be over 30%.

Fig. 2-7: Pluviograph (scales, Ott pluvio 250) with wind shield in the forest hydrological test zone in Sperbelgraben (canton of Berne) operated by the WSL (Swiss Federal Institute for Forest, Snow and Landscape Research) and the Geographical Institute of the University of Berne.

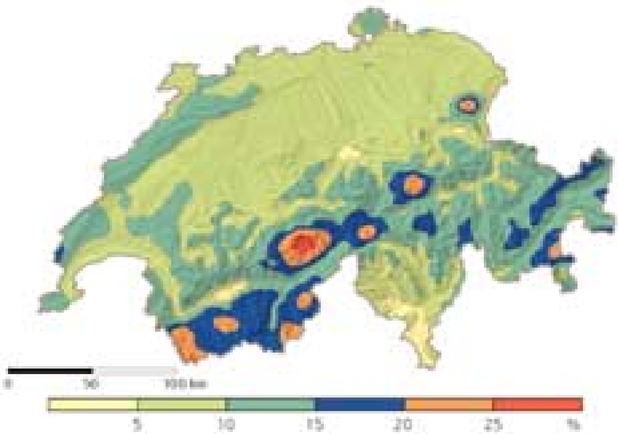


Fig. 2-8: Estimate of mean rate of error in measuring annual precipitation that can be expected in this area (as a percentage of the value obtained) (from SEVRUK & KIRCHHOFER 1992).

2.2 From a point to an area

Often the point precipitation measurements cannot be used directly for hydrological purposes. What is wanted is the volume of precipitation in a given area (area precipitation). Various methods can be used to extrapolate point precipitation mesurements to apply to a given area (see Fig. 2-9). The result can then be checked using the water balance method.

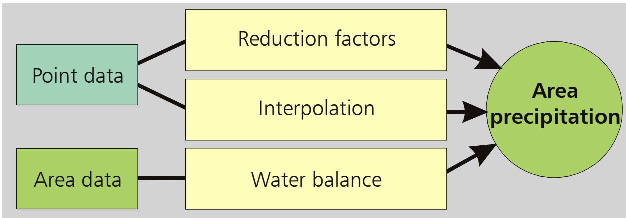


Fig. 2-9: Methods of estimating area precipitation.

2.2.1 Reduction factors

Point measurements are representative only of the point at which the measurement is made and the immediate vicinity, depending on the topography and the precipitation pattern for a maximum of 10 to 100 km^2. Characteristically the volume of precipitation falls with increasing distance from its centre (see Fig. 2-10). Shown as a reduction curve, this fall is determined by the duration of the event and the intensity of the precipitation. Showers (convective precipitation) are short in duration and cover only a small area. Continuous rainfall (advective precipitation) covers larger areas but is less intensive. GREBNER et al. (1999) have published a list of regional reduction factors for the whole of Switzerland.

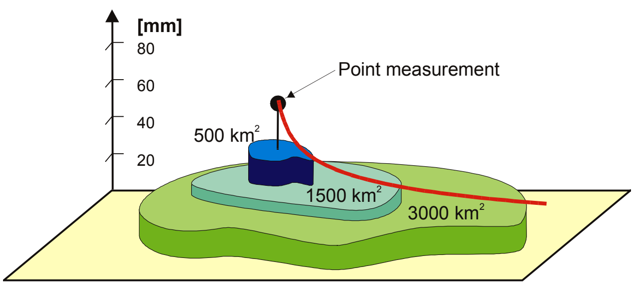


Fig. 2-10: Diagram of the principle of the reduction curve for a 3-hour precipitation event with area precipitation volumes (from GREBNER et al. 1999).

2.2.2 Interpolation

The aim of interpolation is to fill in the information gaps between measuring points. The quality of an interpolation depends to a large extent on the number and distribution of measuring points and the interpolation method used.

The oldest and often highly precise method involves a subjective estimation of precipitation distribution, taking into account the measuring points, the topography and local climatic conditions; isohyets (lines linking places that have equal amounts of precipitation) are then drawn (see Section 2.2.4). Objective methods can also produce good results if they are used in a way appropriate to the prevailing conditions. The estimation of area precipitation for the Reuss catchment described below (see Fig. 2-11) using three common methods (Thiessen polygons, distance weighting and altitude dependent regression) demonstrates the possible variation in the results.

For the Thiessen polygon method the station measurement is taken as representative for an area that extends half-way towards a neighbouring station. The distance weighting method takes into account all stations surrounding the focal point of the interpolation, allotting more weight to those closer than to those further away, however. In the altitude dependent regression method, the available station data are used to calculate volume gradients which are in turn used to interpolate the precipitation.

For the first two methods interpolation is strongly influenced by the stations within the area (see Fig. 2-12). The estimates for flatter land, where precipitation measurements for a vast area are representative, tend to be more reliable. In hilly or mountainous areas precipitation calculated using altitude dependent regression is generally more accurate (see Table 2-2). In any case, the result is strongly influenced by the choice of stations used in the calculations, as the following example shows. The gradient calculated from annual precipitation measured at the stations in Altdorf, Andermatt and Gütsch (21 mm/100 m) results in

Fig. 2-11: Precipitation stations in and around the Reuss catchment (Seedorf runoff measuring station): mean total annual precipitation in mm for the period 1961–1990 (data: MeteoSwiss).

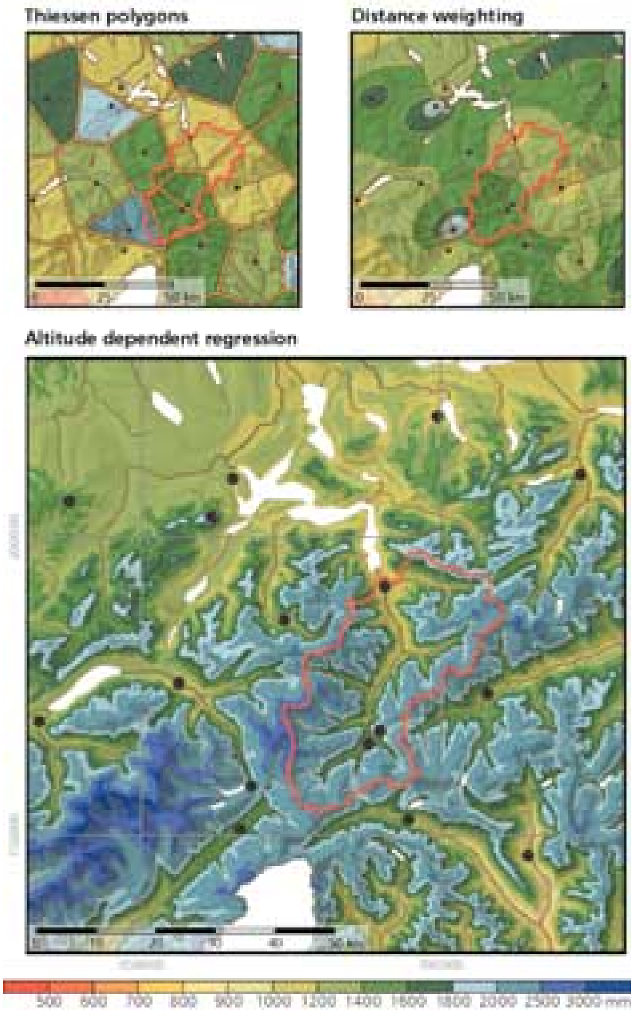


Fig. 2-12: Comparison of three interpolation methods: spatially interpolated total annual precipitation, precipitation stations (points) and the Reuss–Seedorf catchment (outlined in red).

a marked underestimation of area precipitation for the Reuss catchment. The reason for this is that there is no altitude gradient available between the two (quite) high-altitude stations at Andermatt (1442 m) and Gütsch (2287 m) since both stations receive a similar amount of precipitation (see Fig. 2-11). If, however, the figure for the Grimsel Hospice station (1980 m, 2094 mm precipitation) is used instead of Gütsch, the resulting area precipitation gradient of 60 mm/100 m is closer to the reference value (see Table 2-2).

Method	Annual precipitation [mm]
Thiessen polygons	1340
Distance weighting	1387
Alt. dependent regression (Altdorf, Andermatt, Gütsch)	1465
Alt. dependent regression (Altdorf, Andermatt, Grimsel)	1981
Reference value from the water balance	2000

Table 2-2: Comparison of interpolated annual precipitation values (1961–1990) for the Reuss – Seedorf catchment with the reference value, from SCHÄDLER & WEINGARTNER (2002a).

2.2.3 Water balance method

The hydrological characteristics of an area are described in its water balance (see Section 10). The precipitation must be totally accounted for by runoff, evaporation, changes in stored water and underground inflow or runoff. In comparison with the marked inaccuracy regarding measurement and interpolation of precipitation in mountain areas, the rate of error in ascertaining runoff and evaporation is relatively small, normally below 10%. The indirect method of using the water balance can therefore be considered as the most accurate method for determining area precipitation in mountains (SCHÄDLER & WEINGARTNER 2002b).

2.2.4 Precipitation maps

The first precipitation maps for the whole of Switzerland were drawn shortly after the precipitation measuring network was set up. In 1871, when WOLF drew up his ˝Schweizerische Flussgebietskarte mit Niederschlagscurven˝, there were around 40 stations. It is interesting to note that, despite the short duration of measurements, the station values used correspond closely to the standard values for the period 1961–1990 (see Table 2-3). In view of the considerable distances between the stations, however, it was only possible to do a rough interpolation with isohyets (see Fig. 2-13).

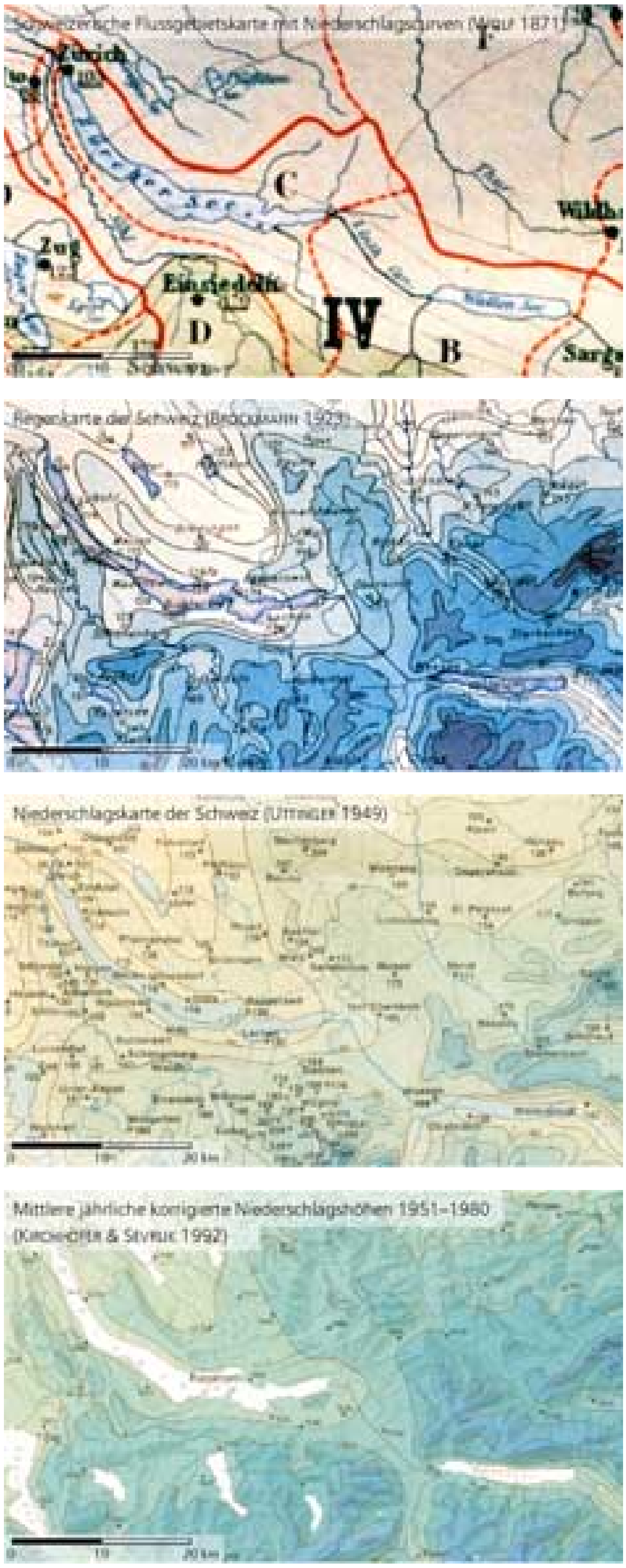


Fig. 2-13: Development of precipitation maps showing the same geographical area (the colours used have a different meaning in each map).

In his ˝Regenkarte der Schweiz˝ (1923) BROCKMANN was the first to use data from annual storage gauges in mountain areas. In 1920 the measuring network comprised over 400 stations and allowed for much more detailed interpolation. The ˝Niederschlagskarte der Schweiz˝ (UTTINGER 1949) is based on series of observations from 1900 on provided by 230 stations; 500 further measurement series, including those from 142 annual storage gauges, were adjusted and/or completed according to the station in question and also used in the map. Unlike the previous maps, altitude dependent gradients were also used in the subjective interpolation. The ˝Mittlere jährliche korrigierte Niederschlagshöhen 1951–1980˝ map (KIRCHHOFER & SEVRUK 1992) represents the shift to objective interpolation methods. Data from around 400 stations were available for the combined process of altitude dependent regression and distance weighting (Kriging). The differences in the station data (see Table 2-3) are principally the result of the preceding correction of the systematic measurement error. Figure 2-15 shows a simplified version of the latest map by SCHWARB et al. (2001a).

Author and year	Period	Zurich	Einsiedeln
WOLF 1871	1864–1869	1050	1700
BROCKMANN 1923	–	1140	1600
UTTINGER 1949	1901–1940	1070	1680
KIRCHHOFER & SEVRUK 1992	1951–1980	1218	1807
Norms (MeteoSwiss)	1961–1990	1086	1753

Table 2-3: Norms for annual precipitation in mm in comparison with values for other periods and authors.

Checking various precipitation maps with area precipitation figures based on water balance shows that objective methods (KIRCHHOFER & SEVRUK 1992, SCHWARB et al. 2001a) are no more accurate (see Table 2-4). It is interesting to note that UTTINGER's map (1949), which was influenced by subjective expert knowledge, is the best product.

Author and year	Precipitation	Deviation
UTTINGER 1949	1461	0
KIRCHHOFER & SEVRUK 1992	1681	15
SCHWARB et al. 2001a	1385	–5
Reference value	1458	0

Table 2-4: Total annual precipitation in Switzerland in mm according to various authors and percentage deviation from reference value taken from the water balance (SCHÄDLER & WEINGARTNER 2002b).

2.3 Precipitation conditions

Mean annual precipitation in Switzerland of 1458 mm (SCHÄDLER & WEINGARTNER 2002a) does not provide much information about the effective conditions within the country. Precipitation is strongly influenced by the position of mountainous areas. There are a great many local differences in precipitation between valley floors and mountain peaks, between leeward and windward aspects, and between the northern and the southern flanks of the Alps.

2.3.1 Annual precipitation

The most obvious influence of the mountains can be seen in the fact that precipitation increases with altitude. On the northern side of the Alps precipitation increases by around 70–80 mm per 100 m rise in altitude. This rather loose correlation applies especially to areas under 1500 m (see Fig. 2-14). Current precipitation maps (SCHWARB et al. 2001a) take the influence of the mountains into account in a differentiated manner. The map of total annual precipitation shown here (Fig. 2-15) uses some 10,000 local gradients.

The wettest area can be seen along the northern flank of the Alpine ridge, with a maximum in the Bernese and Valais Alps. In addition, the whole of the Tessin receives an above-average amount of precipitation. The areas that boast the lowest precipitation figures lie in the rain-shadow of the Alpine ridge. Two north–south profiles reveal the influence of the mountains on total annual precipitation (Fig. 2-15).

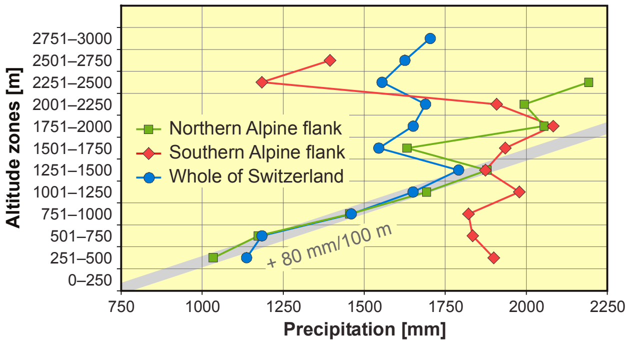


Fig. 2-14: Mean annual precipitation of balance areas by altitude zones (1961–1990, from SCHÄDLER & WEINGARTNER 2002b), with the linear precipitation gradient (+ 80 mm/100 m) from KIRCHHOFER & SEVRUK (1992).

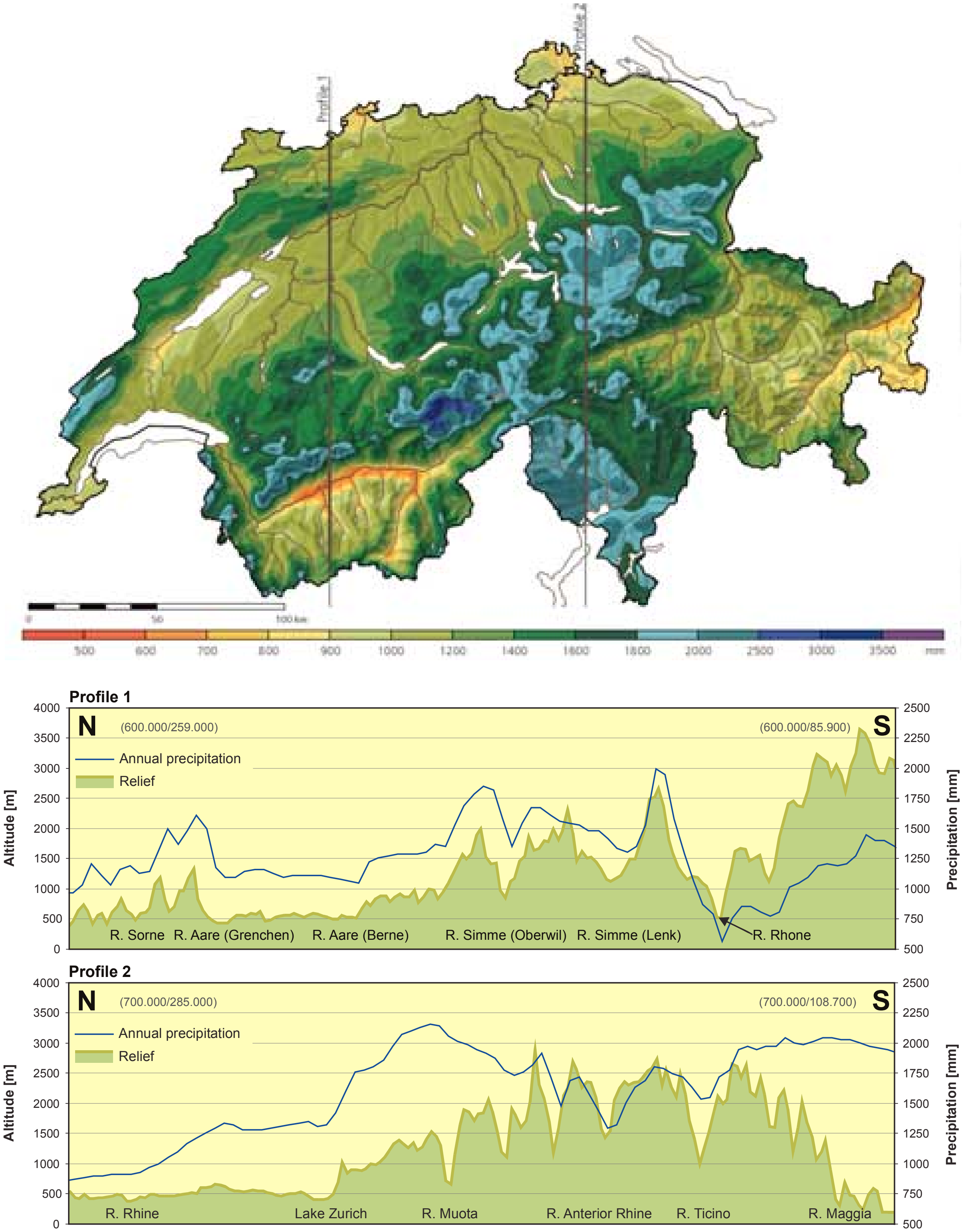


Fig. 2-15: Map of total annual precipitation (1971–1990) with two profiles (data: SCHWARB et al. 2001a).

2.3.2 Seasonal precipitation pattern

From a seasonal point of view the precipitation pattern in Switzerland is extremely balanced (see Table 2-5). Minimum precipitation is in winter and maximum in summer. Figures for spring and autumn are similar. From June to August rainfall is high and experienced mainly in the form of showers. Distribution closely resembles annual precipitation with peaks on the northern Alpine flank and in the Tessin (see Fig. 2-16).

The prevailing winds in winter bring large quantities of precipitation especially in the western part of the country (see Fig. 2-17). In contrast precipitation is at its lowest in the central and eastern parts of the Alps at this time of the year. Precipitation is high in the southern Alps in spring and autumn with frequent prevailing south–west winds.

Spring	Summer	Autumn	Winter
25	29	25	21

Table 2-5: Mean seasonal precipitation for the whole of Switzerland in % (1971–1990) (from SCHWARB et al. 2001b).

Fig. 2-17: Season with the highest precipitation (1971–1990) (from SCHWARB et al. 2001b).

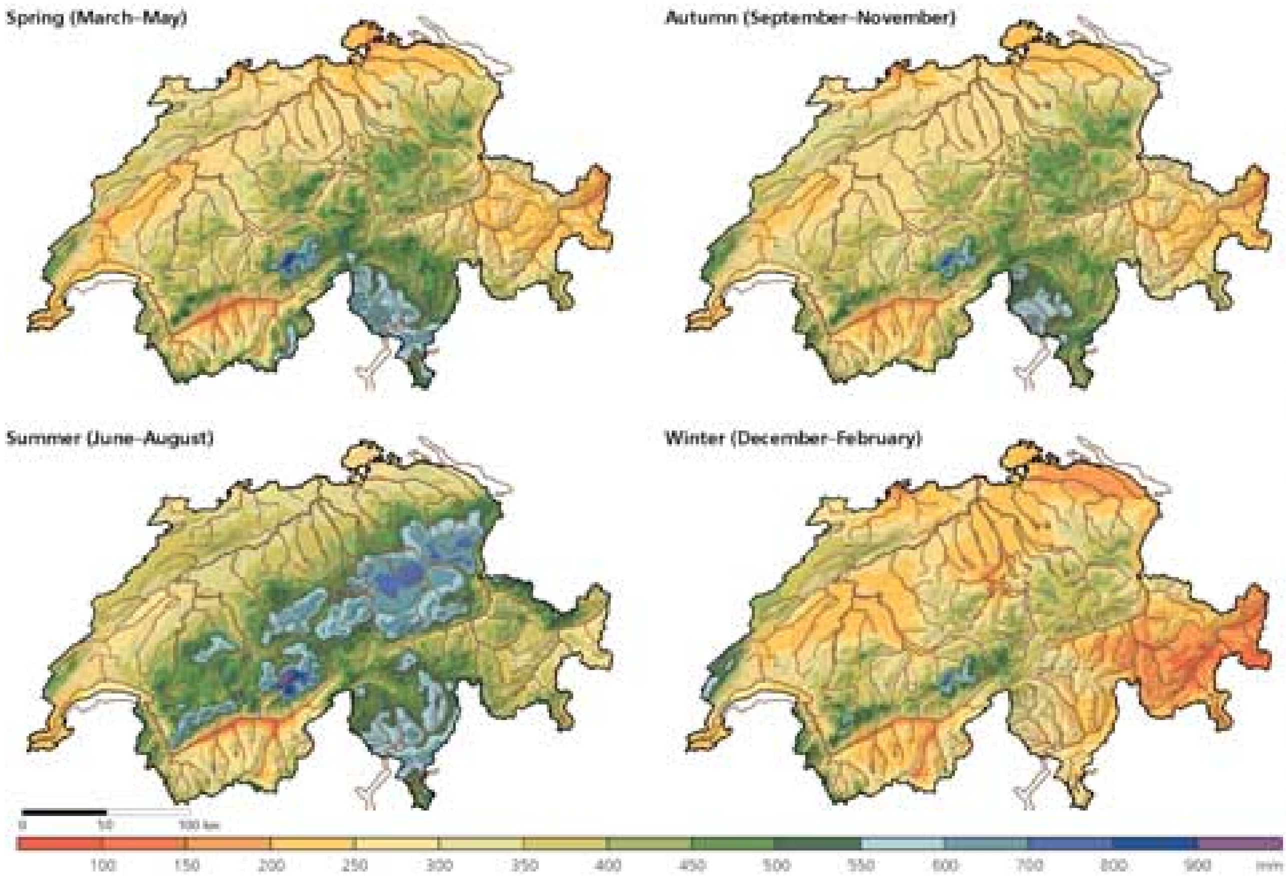


Fig. 2-16: Seasonal total precipitation (1971–1990) (data: SCHWARB et al. 2001b) .

2.4 Extreme values

At times of heavy precipitation there is a strong correlation between the duration of the precipitation and the total volume. Extreme precipitation is therefore indicated by volume and duration or directly by intensity in mm/h. Droughts are indicated only by the duration of the extreme event.

2.4.1 Heavy precipitation

The meaning of the term ″heavy precipitation″ depends on how it is defined. Criteria include threshold values, a number of extreme events or the annual maximum precipitation. It makes sense to consider the northern and southern sides of the Alps separately in relation to the highest measured precipitation in Switzerland (see Fig. 2-18). On the northern side of the Alps heavy precipitation of short duration gives rise to a high level of intensity. Such events normally happen in the form of individual showers during the months of June to September. Heavy precipitation of longer duration is brought by large-scale weather systems and may occur at any time of the year. They bring especially heavy precipitation on the southern side of the Alps (advective situation) where fronts and low pressure areas often combine to bring extremely wet air masses from the Mediterranean to the southern Alps. The rates of precipitation intensity of longer duration (weeks, months) shown in Figure 2-18 have been calculated from total precipitation for the given durations. In general it can be said that intensity falls as duration increases.

The heaviest rates of precipitation at a given point are combined to form extreme value series and classified according to the probability of their occurring. It is usual to represent the 2.33 and 100-year precipitation intensity of a given duration in precipitation density diagrams (see Fig. 2-19).

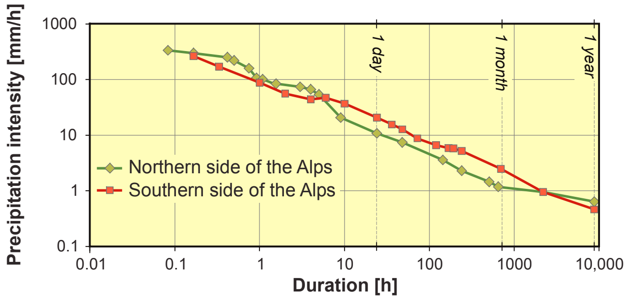


Fig. 2-18: Highest rates of precipitation recorded in Switzerland up to 1990 (from GEIGER et al. 1991).

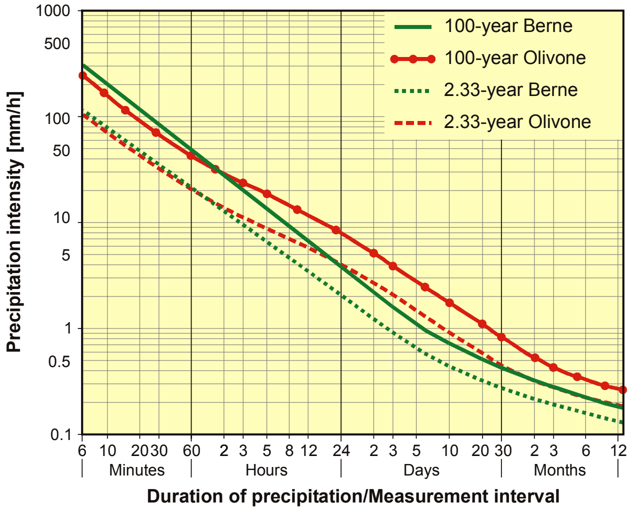


Fig. 2-19: Diagram of precipitation intensity for Berne and Olivone (Tessin) (from GEIGER et al. 1991).

This information is available for the whole of the country in the form of maps of extreme point precipitation of varying duration and recurrence periods (see Fig. 2-20). These data can be used to estimate expected heavy precipitation for any given place in Switzerland.

The highest rates of intensity are observed in the lowlands and the Alpine foothills. In the high Alps the convection effect is less marked and thus the intensity of the showers is lower. Thanks to the effect of the mountains, precipitation from wet air masses that pass over the Alps can result in high daily values, however.

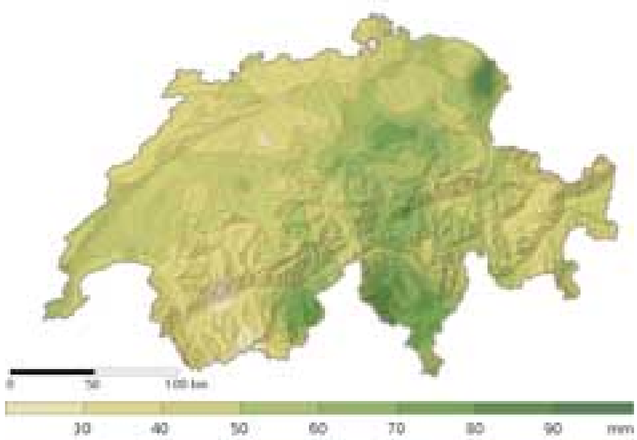


Fig. 2-20: Extreme 100-year point precipitation of 1 hour's duration (from JENSEN et al. 1997).

In the southern part of the Tessin precipitation of over 50 mm is experienced on around 10 days a year. The same daily totals can be observed only once or twice a year on the northern side of the Alps.

The high rates of intensity during heavy precipitation have a positive effect on the accuracy of the measurements. The raindrops are larger, with the result that they are less likely to be deflected from the measuring instrument. In 100-year values that are obtained using a static measuring instrument a rate of error of +/– 10 to 30% must be allowed for in a precipitation intensity diagram (GEIGER et al. 1991).

2.4.2 Drought

Apart from runoff (see Section 5.2.3) purely meteorological evidence is also suitable for identifying droughts. Dry periods or droughts can be determined depending on the data that are available.

Dry periods can be defined as periods of at least 5 consecutive days when the daily total precipitation is less than 0.5 mm. Individual days with over 0.5 mm are possible within a longer period of low precipitation. If the total precipitation over a period of 1 day exceeds 1 mm it must be considered that the dry period is over (MAURER 1975). The main decisive factor in relation to the water balance is the ratio of precipitation to evaporation. Since the risk of drought exists only if considerably more water evaporates than is replaced by precipitation it is necessary to consider additional data to identify a so-called drought.

To date no drought studies have been carried out for the whole of Switzerland. Point analyses by MÜHLETHALER (2004), however, show that droughts occur in particular in summer, when evaporation is greater.

In contrast, dry periods are equally common at all times of the year. Each year 8 to 10 dry periods are experienced in many parts of the Alps and the Jura Mountains, while the Central Lowlands (Swiss Plateau, midland area) and a number of Alpine valleys have between 11 and 15 dry periods; in the Tessin up to 18 dry periods a year can be observed (according to data for 1961–1989). If one adds the individual dry periods to the mean annual total duration, between 68 and 188 days can be included in a dry period, depending on the region (see Fig. 2-21) (MÜHLETHALER 2004).

Switzerland rarely experiences a drought. In this respect, 2003 was an exception. In many parts of the country precipitation was below average from February to September. Throughout Switzerland the first half of the year in particular was exceptionally dry – in some areas the lowest precipitation was recorded since 1901 (see Fig. 2-22). During the 20th century, the early parts of 1921, 1929 and 1944 were similarly dry; even less precipitation was recorded in the first half of 1976. Precipitation values for the six summer months of 2003 were lower in the upper Valais, the Gotthard region, the Tessin and the Grisons than the previous record in summer 1947 (BUWAL/BWG/MeteoSchweiz 2004).

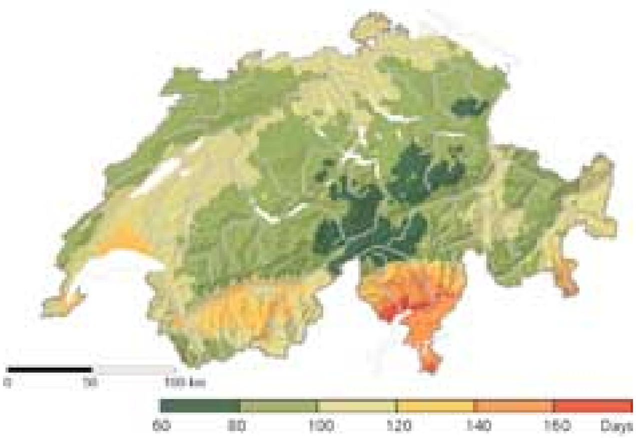


Fig. 2-21: Mean total annual duration of dry periods between 1961 and 1989 (from MÜHLETHALER 2004).

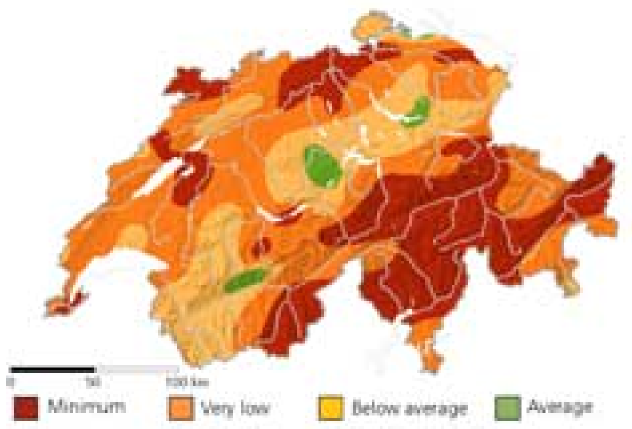


Fig. 2-22: Total precipitation for January to June 2003 in comparison with half-year totals since 1901 (from ZBINDEN 2003).

2.5 Detailed aspects

So far, we have tended to focus on rain as the most important form of precipitation. Apart from snow (Chapter 3) we should also consider various special types of precipitation such as net precipitation, condensation from fog, and hail.

2.5.1 Net precipitation

Under a canopy of vegetation or under plant litter, the amount of precipitation that reaches the soil is generally less than in open country since part of the water is intercepted and held by the vegetation and never reaches the soil below. The rate of loss through interception depends on the vegetation, the duration and the intensity of the precipitation, as well as conditions governing evaporation. The amount of water that actually reaches the soil is made up of that part which is intercepted by the larger vegetation and runs down stems and trunks directly to the ground (stem flow) plus the rain that can avoid the vegetation (throughfall) and the drops that fall from it (see Fig. 2-23).

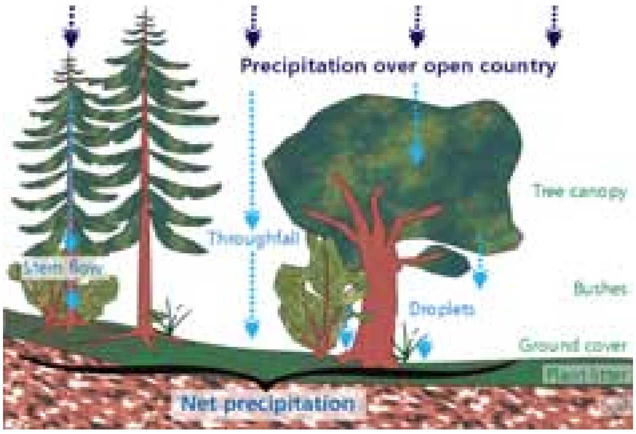


Fig. 2-23: Explanation of net precipitation.

Figure 2-24 shows the distribution of precipitation over a forested test area of around 100 m^2 on 31 August 2003. On that day 54.4 mm of rain fell over the open country. The mean loss through interception was 18.4 mm (33.8%). A number of rain gauges were set up under the ground cover, which explains the high rate of interception at certain points. In reverse, vegetation can also cause a higher concentration of water and thus result in higher precipitation than in open country. Accounting for a proportion of 10 to 50% of annual precipitation (GEIGER 1985), interception should be considered an important factor in the water balance in areas covered by vegetation.

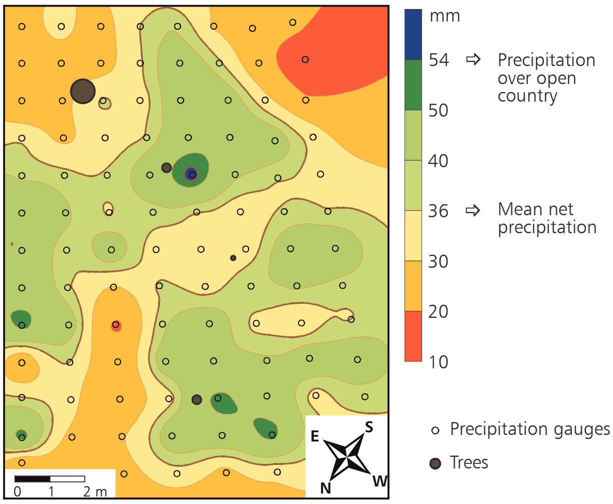


Fig. 2-24: Variability of net precipitation on 31 August 2003 in a test area in the Sperbelgraben (canton of Berne) with rainfall over open country of 54.4 mm (from KÖNITZER 2004).

2.5.2 Condensation from fog

The contribution made by fog is important in exposed areas covered with vegetation. Droplets driven by the wind are deposited on solid objects. Thick vegetation has the effect of catching droplets of water suspended in fog (see Fig. 2-25). As rainfall that drops from the vegetation onto the ground or stem flow, this sort of precipitation is not recorded by normal precipitation measuring networks.

Fig. 2-25: Forest as a fog filter, Sperbelgraben (Berne) on 8 September 2003.

Fog is defined as restricted visibility due to water droplets suspended in the air. As soon as horizontal visibility is restricted to less than 1 km the term ″fog″ is used for meteorological purposes, regardless of whether it is ground fog or low cloud. This means that fog can occur in any place, not only in the typically foggy Central Lowlands, as shown in Figure 2-26. Thanks to the abundance of cloud, fog occurs most frequently in higher and exposed locations (Fig. 2-27). Measurements taken in locations within the Alps where fog occurs relatively rarely have revealed an additional precipitation from fog of 5–25% (TURNER 1985). Figures for locations exposed to wind in the main areas where fog occurs will be far higher.

2.5.3 Hail

Switzerland is one of the European countries where hail is most frequent. Each year, thunderstorms with hail cause damage to the value of over 10 million francs (2003: CHF 46 million). Within the country, the danger of hail varies from one place to another. The highest risk is in the foothills to the north and south of the main Alpine ridge (see Fig. 2-28). Hail is defined as small balls or pieces of ice with a diameter of over 5 mm. Hailstorms are regional occurrences with high precipitation intensity (see Fig. 2-29). The capacity of the measuring instruments may be exceeded by the large volume of hailstones, which results in false precipitation measurements.

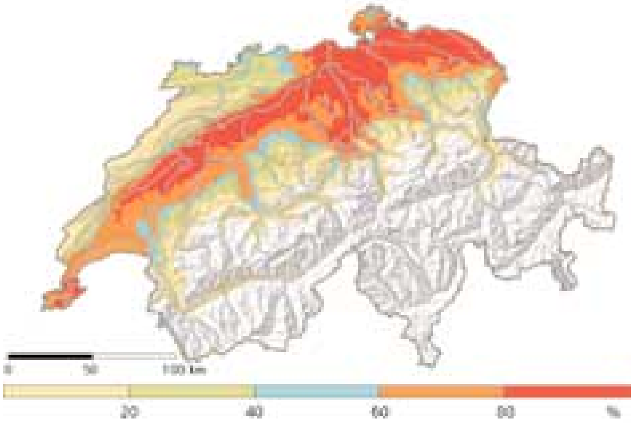


Fig. 2-26: Mean frequency of fog in the Central Lowlands (percentage occurrence as observed on 80 satellite images between 1989 and 1991, winter half-year) (from BACHMANN & BENDIX 1993).

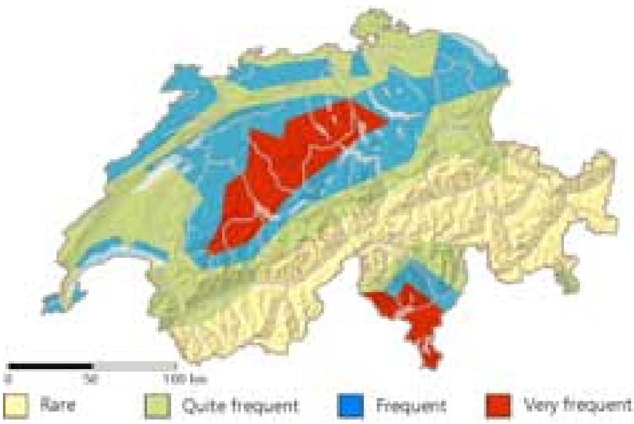


Fig. 2-28: Frequency of hail (1956–1999) (Source: Swiss Hail Insurance company).

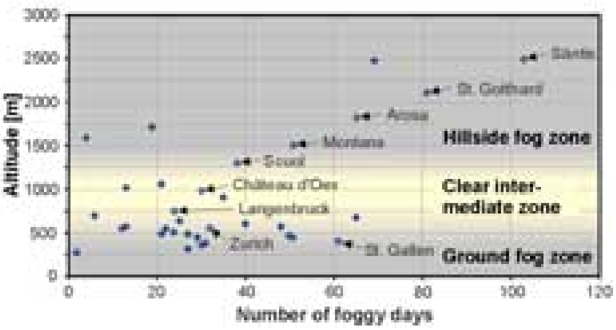


Fig. 2-27: Mean frequency of fog in the winter half-year as observed at 34 stations (1970–1975) with simplified zoning (from TROXLER & WANNER 2000).

Fig. 2-29: Hail damage in Aathal–Seegräben (canton of Zurich) on 12 August 2004.

2.6 Precipitation: Switzerland – Europe – Worldwide

Switzerland is often called the "water tower" of Europe. This suggests that it receives more precipitation than the surrounding countries. But how does Switzerland really compare with Europe and the rest of the world in this respect?

Precipitation is caused by the cooling of relatively humid air. The main sources of air humidity are the oceans. From there atmospheric circulation systems drive the humid air masses over the continents where they release their humidity, principally over barriers formed by mountains. The wettest areas of the world are therefore to be found on the edges of continents near the main sources of evaporation. High rates of precipitation can be observed in the middle of continental masses around mountain massifs and in rain forests (see Fig. 2-30).

In Switzerland maximum precipitation levels during short rainstorms reach only half the world records, and during longer periods of rain around a quarter (see Fig. 2-31). This does not mean that high precipitation density does not occur in the Alps, however. The overall world record over a period of three hours, namely 635 mm, was measured in Steiermark (Styria) in Austria on 16.7.1913.

In Europe mountain regions, and in particular the Alps, play a special role. Being relatively close to three seas – the Atlantic Ocean, the Mediterranean and the North Sea – and in an area of prevailing west winds, wet air masses are frequently driven towards the Alps. The high rate of precipitation leads to the abundancy of water in the Alps (see Table 2-6). But it is the proportion of this precipitation that runs off which decides whether the Alps and thus Switzerland can justifiably be called a "water tower" (see Section 10.3).

	World	Land masses	Europe	Alps
Precipitation	973	746	780	1460

Table 2-6: Mean annual precipitation in mm (sources: BAUMGARTNER & LIEBSCHER 1990; MOUNTAIN AGENDA 1998).

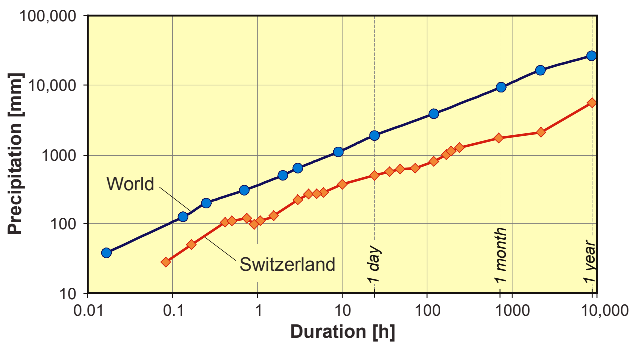


Fig. 2-31: Comparison of observed record precipitation in Switzerland and the world as a whole (from GEIGER et al. 1991).

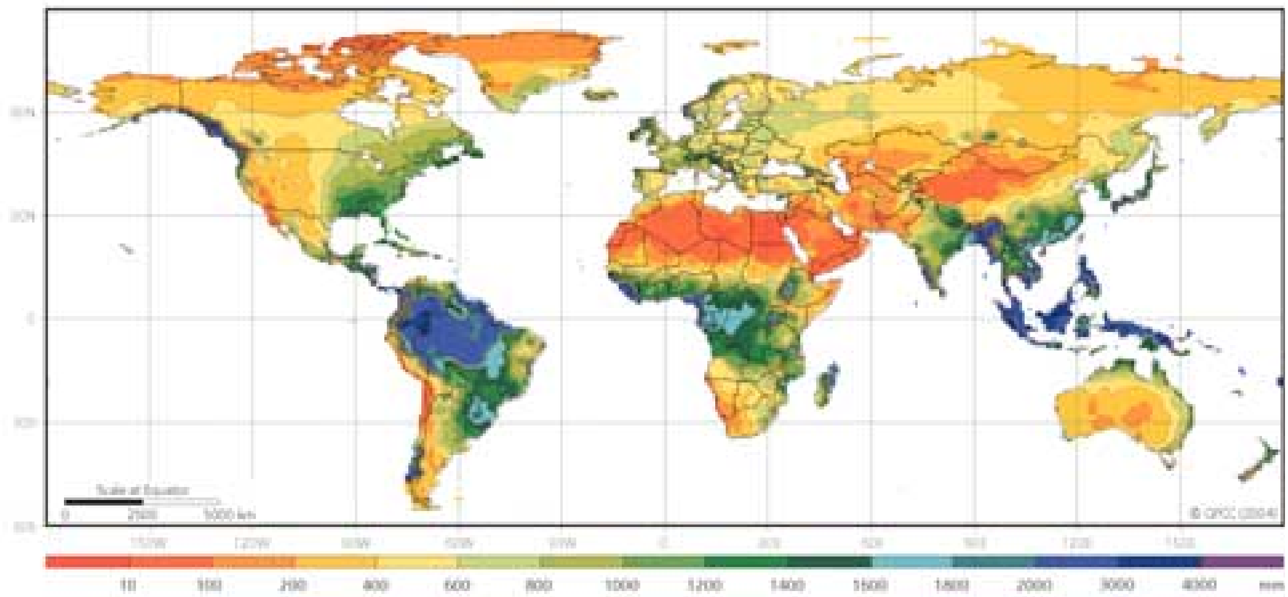


Fig. 2-30: Global distribution of total annual precipitation 2003 (data: www.dwd.de).

2.7 Trends and prospects

On the basis of the climatic changes that have been observed trends can be identified and prospects can be foreseen. Has the rate of precipitation changed over the last century and what can we expect in the future?

In Switzerland there has been a significant increase in winter precipitation (see Fig. 2-32). No significant trends can be observed in relation to other times of the year and in annual totals (see Fig. 2-33). It is the intensity of the precipitation that has changed and not the frequency of wet weather. In contrast, weather patterns that typically bring hail are now more frequent (BADER & KUNZ 1998). There has also been a slight increase in the length of dry periods. Definite trends during the 20th century for the Alpine stations in Davos and on the Säntis were identified some time ago (MÜHLETHALER 2004).

The future will probably bring a rise in continental dry periods in the summer and the associated risk of drought. Climatic simulation exercises (see Fig. 2-34) indicate in which areas an increase or decrease in mean annual precipitation is to be expected. The rise in mean precipitation intensity and the increase in the frequency of intensive daily precipitation that have been calculated for Europe as a whole have not yet been confirmed for Switzerland (OcCC 2003).

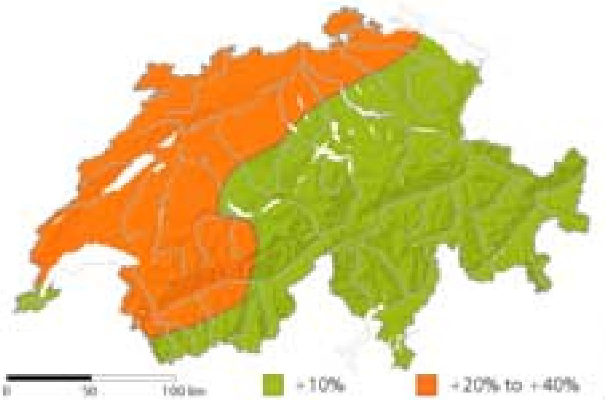


Fig. 2-32: Significant changes in precipitation for the winter months for 1901–1990 (from WIDMANN & SCHÄR 1997).

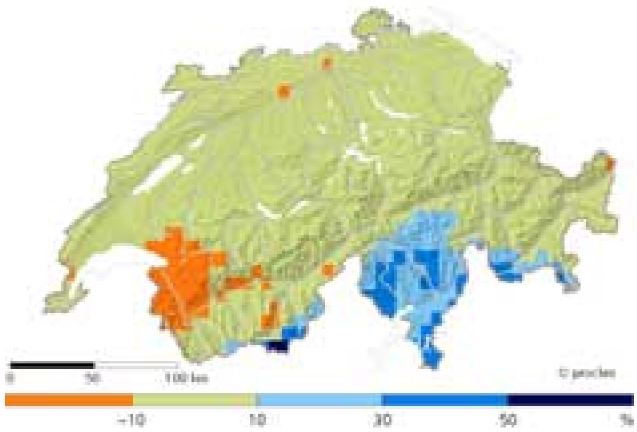


Fig. 2-34: Percentage deviation in mean annual precipitation around 2050 in comparison with the mean for 1931–1980 with double the concentration of CO_2 in the atmosphere. Climatic simulation exercise carried out at the Max Planck Institute of Meteorology in Hamburg (ECHAM-T21/LSG-GCM) (from www.proclim.ch).

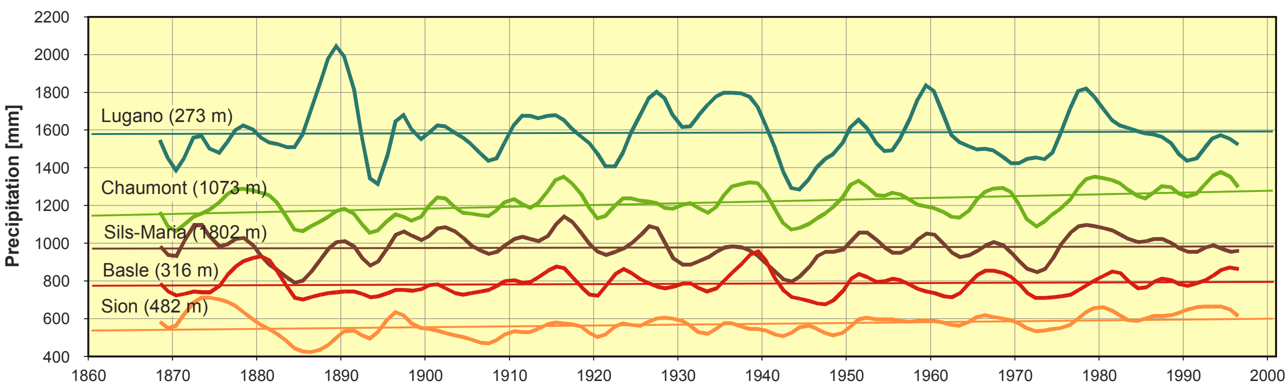


Fig. 2-33: Total annual precipitation (modified using Gaussian curves) and linear trends for selected stations. Slight increases on the Chaumont and in Sion (data: MeteoSwiss).

3 Snow and ice

Statistics

Greatest depth of snow in 24 h	160 cm	Simplon, 15.3.1980	Source: SLF
Greatest depth of snow ever measured	690 cm	Grimsel Hospice, 3.5.1970	Source: SLF
Mean no. of days with snow-cover at 500 m	48 days	Zurich	Source: MeteoSwiss
Mean no. of days with snow-cover at 2500 m	287 days	Weissfluhjoch (Grisons)	Source: SLF
Mean no. of destructive avalanches per winter	138		Source: SLF
No. of destructive avalanches in 1999	1200		Source: SLF
No. of glaciers in the Swiss Alps (1973/2000)	c. 2000	(recorded glaciers)	Source: MAISCH et al. 1999, 2004
Area covered by glaciers in Switzerland (1850)	1800 km^2	(4.4% of total land surface)	Source: MAISCH et al. 1999
Area covered by glaciers in Switzerland (1973)	1300 km^2	(3.1% of total land surface)	Source: MAISCH et al. 1999
Area covered by glaciers in Switzerland (2000)	1050 km^2	(2.5% of total land surface)	Source: MAISCH et al. 2004
Loss of glacier coverage (1850–1973)	500 km^2		Source: MAISCH et al. 1999
Loss of glacier coverage (1850–2000)	750 km^2		Source: MAISCH et al. 2004
Volume of all glaciers (1850)	c. 110 km^3		Source: MAISCH et al. 2004
Volume of all glaciers (1973)	c. 75 km^3		Source: MAISCH et al. 2004
Volume of all glaciers (2000)	c. 55 km^3		Source: MAISCH et al. 2004
Longest glacier (2003)	23.95 km	Great Aletsch Glacier	Source: GK/SANW & VAW/ETHZ 2003
Glacier ablation in 2003	> 5%	(volume)	Source: HÄBERLI et al. 2004

3.1 The significance of snow

During the winter half-year a large part of Switzerland lies under snow, which constitutes an important temporary interruption in the water cycle. The duration of this retention varies enormously: while it may last only weeks, days or even hours in the Central Lowlands, retention in the Alps normally lasts for a matter of months. In the high Alps the snow may be converted into hard glacier ice and thus be stored for many years (cf. Section 3.7).

Snow has an effect on the human environment. Accumulated snow may block roads and railway lines in the mountains and paralyse major transit routes. Avalanches may endanger villages and towns, block roads and cause enormous damage to protective forests. On the other hand a substantial snow-cover is an important factor for winter tourism. Furthermore, a protective snow-cover is an essential element in the annual cycle for the survival of many (mountain) plants.

The systematic measurement of snow and of its characteristics is important from various points of view. Thanks to long measurement series of snow parameters, medium and extreme conditions as well as climatic change can be foreseen. Snow studies also have a practical use, such as for weather forecasting, avalanche warnings or in drawing up hydrological runoff models.

3.2 The development of measuring networks

The first known snow measurements were carried out in the 18th century. Over time a network of stations was set up of which the oldest, for example the station at the Physico-Meteorological Observatory in Davos (1560 m), have been making daily measurements for over 100 years. Data from all stations are collected and evaluated by the Swiss Federal Institute for Snow and Avalanche Research in Davos (SLF).

The history of snow measurement is closely linked with the development of the SLF. In autumn 1936 a team of seven researchers started operating in a wooden hut on the Weissfluhjoch (Grisons). At the same time, the first snow-measuring station specifically for research was installed on the SLF test area slightly below the summit station of the Davos Parsenn Railway at an altitude of 2540 m. With the expansion of the military avalanche service in the early 1940s further stations were set up such as at Trübsee and Andermatt.

In 1942 the SLF was officially founded and its premises on the Weissfluhjoch were inaugurated. Following the many avalanches in the winter of 1950/51, which killed around 100 people in Switzerland, research was realigned in a more practical direction. A measuring network with measuring points and comparison stations was subsequently set up. The data provided by these conventional stations were published in the SLF's winter reports (1936–1998). At the beginning of the 1990s the first automatic snow measuring stations

(ENET) were installed in collaboration with MeteoSwiss for collecting snow and weather data in isolated and high-altitude areas. In 1996 the IMIS network (Intercantonal Measuring and Information System, see Fig. 3-1) was set up for the specific purpose of researching into avalanches.

The measurements obtained through the various measuring networks (see Table 3-1 and Fig. 3-3) are collected at the SLF, evaluated, analysed and stored. Further snow data are also collected by cantonal and private institutions (e.g. Rhaetian Railways, various power stations).

Fig. 3-1: IMIS snow station in the Lower Valais. The Donin du Jour station is situated at 2390 m above the Vallée de la Sionne and has been in operation since 1998.

3.3 Basic conditions for collecting snow data

Snow measurements are based on a standard measuring principle applicable in all scientific studies. In brief, this principle centres around where (station), when (time) and what (parameter) is relevant. The system summarised below has proved useful for measuring snow. Thanks to recent developments in communication technology it has been possible to transform the measuring networks into information systems (Russi et al. 2003).

3.3.1 The basic station – time – parameter triangle

The structure of a measuring network is mainly based on the interrelationship between the three elements of the basic triangle: station, time and parameter (see Fig. 3-2).

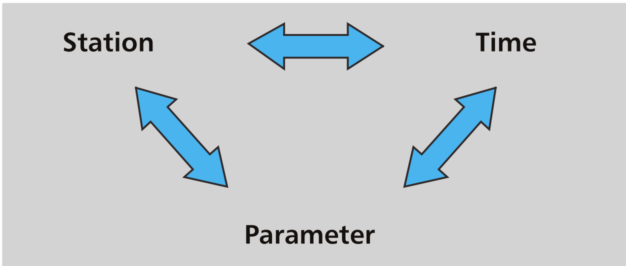


Fig. 3-2: The basic triangle for scientific observations.

Station

Stations should be located in such a way that they represent as large an area as possible. For example, it should be possible to exclude snow drifts at measuring stations. Another important aspect is a balanced exposure to solar radiation and shade. For this reason snow measuring stations are not situated in depressions or on the tops of mountains but in flat open areas protected from the wind.

A distinction is made between conventional and automatic stations, the former being operated by an observer and the latter being installed with sensors.

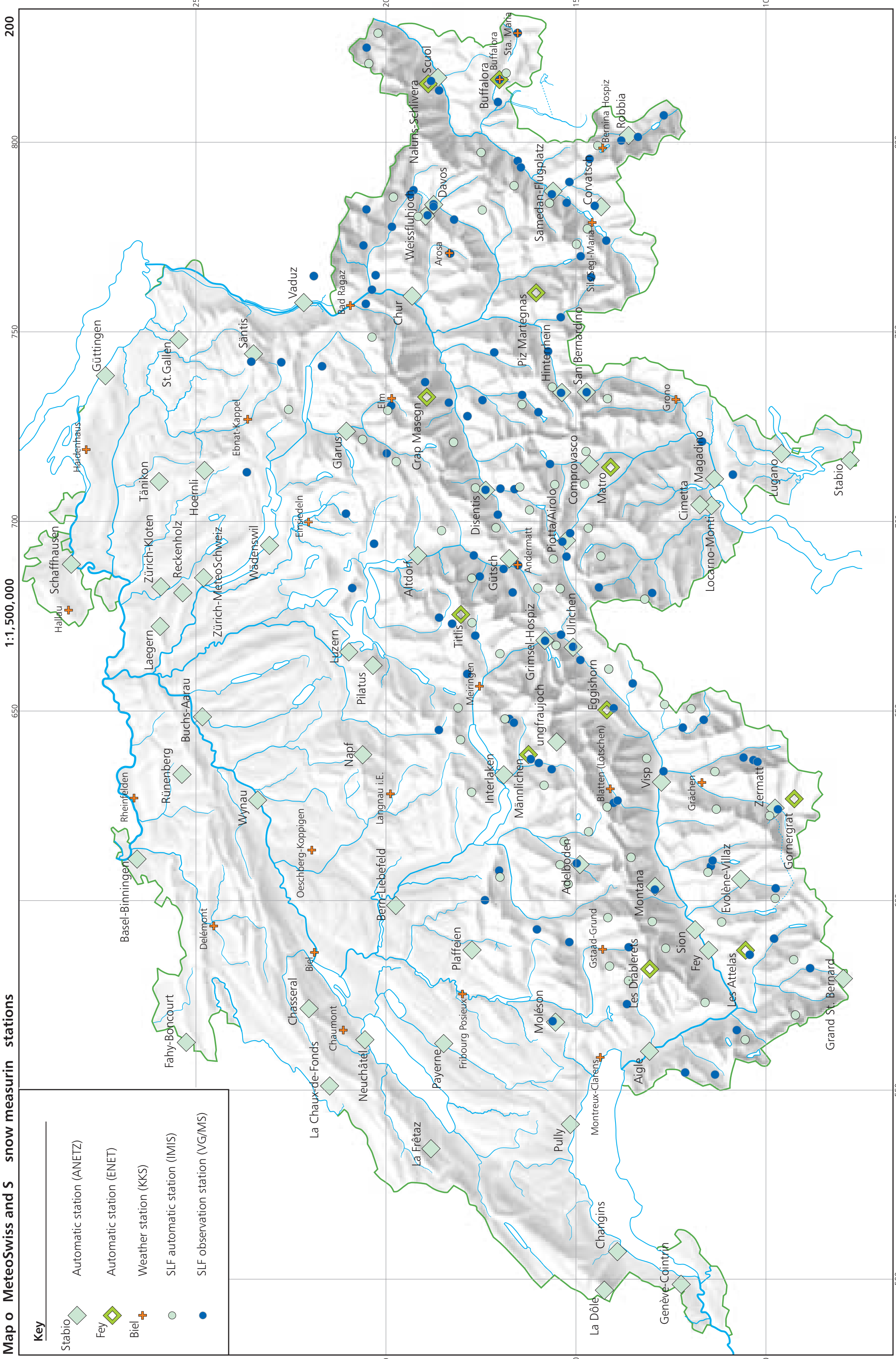


Fig. 3-3: Map of MeteoSwiss and SLF snow measuring stations (data: SLF).

Since the conventional stations are operated manually they tend to be located near settlements. A small number of such measuring stations have been set up in the mountains, near cable-car stations and power stations. With particular reference to avalanche prediction, it is extremely important to have snow information that covers as large an area as possible including high altitudes and sites where avalanches are likely to start, i.e. above 2000 m. Thanks to the development of automatic measuring stations in the high Alps, some of which run on solar power, that have been transmitting the data collected by radio and telephone since 1993, it has been possible to fill in the gaps in the measuring network.

Time

At conventional snow measuring stations the parameters are measured once daily, at around 8 am, from the beginning of October until the end of May. Since 1997 additional measurements have been taken at around 1 pm at certain stations. The automatic stations operate on a continuous basis; half-hour means are calculated from the measurements taken.

Parameter

The two most important parameters are snow depth (SD) and precipitation in the form of new snow (NS). Further parameters are measured, such as the water equivalent of the new snow, the temperature of the snow and snow surface, the quality of the snow, its compactness, but also air temperature, wind speed and direction, atmospheric humidity and radiation.

Moreover, weather observations are also made at conventional stations using a simplified code. Avalanches are recorded; the risk of avalanches is estimated and the profile of the snow is examined every 2 weeks.

3.3.2 Measuring instruments and methods

Snow depth (SD)

Probes with 1-cm graduations are suitable for determining snow depth at conventional stations (MSs, VGs and KKSs) (gauge measuring). The same applies to the ANETZ stations operated by MeteoSwiss: although these are automatic stations snow parameters are measured manually.

At the other automatic stations (IMIS and ENET) total snow depth is measured through the time it takes for ultrasound waves to travel from the transmitter, which is mounted vertically above the snow (see Fig. 3-1), to the surface of the snow and back. The mean error using this method is 2 to 3 cm.

New snow (NS)

The depth of the new snow is measured using a board: each morning the twin-gauge is sunk into the snow. The board is cleaned off and reset on the undisturbed surface of the snow. The difference between two readings on the gauge does not represent the depth of new snow, however, since the latter will have had a certain compaction effect on the snow beneath. To date it is not possible to measure the depth of new snow at automatic stations.

Water equivalent of the snow-cover

The question of the water equivalent of the snow-cover is of particular interest in relation to hydrological

Network		Frequency	No. of stations	Parameters
MS	Measuring point (SLF)	Daily	35	Snow depth, depth of new snow
VG	Comparison station (SLF)	Daily	78	Snow depth, depth of new snow, water equivalent, weather conditions, temperature of snow and snow surface, compactness, quality of surface, avalanche observations
IMIS	Intercantonal Measuring and Information System (SLF)	30 min.	71	Snow depth, air and snow temperature, snow surface temperature, wind speed and direction, atmospheric humidity, radiation
ENET	Automatic station (SLF)		11	
KKS	Conventional weather station (MeteoSwiss)	Daily	26	Snow depth, depth of new snow among others
ANETZ	Automatic measuring network (MeteoSwiss)		67	
Total			288	

Table 3-1: SLF and MeteoSwiss measuring stations that provide snow data (as at 2004).

analyses. The standard method for determining the water equivalent is to take a snow sample in an aluminium cylinder. These cylindrical probes are normally between 20 and 50 cm long and have a cross-section area of 20 to 70 cm^2. The water equivalent is calculated from the volume and weight of the snow. Other ways of determining the water equivalent of snow include pressure cushions, neutron probes and complicated microwave systems.

Snow temperatures

Snow temperatures are measured with a thermometre 10 cm under the surface, the thermometer being inserted horizontally and read off after about one minute.

Snow profile

A description of the characteristics of the layers of snow in the snow-cover is especially important for assessing the risk of avalanches and for nivo-hydrological calculations. For this reason, every 2 weeks trained observers examine a snow profile, containing a ram profile and the determination of the layer characteristics.

The ram profile continually measures the hardness over the entire snow-cover. Since this measurement is taken using a calibrated instrument ram profiles can be directly and quantitatively compared with each other.

The determination of the layer characteristics involves digging a shaft in the snow. The following tests are carried out on the vertical wall of the shaft:

– the snow temperature is measured at intervals of 10 cm in the upper 1 m, and at intervals of 20 cm lower down;
– the different layers are identified either by the naked eye (lightness, see Fig. 3-4) or on the basis of differences in hardness and consistency;
– a code is allotted to each layer for hardness, the prevalent type of grains, mean grain diameter and wetness;
– the water equivalent of the whole snow-cover is calculated.

The characteristics of each layer of snow can be determined even more precisely with the new SnowMicroPen. A rod with a metal tip is slowly inserted into the snow. The effort needed to achieve penetration to a depth of 4 μm is measured and entered into the computer. Even weak, thin layers of snow, which often play an important role in setting off an avalanche, can be detected using the SnowMicroPen (PIELMEIER 2003).

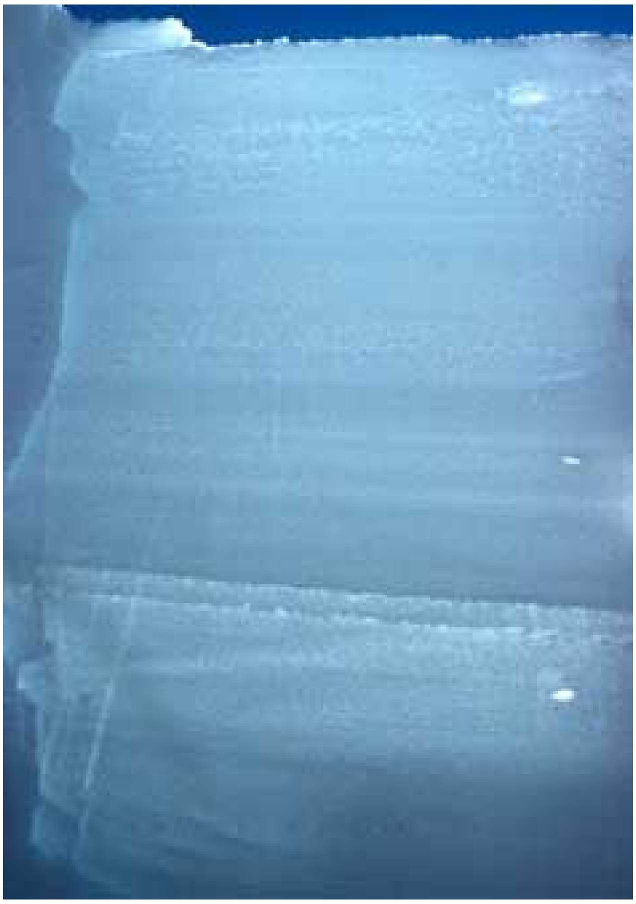


Fig. 3-4: Translucent snow profile; the individual layers of snow are easily visible.

Avalanche observation

Observers record the avalanches that occur in their areas, which are then morphologically and genetically classified. Geographical and geometric information is also important. Avalanches are classified morphologically according to an international code and, using several pairs of criteria, a distinction is made between the breakaway zone, the path and the place where the avalanche finally comes to rest (UNESCO 1981). In the breakaway zone a distinction is made between loose snow and a slab avalanche, for example, depending on the appearance of the breakaway point (see Figs. 3-6 and 3-7).

In the genetic avalanche classification a description of how the avalanche forms and its impact are important. From the geographical point of view, the altitude, aspect and angle of the slope are of interest. An indication of the dimensions of the avalanche, or at least information on length and breadth can also be of value.

Assessing avalanche risk

The avalanche specialist can assess the risk of avalanches on the basis of these measurements and observations. This assessment is done daily and requires a wealth of experience that can be gained from courses and in the field. The risk is classified according to a standard scale. In addition, since 1993 a scale of 1 to 5 has been used in the Alpine countries (see Fig. 3-5), which has now become established throughout Europe (STOFFEL & MEISTER 2004).

Level of risk	Warning for off-piste snow-sports areas
1 slight	Conditions generally favourable. Extremely steep slopes should be crossed in single file! Avoid fresh snow drifts on crests! Beware of falling!
2 low	Conditions mostly favourable. Avoid extremely steep slopes with aspects and at altitudes specified in avalanche bulletins as well as fresh snow drifts! Extremely steep slopes should be crossed with care and in single file!
3 medium	Conditions not favourable in places. Experience of assessing avalanche risk required! Inexperienced skiers should therefore stay on the piste or join a group with a professional guide! Avoid all extremely steep slopes!
4 great	Conditions not favourable. Restrictions on slopes of medium steepness, steep slopes should be avoided! Be aware of avalanche paths (remote triggered and/or spontaneous avalanches)! Staying on the piste is recommended!
5 very great	Conditions totally unfavourable. No snow sports off piste recommended. Essential to remain on marked pistes that are open!
Steep slopes > 30°, very steep slopes > 35°, extremely steep slopes > 40°. This scale of risks is used throughout the Alps.	

Fig. 3-5: Avalanche risk scale of 1 to 5 (STOFFEL & MEISTER 2004).

3.4 Models

In simple terms, models serve to fill in the gaps in the basic triangle described above (see Fig. 3-2). In other words, theoretical considerations and calculations are used to obtain data where no measurements were taken. Missing parameters can also be obtained theoretically from a model through the use of physical laws. The aim is to be able to draw up predictions that are as comprehensive as possible from both a geographical and temporal point of view. A number of models developed by snow and avalanche researchers are described below; they are all based on the comprehensive data supplied by the snow measuring networks already mentioned.

3.4.1 SNOWPACK – A snow-cover model

Just as weather forecasting is based on numerical computer models, the SLF develops models to describe the state of the snow-cover.

Fig. 3-6: Several wet, loose snow avalanches that have broken away from single points (Radüner Rothorn, Flüela massif).

Fig. 3-7: Dry slab avalanche with sharp breakaway line (Pischa, Davos). The depth of the snow along the breakaway line can be up to 2.2 m.

Switzerland is in the comfortable position of having a dense measuring network that supplies information about the weather and snow conditions. This network cannot measure conditions inside the snow-cover, however. The SNOWPACK snow-cover model (LEHNING et al. 2002) was devised to fill this gap by calculating the condition of the snow-cover from data provided by the automatic stations. The principal purpose is to improve avalanche warnings.

Figure 3-8 shows, as an example, the grain forms, snow layers and snow-cover stability at an IMIS station calculated using the model. In the upper part, the areas of instability that could lead to a windslab are indicated in red. In the lower part the grain forms (coded) are visible.

SNOWPACK is also used to provide answers to general ecological, climatic or hydrological questions, as well as for snow sports.

3.4.2 AVAL-1D – Dynamic avalanche risk assessment

The comprehensive measurements taken at observation stations are also a prerequisite for identifying danger zones. The winter of 1999, which saw a large number of avalanches, showed clearly to what extent communities and communication routes in the Swiss Alps are exposed to the danger of avalanches (SLF 2000). For this reason, the SLF has since been working intensively on improving computer-assisted calculations of airborne powder and flowing avalanches (CHRISTEN et al. 2002).

Maximum increases in snow-cover are also of decisive importance for calculating avalanches. Winds which drive snow and thus add to the load in potential breakaway zones also have to be taken into account.

Since it was first used in 1999, AVAL-1D, a one-dimensional model for calculating avalanches, has

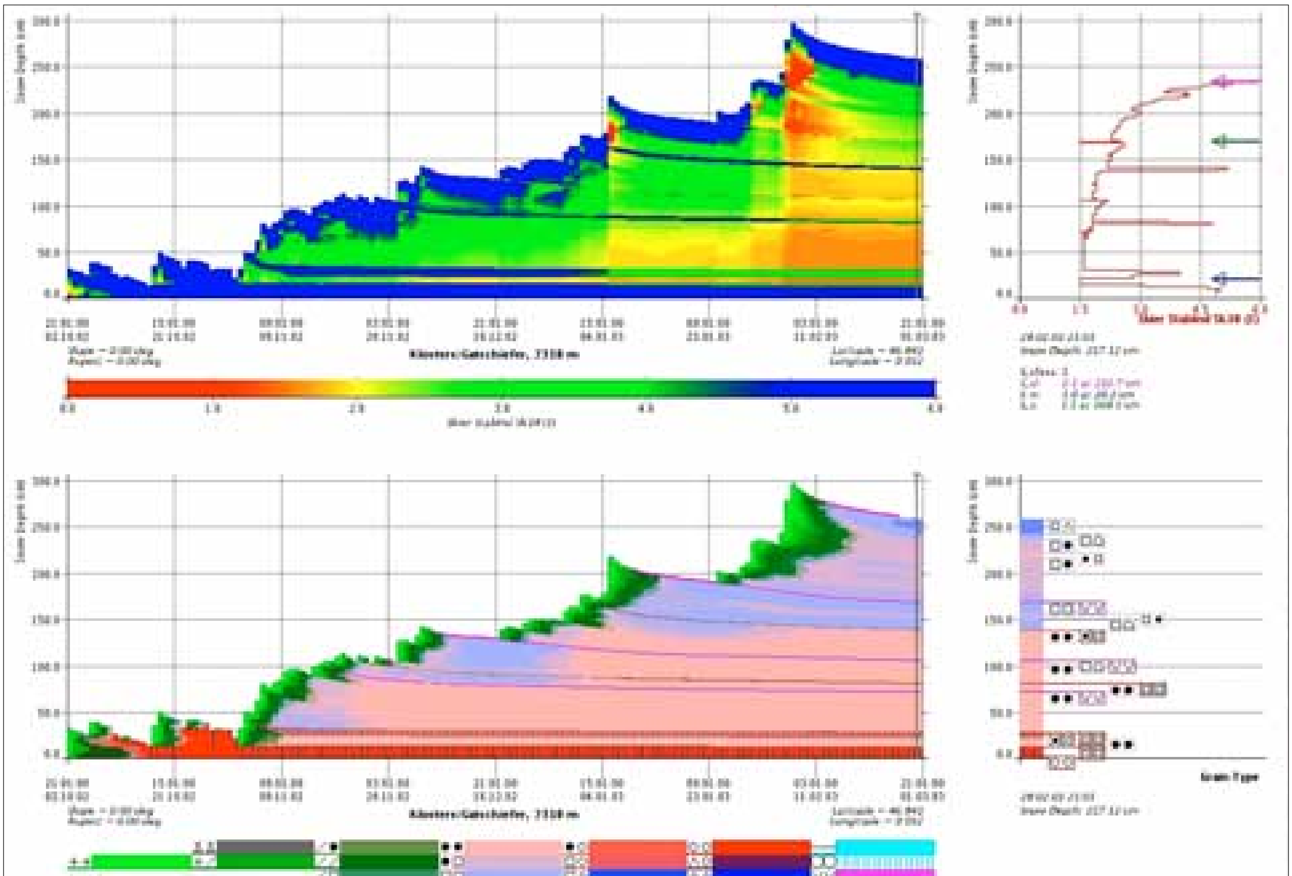


Fig. 3-8: SNOWPACK image: Temporal development and profiles of snow-cover stability and snow types from the IMIS station at Gatschiefer, Klosters (2310 m) (from LEHNING et al. 2002).

proved its worth for such calculations. It partly replaces the Voellmy model (VOELLMY 1955), which is now 50 years old. AVAL-1D can be used to calculate the depth of the avalanche, its speed and the pressure it will exert the length of its path, as well as for forecasting the distance it will travel and the distribution of its load where it finally comes to a halt (see Fig. 3-9).

Since avalanches are 2-dimensional phenomena, however, a 1-dimensional model will not provide answers to certain questions, for example:

– What exactly will be the path of the avalanche?
– How wide will the avalanche be?
– Which part of the avalanche will take path A and which part path B?

In order to obtain better answers to such questions the SLF is busy developing the 2-dimensional AVAL-2D avalanche flow model with which it should also be possible to calculate the exact path and the width of the avalanche right down into the valley (see Fig. 3-10).

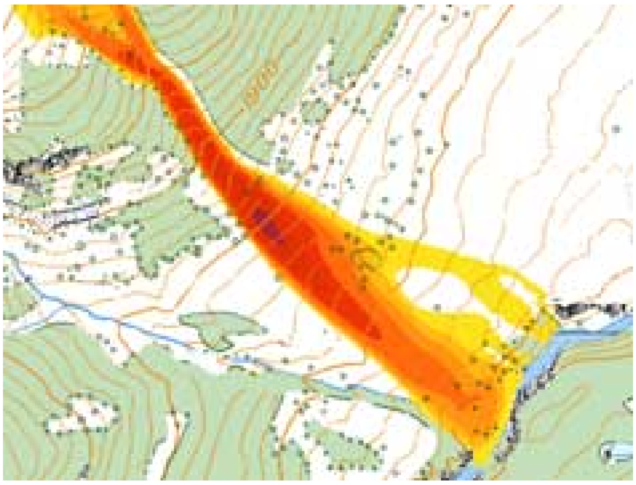


Fig. 3-10: Verification of an avalanche using AVAL-2D. The colours indicate the different flow speeds from 40 m/sec (purple) to 5 m/sec (pale yellow) (from CHRISTEN et al. 2002).

Fig. 3-9: Deliberately triggered powder avalanche below the Walenstadterberg, January 2003.

The basic elements needed for calculating the characteristics of an avalanche are topographical details (e.g. slope), qualitative and quantitative details about the snow (e.g. maximum increase in the snow-cover, thickness of the snow) and physical laws. The aim is also to integrate artificial obstacles such as diversion banks into the topographical model to test their effect.

3.4.3 NXD avalanche-forecasting models

Data from the measuring stations are used operatively, i.e. when adjusted to the current situation. The SLF has developed the NXD avalanche computer programme which supports assessments of avalanche risk within a limited area. This model is a help when deciding whether a road can remain open or whether an avalanche path should be secured by detonating a snow mass, for example.

The model is based on a comparison of current weather and snow conditions with those in earlier years. The programme searches for similar situations in the database and lists the avalanche events that were observed at the time. On the assumption that the risk of avalanches on that day can be likened to the risk in a similar situation in the past, measures can be taken immediately.

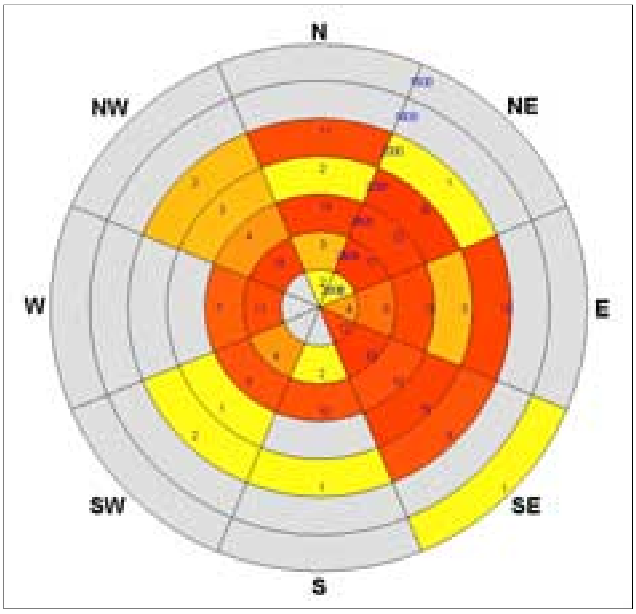


Fig. 3-11: Example of an assessment using the NXD: aspect/altitude diagram. This diagram shows the distribution of frequency of avalanches by aspect and altitude (from HEIERLI 2003).

The model is more reliable the longer the observation series and the more complete the observations. The number and volume of the avalanches are of primary interest. The altitude and the gradient of the slope indicate possible danger areas (see Fig. 3-11) (HEIERLI 2003). Using the NXD avalanche-forecasting model, those responsible for avalanches can compare their own assessment of the risk with the avalanches shown on the computer.

3.5 Snow depths across Switzerland

In the Alps, 80% of precipitation that falls above 2000 m is snow. The pattern of snow depth is extremely irregular in Switzerland, local climatic conditions playing a central role. Climatological statistics, of which a few are described below, can be obtained from long measurement series provided by snow measuring stations.

3.5.1 Duration of snow-cover

Snow depth has been measured daily at the Weissfluhjoch comparison station (2540 m) for nearly 70 years. There is snow on the Weissfluhjoch for an average of 265 days per year. With the relatively long time series (see Fig. 3-12) no trend towards shorter winters can be concluded from the general means. On the contrary, at this altitude recent winters have been generally somewhat longer than when measuring was started. The situation is totally different at lower altitudes, however, where the duration of the snow-

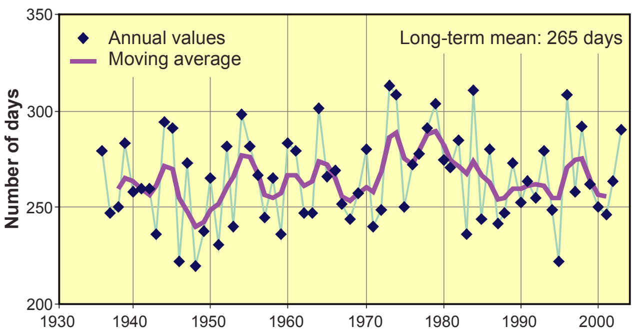


Fig. 3-12: Duration of permanent snow-cover on the Weissfluhjoch (2540 m) between 1936 and 2004. The year 1940 indicates the winter of 1939/40, with the first snow falling in autumn 1939 and the snow melting in spring 1940 (data: SLF).

cover has decreased. A fact that is common to all altitudes is that the duration of snow-cover varies considerably from one winter to another.

3.5.2 Correlation of snow depth with altitude

The correlation of snow depth with altitude can be clearly seen from the mean point at which the maximum average winter snow depth occurs. In areas under around 1300 m the maximum average snow depth is reached in February, between 1500 m and 1800 m in March and above 1800 m in April (see Fig. 3-14).

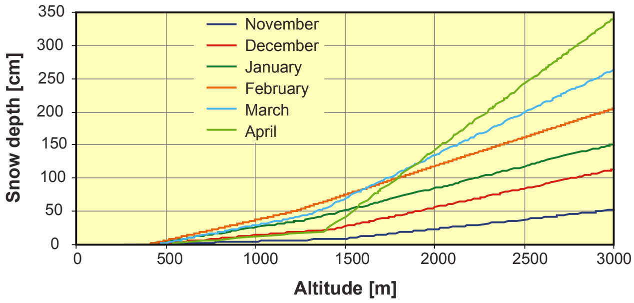


Fig. 3-14: Linear correlation of snow depth with altitude for the months of November to April (from AUER 2003).

3.5.3 Maps of snow depths

Maps of snow depths are used as a basis for avalanche warnings and are also important for drawing conclusions concerning the snow guarantee in snow-sports areas, for hydrological runoff models and for climatic maps.

Data provided by individual stations are extrapolated using a model in order to draw conclusions concerning snow depth for the whole area. Snow depth maps are based on a model used to calculate the regional, altitude-related and temporal differences in snow-cover. Figure 3-13 shows the mean annual snow depth in Switzerland as means for the months of November to April. A clear distinction can be seen between the abundance of snow in the high Alps and the lack of

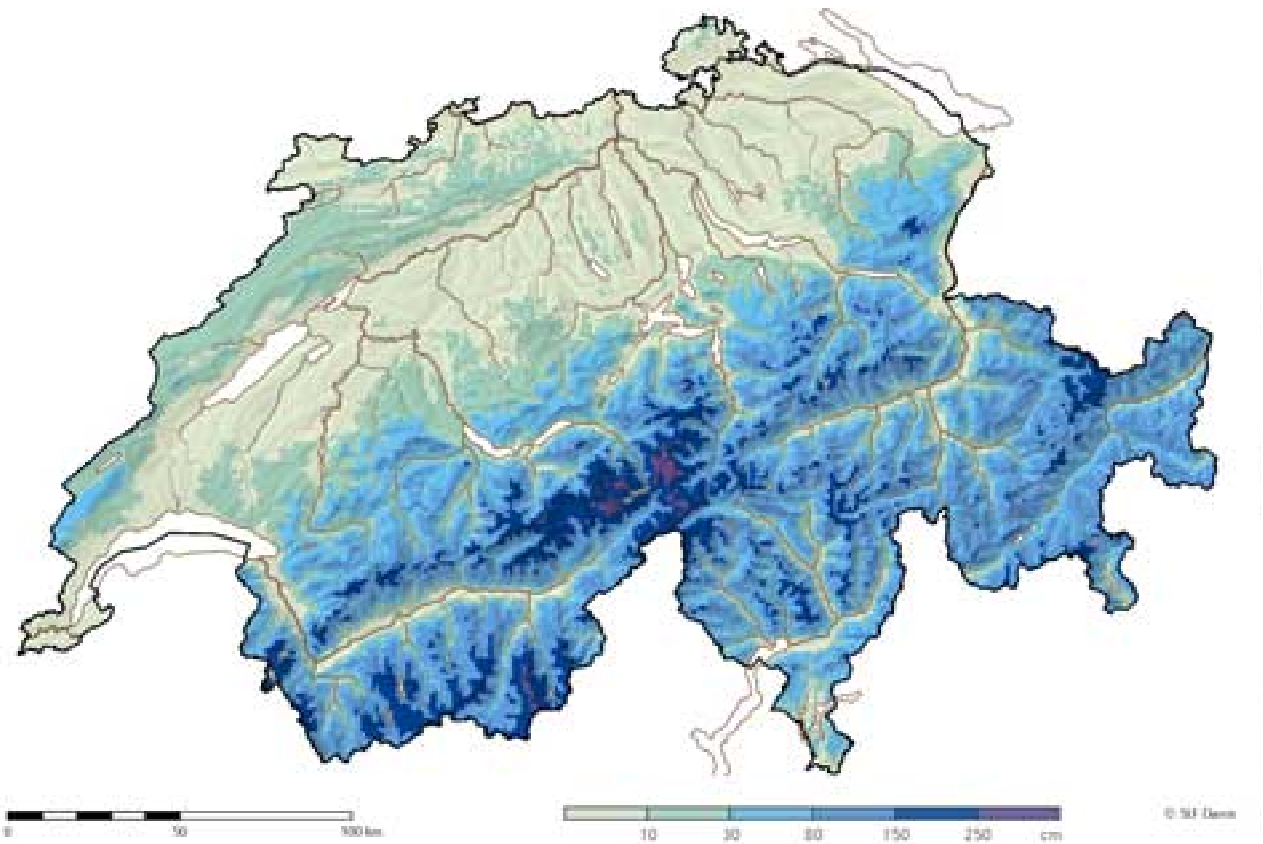


Fig. 3-13: Mean snow depth in Switzerland (winter mean for November to April, 1983–2002) (from AUER 2003).

snow in the valleys and the Central Lowlands. In the Central Lowlands the mean snow depth is less than 10 cm, while in areas over 2000 m the winter mean is over 100 cm.

3.5.4 Regional snow depth pattern

Figure 3-15 indicates the relative snow depths in comparison with the mean for the whole of Switzerland and clearly shows the snow depth pattern over the different climatic regions. It can be seen that in certain areas the mean snow depth is higher (positive deviation, blue) and in others lower (negative deviation, orange/red) than the mean for the whole of the country.

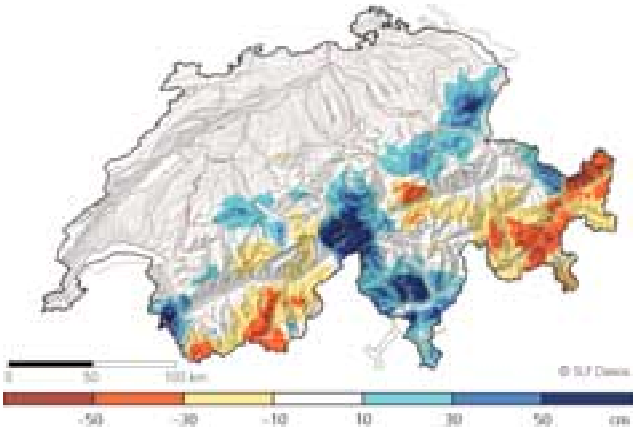


Fig. 3-15: Snow depth pattern over different climatic regions (deviation from national mean) (from AUER 2003).

There is a clear arc of relatively abundant snow that stretches from the Tessin via the Gotthard and Grimsel areas to the Goms, Central Switzerland, the Glarus Alps, Toggenburg and Alpstein. Other areas with abundant snow are the Prättigau, the Chablais in the lower Valais, the Saanenland and the foothills of the Bernese Oberland. Areas where the mean snow depth is below the average for the whole of the country include the southern valleys of the Grisons, the Engadine, the Central Grisons, the Grisons Oberland, the Jungfrau and Aletsch areas and the southern bank of the Rhone in the Valais, i.e. principally the Alpine valleys. An example shows these differences very clearly: while Grächen (Valais), at 1550 m, has a winter average snow depth of only around 21 cm, the winter mean for St. Antönien (Grisons), at 1510 m, is almost three times as much at 62 cm.

3.6 Further focal points of current snow research

Snow research is important in ensuring the safety of those who use the mountains. The research work carried out in relation to snow sports, protective forests and permafrost has a direct effect on those living and working in the Alps.

3.6.1 Snow sports

Anything that slides over the surface of snow causes melting through friction and the melted snow acts as a lubricant. Although a good deal of research has been done on the friction between a ski and the snow some important questions still remain unanswered, concerning for example the amount and distribution of this lubricating melted snow. A joint project run by the SLF (Team Snow Sports) and representatives from the industry is currently investigating the phenomenon of ski–snow friction. This project should provide new information that will result in improvements to the ski–wax system or new technology for treating the undersurface of skis.

Fig. 3-16: Mobile weather station on the World Cup piste in St. Moritz (Grisons).

At a popular and competitive level, ski pistes are an important if not decisive element in winter sports (see Fig. 3-16). Creating and maintaining the pistes involves the regular use of technical equipment and is a costly business. The aim of the research on snow sports

Fig. 3-17: The best known protective forest in Switzerland above Andermatt (Uri).

Fig. 3-18: Active rock glacier below the Piz d'Err (Grisons), 2001.

being carried out by the SLF is to provide a precise definition of what is required of ski pistes and to develop and optimise methods of preparing and maintaining them (FAUVE et al. 2002).

The SLF is also pursuing other projects in collaboration with the Swiss Ski Association. In one of these projects, the focus is on the structure of the under-surface of cross-country skis. This structure is being developed and optimised for different types of snow, for which it is necessary to characterise and analyse all the relevant parameters in field tests, such as temperature, radiation, the hardness of the snow and the shape of the grains.

3.6.2 Protective forests

The snow-cover and the surface soil on steep slopes can be stabilised by dense forest. Without such protection many areas in the mountains would not be habitable and communication routes would be vulnerable to avalanches (see Fig. 3-17).

The snow is caught in the treetops and is either sublimated back into the atmosphere or falls to the floor of the forest in drops and lumps. This results in the formation of layers of snow that are far less unstable than in open country. In addition, the less extreme microclimate within the forest (little wind) and the stabilising effect of standing and fallen tree trunks do not favour the release of avalanches. In an open, less dense forest the protective effect is less strong.

Avalanches that break away above the treeline may destroy forests in their path. Using observations over many years and analyses of growth rings in tree trunks it is possible to reconstruct avalanche behaviour and to obtain information about the resistance of certain trees.

Forests not only constitute an ideal protection against avalanches but also make a valuable contribution towards attenuating other natural hazards such as rockfall, landslides and mudslides.

3.6.3 Permafrost

Soil that is permanently frozen is called permafrost. In principle, permafrost is defined by temperature. The ice in permafrost, which is in fact frozen water in the soil, is merely a consequence. This means that there can also be dry permafrost that contains almost no ice.

Permafrost can be seen especially easily when it involves non-solid material that is loosened by the pressure of the ice forming in the gaps. On a slope this mixture of debris and ice will slowly slide downhill, being clearly recognisable in the landscape (see Fig. 3-18). This is called a rock glacier, although its origins and behaviour have nothing to do with glaciers.

Permafrost can normally be found above the tree line, but it is only above an altitude of 3000–3500 m that areas of permafrost merge to form a whole. The extent of the permafrost is mainly determined by the mean annual air temperature and the degree of radiation.

Permafrost covers around 4 to 6% of the surface area of Switzerland, which corresponds to twice the area covered by glaciers (VONDER MÜHLL & PERMAFROST COORDINATION GROUP OF THE SAS 1999). The hydrology of these areas is considerably influenced by the almost impermeable permafrost layer. The presence of permafrost also delays the snow melt, which occurs between 15 and 20 days later in permafrost areas.

As a result of rising temperatures – it is estimated that the lower limit of the permafrost has risen by 150 to 250 m over the last 100 years (BADER & KUNZ 1998) – permafrost soils represent a potential danger for inhabited mountain areas. Permafrost zones also present problems for construction (PHILLIPS 2000). If anti-avalanche barriers, cable-car pylons or even cable-car stations are built on this unstable base they have to be secured through complicated safety structures.

Fig. 3-19: The Rhone glacier with access to caves in the snout (September 2004).

3.7 Glaciers

Glaciers and their evolution are important evidence of present climatic change and earlier variations in climate. Since the last maximum glaciation at the end of the Little Ice Age around 1850, glaciers have generally shrunk in Switzerland. Between 1850 and 2000 the total surface area of glaciers decreased by over 40% and the volume of all the Swiss glaciers by about one half.

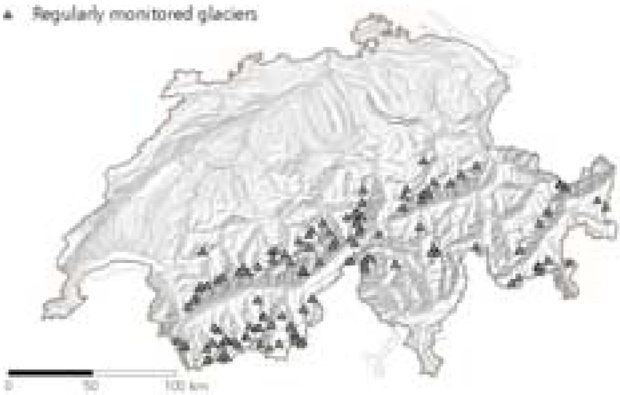


Fig. 3-20: Location of the 120 regularly monitored glaciers within the Swiss Glacier Measuring Network (from MAISCH et al. 2004).

3.7.1 Measuring networks

The first surveys of the Rhone glacier (Fig. 3-19) were started in 1874. Since then glaciers in Switzerland have been continually observed as part of basic scientific research (MARTINEC et al. 1992). The Swiss Glacier Measuring Network (see Fig. 3-20) is run by the Glaciology Committee of the Swiss Academy of Natural Sciences (GK/SANW, now called the SCNAT) in collaboration with various university institutes (Department of Glaciology of the VAW/ETHZ and the Geographical Institute of the University of Zurich).
Its aim is to provide documentation and to research into the evolution of glaciers in the Swiss Alps. In 2003 98 out of the 120 glaciers in the measuring network were surveyed. All glacier snouts had clearly receded (http://glaciology.ethz.ch/swiss-glaciers/).

Within the measuring network, the change in volume and movement of around a dozen glaciers are also observed. Furthermore, 84 dangerous glaciers that have also caused damage or could potentially cause damage are included in a special inventory. Survey flights are used to monitor 37 glaciers once a year or when the need arises (http://glacierhazards.ch).

3.7.2 Methods of investigation

Moraine deposits are used to help reconstruct earlier states of glaciers which extended into the lowlands of Switzerland during the last Ice Age (see Fig. 3-24). In order to establish historical maximum glaciation old drawings, paintings and photographs are also used. Figure 3-21 shows the Rhone glacier in 1856 and 1998. Part of what was terminal moraine in 1856 can still be seen at Gletsch.

Fig. 3-21: The Rhone glacier at Gletsch in 1856 and 1998 (HOLZHAUSER & ZUMBÜHL 1999).

Current changes in the length of glaciers can be determined from the movement of the snout. Flow behaviour and changes in the depth of the ice can be deduced on the spot using rows of stones and, more precisely, gauge poles. Furthermore, aerial photogrammetric surveys of the surface provide information as to the loss of volume over longer intervals.

The balance of volume of glaciers can be calculated using various approaches, for example using a glaciological or hydrological model. In the glaciological model, the change in volume is the balance between the accumulation of snow in the firn area (firn accumulation) and the loss of ice (ice ablation) in the lower part of the glacier. In the hydrological model the balance is calculated from precipitation, runoff and evaporation in glaciated catchments (MARTINEC et al. 1992).

3.7.3 Glacial processes

The surface of a glacier is divided into the accumulation zone and the ablation zone (see Fig. 3-22). At higher altitudes not all of the snow that accumulates during one winter will melt the following summer. It is continually covered with fresh snow and compacted. The transformation of snow to firn and to ice takes about 15 to 20 years in the Alps (VEIT 2002). In the ablation zone, however, more material melts than can be replaced by winter alimentation (ice ablation). If there is a balance between the accumulation and the ablation the area of the accumulation zone at the end

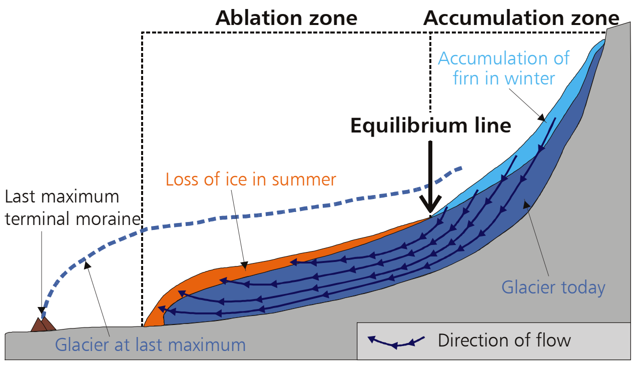


Fig. 3-22: Diagram of a glacier (from MAISCH et al. 1999).

of the summer melt will be around twice that of the ablation zone.

In the transition zone between accumulation and ablation the two processes are in balance (equilibrium line). If this line moves higher a glacier will melt. If it remains for several years in a lower position the glacier may increase in volume and size and thus advance.

A glacier advances or retreats, depending on weather patterns and in particular on the following factors (see MAISCH et al. 1999):

– air temperature,
– atmospheric humidity,

– the accumulation of snow in winter, and
– direct solar radiation.

In the parts of Switzerland covered by glaciers the equilibrium line is generally above 2000 m and, depending on prevailing precipitation, is subject to a mean annual temperature of between –4 and +1°C (see Fig. 3-23).

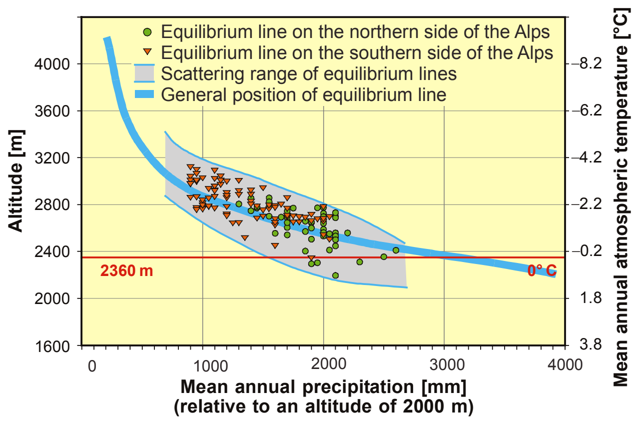


Fig. 3-23: Position of the equilibrium line of Swiss glaciers as a function of temperature and precipitation (cryospheres model) (from MAISCH et al. 2004).

No.	Glacier	1850 [km²]	1973 [km²]	2000 [km²]	1850–2000 [%]
1	Great Aletsch	105.6	96.1	90.1	–14.7
2	Gorner	66.0	59.7	57.1	–13.5
3	Fiescher	37.4	34.2	31.3	–16.3
4	Unteraar	33.4	29.5	26.7	–20.1
5	Oberaletsch	26.6	22.8	19.8	–25.6
6	Lower Grindelwald	23.2	20.8	19.3	–16.8
7	Findelen	20.0	17.4	17.0	–15.0
8	Corbassière	20.7	18.3	16.8	–18.8
9	Gauli	22.6	17.7	16.5	–27.0
10	Morteratsch	19.3	16.4	16.1	–16.6
11	Rhone	20.2	17.6	16.1	–20.3
12	Trift	19.3	16.6	16.0	–17.1
13	Zmutt	19.8	16.9	15.0	–24.2
14	Zinal	17.9	15.4	14.3	–20.1
15	Otemma	20.5	17.5	14.1	–31.2
16	Kander	16.0	13.9	13.2	–17.5
17	Hüfi	15.1	13.6	13.2	–12.6
18	Turtmann–Brunegg	15.0	12.8	11.5	–23.3
19	Mont Miné	12.5	11.0	10.3	–17.6
20	Arolla	16.4	13.2	9.8	–40.2

Table 3-2: Changes in the area of the 20 largest glaciers in Switzerland between 1850 and 2000 (for the location of the individual glaciers see Fig. 3-24) (MAISCH et al. 2004).

3.7.4 Results

The warming process that has been observed since the middle of the 19th century (in Switzerland: 1.0–1.6°C in the 20th century, OcCC 2002) led to an overall reduction in the total area covered by glaciers from around 1800 km² to 1300 km² between 1850 and 1973. By 2000 the total area had fallen by a further 250 km². In this respect, large glaciers generally show a lower percentage reduction than smaller ones (see Table 3-2).

At the same time as a reduction in area, glaciers in the Swiss Alps have also considerably decreased in length since 1850. Depending on the size, type and aspect of the glacier, the loss of length has been regular or interrupted by short-term advances.

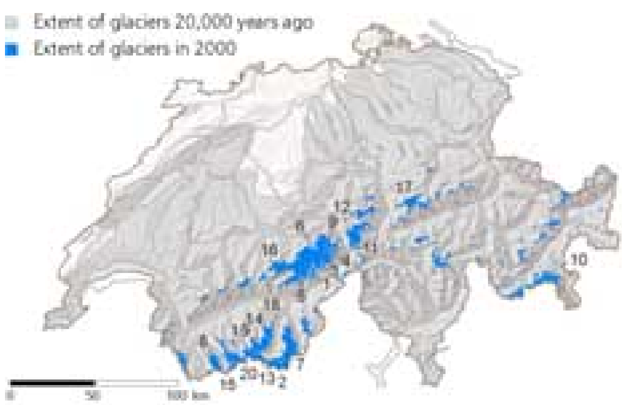


Fig. 3-24: Areas of Switzerland covered by glaciers in 2000 (MAISCH et al. 2004) and during the last Ice Age (c. 20,000 years ago, from VEIT 2002). (For glacier numbers see Table 3-2.)

Figure 3-25 shows changes in the length of the Great Aletsch and the Upper Grindelwald glaciers. While the snout of the rather slow-moving Aletsch glacier has continually melted back the Upper Grindelwald glacier twice showed clear growth during the 20th century; this was in reaction to short-term, cooler weather conditions favourable to glaciers.

The Findelen glacier (Valais) has also been seen to have gone through several phases of growth in recent times. During the most marked of these phases (1978–1986) this glacier grew by around 250 m (IKEN 1995). Figure 3-26 shows the extent of the Findelen glacier in 1850, 1873 and 2000. Since the length of this glacier was first measured in 1885 the snout has receded by 1845 m (length in 2003: 7.8 km) (GK/SANW & VAW/ETHZ 2003).

3.7.5 Glaciers as water reservoirs

Glaciers act as water reservoirs in the short and long term. Thanks to the melting process, which in the case of glaciers continues in summer after the snow has stopped melting, mountain streams carry an abundant quantity of water even during longer dry periods. If the amount of water stored in Swiss glaciers in 1850 (around 107 km^3 ice) were to be distributed evenly over the country it would give a water depth of 2300 mm. This means that at that time Swiss glaciers were storing a good 1.6 years' worth of precipitation in the form of ice (see Chapter 2). By 1973 as much as 33 km^3 of ice (corresponding to around 700 mm of water or around half the country's annual precipitation) and by 2000 almost a further 20 km^3 of ice (corresponding to a depth of 500 mm water) had melted away. In the area of the Great Aletsch glacier alone (see Fig. 3-27) some 4 km^3 of ice have melted since 1850. The water stored in the form of glaciers today corresponds to around one sixth of the volume of water stored in the whole of the country and is decreasing (MAISCH et al. 2004).

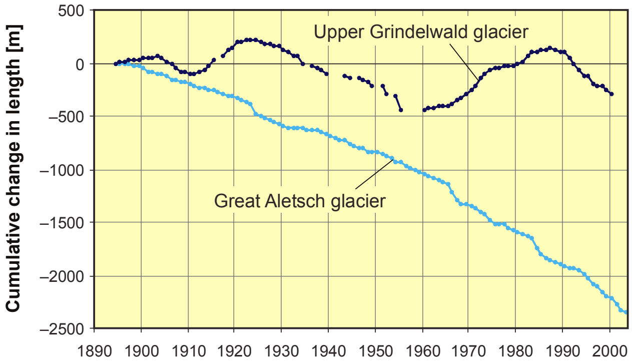


Fig. 3-25: Changes in the length of the Great Aletsch and the Upper Grindelwald glaciers between 1894 and 2003 (GK/SANW & VAW/ETHZ 2003).

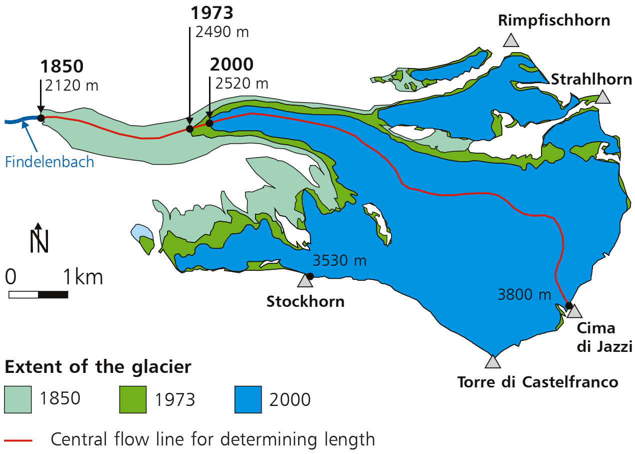


Fig. 3-26: Extent of the Findelen glacier and its tributaries in 1850, 1973 and 2000 (from MAISCH et al. 2004).

Fig. 3-27: Illustration of the volume of ice that disappeared from the Great Aletsch glacier between 1850 and 2001.

4 Evaporation

Statistics

Mean annual evaporation Switzerland	484 mm	(calculated from energy balance)	Source: MENZEL et al. 1999
Mean net radiation Switzerland	44 W/m²		Source: Z'GRAGGEN & OHMURA 2002
Maximum annual evaporation	1029 mm	(Lake Maggiore)	Source: MENZEL et al. 1999
Evaporation gradient Switzerland	−22 mm/100m	(< 3000 m above sea level)	Data: MENZEL et al. 1999
Maximum evaporation values	7 mm/day		Source: LANG 1978

4.1 Evaporation – The Earth's natural cooling system

All over the world over 80% of the energy supplied by the Sun is used in water evaporation. This process prevents the surface of the Earth becoming overheated.

4.1.1 Energy balance

The Sun provides energy in the form of short-wave radiation (solar constant = 1366.5 W/m²). Since at any one time only half the Earth is in sunlight and the Earth is a globe, mean solar radiation is one quarter of the solar constant, i.e. 342 W/m². The radiation is reflected several times and converted in the atmosphere and on the surface of the Earth, with the result that the worldwide mean net radiation at the Earth's surface is 30% of the mean solar radiation, or 102 W/m² (Z'GRAGGEN & OHMURA 2002).

In Switzerland the mean net radiation is 44 W/m². Some 20% of this energy is used to warm the Earth's surface and the lower layers of air, the remainder drives the hydrological cycle through evaporation (Z'GRAGGEN & OHMURA 2002). Air temperature at the Earth's surface consequently depends to a large extent on evaporation. "If, during a summer drought, evaporation was reduced to zero owing to the fact that the ground was totally dry, on a sunny day the temperature of the lowest layer of air above land up to 1000 m could rise by around 10°C more than when conditions are ideal for evaporation" (BADER & KUNZ 1998).

4.1.2 Evaporation – Evapotranspiration

Evaporation is defined as the transfer of water from a liquid to a gaseous state. Water vapour is taken up by the air as an invisible gas. The maximum amount of humidity that the air can carry depends greatly on temperature (see Fig. 4-1). The term evapotranspiration comprises evaporation from barren surfaces (evaporation) plus evaporation through vegetation (transpiration); the two words are often used synonymously, however.

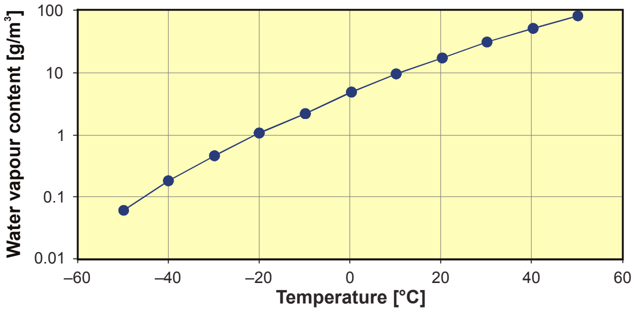


Fig. 4-1: Maximum humidity carried by the air as a function of temperature.

The maximum potential evaporation can be determined from the net radiation at the Earth's surface.

$$ETM = \frac{N \cdot t}{r_V}$$

where ETM is the maximum possible evapotranspiration [mm],
N is the net radiation [W/m² = J/(m²·s)],
t is time [s],
r_v is the evaporation warmth of the water [2.446 · 10⁶ J/kg at 20°C].

Figure 4-2 shows the maximum potential evaporation calculated from net radiation. Results of over 1000 mm are obtained for lower land and south-facing slopes. The noticeable fall in net radiation and thus evaporation with rising altitude is principally due to the snow-cover. Surfaces covered in snow reflect an average of 71% of the short-wave radiation they receive, while snow-free surfaces reflect less than 20%. Above around 3000 m the annual energy balance is negative. During daylight hours there are period of positive net radiation and thus evaporation, however (see Fig. 4-9).

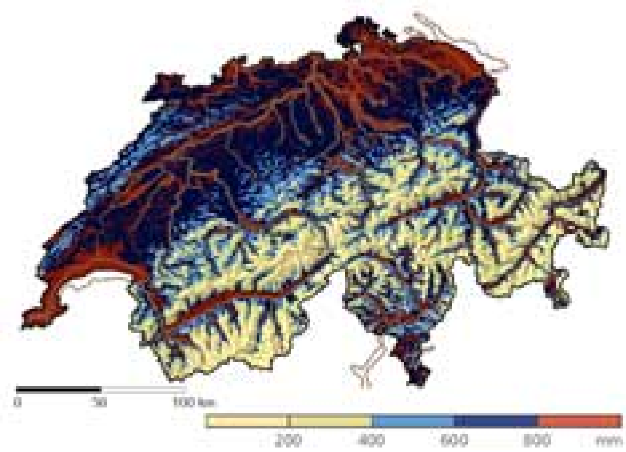


Fig. 4-2: Maximum potential annual evaporation calculated from net radiation (1984–1993); mean for the whole of Switzerland: 600 mm (after Z'GRAGGEN & OHMURA 2002).

4.1.3 Potential and actual evaporation

When the level of humidity on the Earth's surface is ideal, the rate of evaporation is determined by atmospheric conditions within the limits of the available energy. This is termed potential evaporation and rises with:

– the dryness of the air,
– wind,
– air pressure.

The actual amount of water that evaporates is also limited by the availability of water and is normally lower than the potential evaporation rate (see Fig. 4-3). Actual and potential evaporation are almost identical over open water.

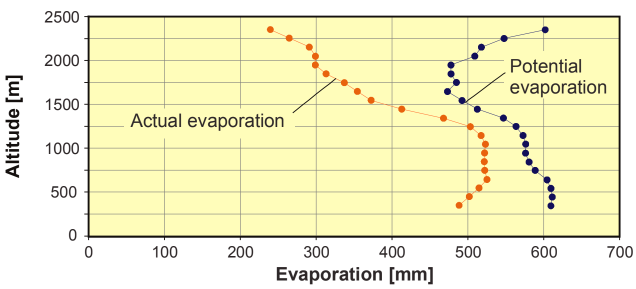


Fig. 4-3: Actual and potential mean annual evaporation in the Thur–Andelfingen catchment (1993–1994) (after GURTZ et al. 1997).

Actual evaporation is largely determined by ground cover and the amount of water in the soil. Barren surfaces dry out quickly after precipitation has ceased, evaporation decreases rapidly and surface warming increases. In the case of surfaces covered with vegetation, active transpiration can compensate for the reduction in evaporation if the soil contains enough water available to the vegetation. Forested surfaces have a greater rate of transpiration than meadowland (see Fig. 4-8). In Switzerland mean annual actual evaporation is as much as 80% of maximum potential evaporation, namely 484 mm per year (MENZEL et al. 1999).

4.2 Measuring evaporation

It is only possible to directly measure actual evaporated water on small test surfaces. Potential evaporation can be measured using simple apparatus. For measuring actual evaporation test pans containing natural vegetation have to be incorporated into the measuring device.

4.2.1 Measuring potential evaporation

Instruments for measuring potential evaporation allow evaporation under controlled conditions. Probes (atmometers and evapotranspirometers) measure the amount of water that evaporates from humid surfaces, while evaporimeters measure that evaporated from open water.

An evaporimeter (class A pan) is used worldwide as the standard instrument of the World Meteorological Organization (WMO) for measuring evaporation (see Fig. 4-4). This instrument consists of a pan which is 122 cm in diameter and has sides that are 25 cm high. Evaporation is determined by the simultaneous measurement of the water content (in Fig. 4-4 using ultrasound) and precipitation. Since the instruments are in effect humid islands in a normally dry environment (oasis effect), the evaporation measured is on average too high. In addition, the class A pan is also exposed to full solar radiation, which often leads to warming in comparison with the environment. Consequently, it is necessary to correct the measured rate of evaporation using the pan coefficient (0.75) (BAUMGARTNER & LIEBSCHER 1990).

Fig. 4-4: Evaporimeter (class A pan) with an Ott-Pluvio precipitation gauge (background) at the ETHZ's Rietholzbach hydrological testing site (canton of St. Gallen).

Fig. 4-6: Lysimeter and two precipitation gauges sunk into the soil (background) at the ETHZ's Rietholzbach hydrological testing site.

4.2.2 Measuring actual evaporation

An instrument called a lysimeter is used to measure evapotranspiration (E) under as natural conditions as possible. A lysimeter consists of a vessel containing local soil placed with its top flush with the ground surface and is used to study several phases of the hydrological cycle (see Figs. 4-5 and 4-6). The precise water balance can be calculated from the change in weight (δS) and the measured precipitation (P) and runoff (R) using the formula ($E = P - R - \delta S$). Measurement using a lysimeter is considered to be the most accurate way of determining actual evaporation.

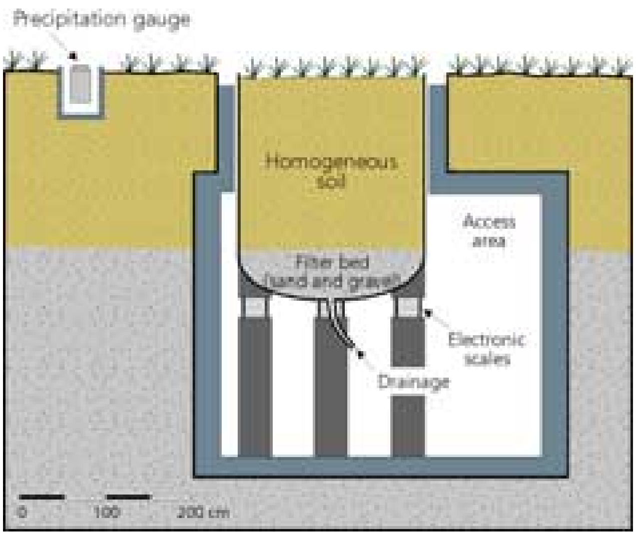


Fig. 4-5: Cross section of the ETHZ's lysimeter used at the Rietholzbach hydrological testing site (after www.iac.ethz.ch).

4.3 Calculating evaporation

The potential evaporation at given points or in whole areas is calculated from the relevant meteorological parameters. The classical method for determining actual evaporation involves using the water balance for entire catchments. Using water balance models, actual evaporation can be calculated for both small surfaces and large catchments.

4.3.1 Calculating potential evaporation

Potential evaporation can be determined approximately using empirical formulae. Table 4-1 indicates the necessary parameters of a number of selected formulae.

	Thornthwaite (1948)	**Penman (1948)**	**Haude (1958)**	**Turc (1961)**	**Primault (1962)**	**Penman-Monteith (Monteith 1981)**
Temperature	☑	☑	☑	☑		☑
Radiation		☑		☑	☑	☑
Atmospheric humidity		☑	☑		☑	☑
Others		☑				☑
Time period	*M*	*H*	*D*	*D*	*> 5 D*	*H*

Table 4-1: Parameters for determining potential evaporation *(time period: M = month, D = day, H = hour).*

The shorter the time period used for the calculations, the more information has to be known. HAUDE (1958), for example, calculated potential evaporation for one day from the loss of humidity at 14.00 hours.

$$ETP = k \cdot (E_{14} - e_{14})$$

where ETP is potential evapotranspiration [mm/d],
k is the seasonal coefficient [mm/hPa],
E_{14} is the vapour saturation pressure at 2 pm [hPa],
e_{14} is the actual vapour pressure at 2 pm [hPa],
$E_{14} - e_{14}$ is the difference in humidity at 2 pm [hPa].

4.3.2 Calculating actual evaporation

Mean annual evaporation can be calculated from the remainder of the water balance (see Chapter 10). At the same time, however, errors in determining individual water balance components cumulate to give an overall error, which in certain regions can lead to drastically inaccurate estimations (SCHÄDLER & WEINGARTNER 2002b). Imprecision in calculating precipitation and subterranean runoff in karst areas is in particular a potential source of error.

Depending on the influencing factors (see Section 4.1) the natural conditions in the target area must be taken into account when calculating actual evaporation. Special computer programmes are available for making catchment models and simulating the relevant physical processes. With the resulting evaporation maps (see Fig. 4-9) the water balance method can be hydrologically reinterpreted (see Section 10.2).

4.4 Evaporation conditions

With good basic data it is possible to create models with a high spatial resolution (< 1 km²) for the whole of Switzerland. Using these models scientists can determine in detail the horizontal and vertical distribution of the 470 mm or so of water that evaporates each year.

4.4.1 Annual evaporation

The processes discussed in Section 4.1 result in evaporation being the only parameter of the water balance that decreases with rising altitude (see Fig. 4-7). In addition, in mountainous areas evaporation is limited through the amount of water available, despite the tendency to higher precipitation. Flatter areas and steep gradients mean that less water can be stored.

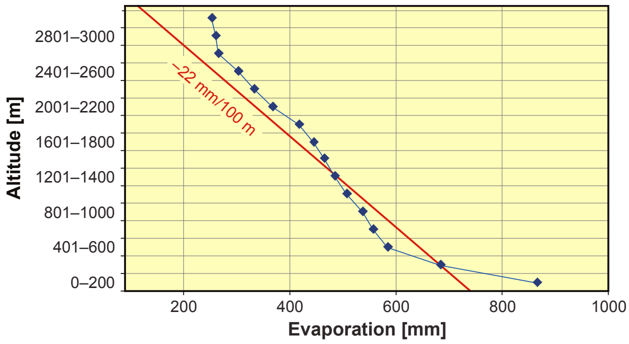


Fig. 4-7: Mean annual evaporation at different altitudes and linear evaporation gradient, calculated for the whole of Switzerland (data: MENZEL et al. 1999).

The fact that evaporation is dependent on altitude also determines the character of the evaporation map (see Fig. 4-9). Moreover, it is noticeable that the rate of evaporation over lakes is high and that there are marked differences within short distances. The extreme spatial variation is due to local ground cover (see Fig. 4-8). The evaporation rate also varies along a north–south line. The lowest mean annual evaporation rate in profile 1 (Fig. 4-9) has been calculated for the Alpine peaks and the Berne agglomeration. The highest rates in profile 2 are accounted for by evaporation from Lake Zurich and Lake Maggiore.

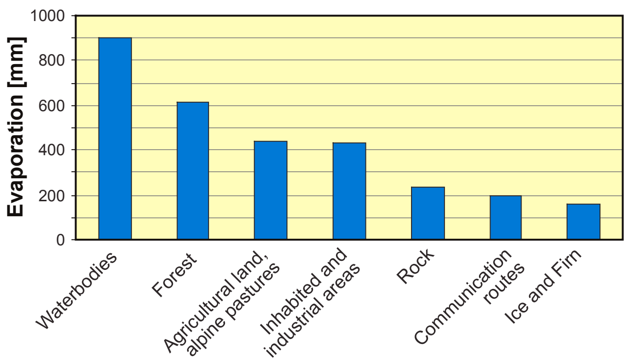


Fig. 4-8: Mean annual evaporation from areas with varying ground cover (1973–1992) (after MENZEL et al. 1999).

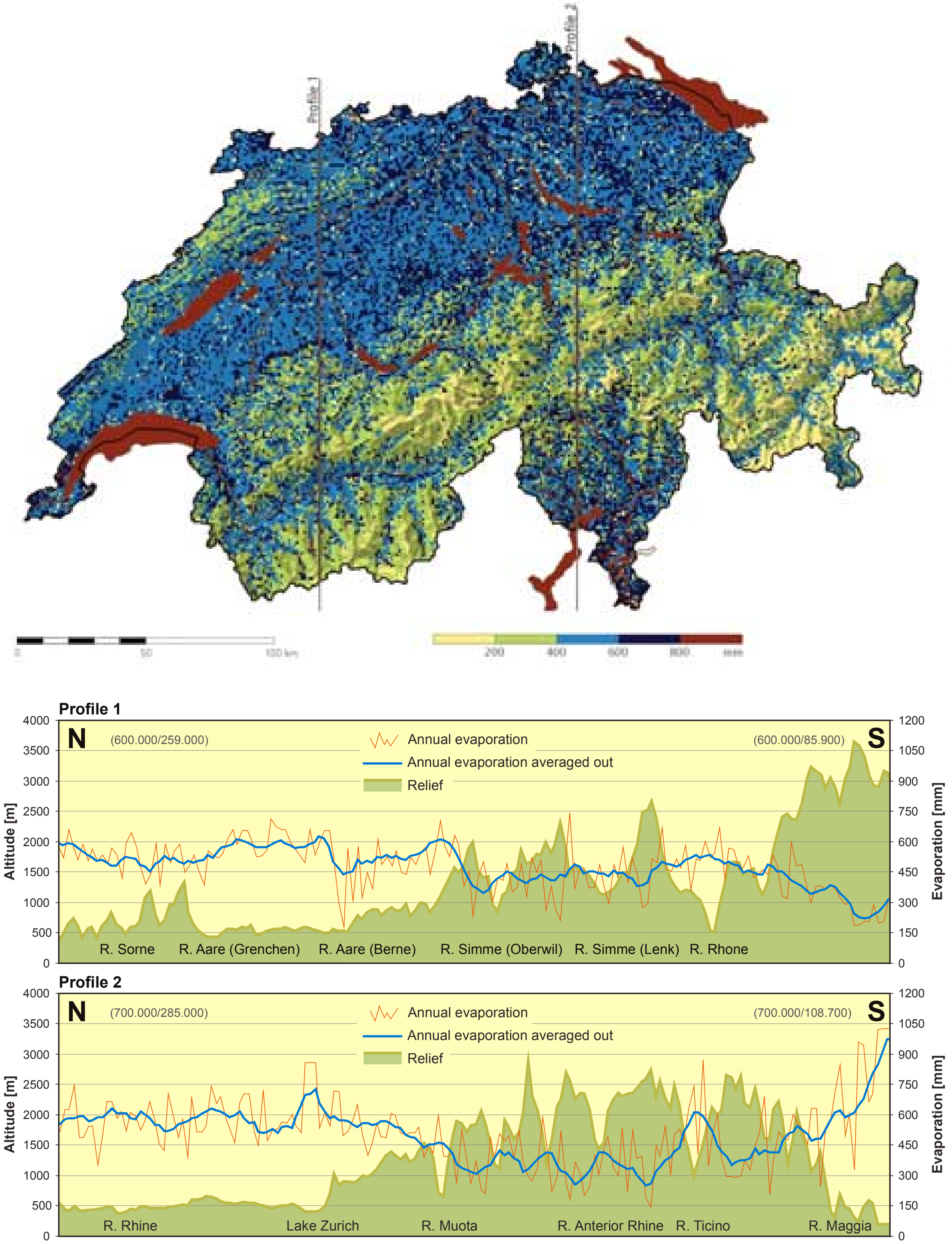


Fig. 4-9: Map of mean annual actual evaporation (1973–1992) and two north–south profiles (data: MENZEL et al. 1999).

4.4.2 Seasonal variation in evaporation

Figure 4-10 shows the seasonal pattern of daily evaporation from three areas with varying ground cover. During the winter months there is hardly any evaporation from agricultural land in the Central Lowlands. During the principal growth phase in April and May daily evaporation increases considerably; in July it starts to decrease. Most of the year there is a far higher evaporation rate from forested areas than from agricultural land. In winter humid surfaces account for the greater part of the water that evaporates.

In order to obtain a regional overview, a comparison is made of areas with similar agriculture. Figure 4-12 summarises evaporation from forested areas at between 800 and 1000 m in various parts of the country. Summer peaks can be seen for the forests in the eastern Central Lowlands.

In contrast, transpiration from forested areas in the Jura, the Grisons and the Tessin is limited during the summer, indicating the comparatively unfavourable soil conditions. Evaporation from forests is highest in the Tessin during the six winter months owing to climatic conditions.

4.4.3 Trend over the 20th century

A significant increase in evaporation can be seen during the 20th century (see Fig. 4-11). Although estimations for the Thur catchment obtained using a model indicate a further increase in evaporation of around 12% during the 21st century one should not draw any simple conclusions such as "higher mean temperatures lead to increased evaporation" (GURTZ et al. 1997).

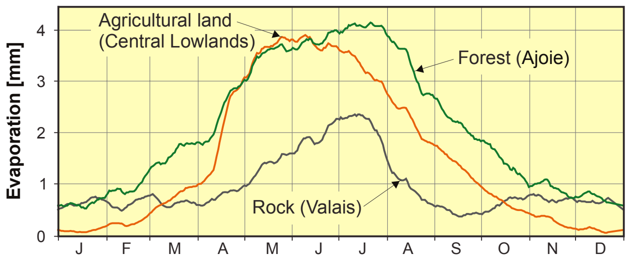


Fig. 4-10: Examples of mean daily evaporation from varying surfaces (after MENZEL et al. 1999).

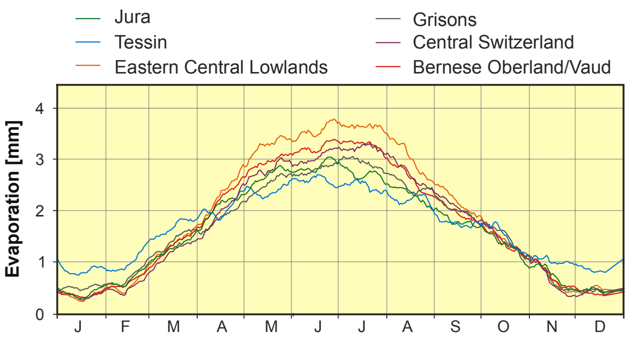


Fig. 4-12: Mean daily evaporation from forested areas (altitude 800 to 1000 m) in various regions (1973–1992)
(after MENZEL et al. 1999).

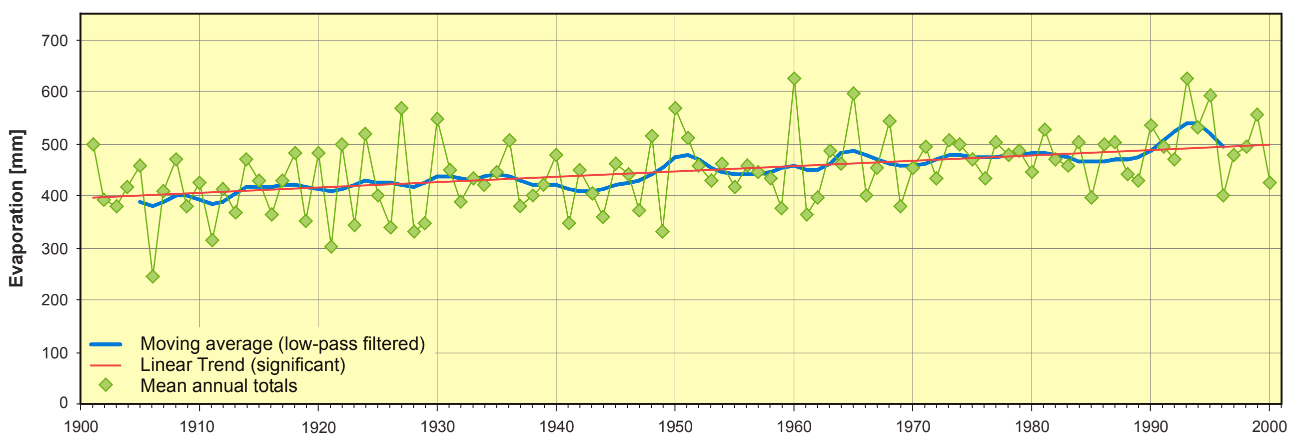


Fig. 4-11: Mean annual evaporation for the whole of Switzerland in the 20th century (data: B. SCHÄDLER, FOWG).

5 Discharge

Statistics			
Mean annual discharge, Switzerland (1961–1990)	991 mm		Source: SCHÄDLER & WEINGARTNER 2002a
Mean annual specific discharge, Switzerland (1961–1990)	31 l/s·km^2		Source: SCHÄDLER & WEINGARTNER 2002a
Mean annual discharge volume, Switzerland (1961–1990)	1297 m^3/s		Source: SCHÄDLER & WEINGARTNER 2002a
Highest recorded discharge	5090 m^3/s	Rhine – Basle, 1999	Source: FOWG
Longest discharge measurement series	from 1808	Rhine – Basle	Source: SIGRIST 1988

5.1 Discharge measurement

Water levels and discharge are recorded through regular measurements made at permanent measuring stations and spot measurements at temporary points by the Swiss National Hydrological Survey (LH), a number of cantons, research institutes and private bodies. At times of flood peak discharge is recorded and during dry periods minimum discharge. A range of measuring instruments and methods are used depending on the different types of rivers and lakes and the enormous range of variation in results.

5.1.1 Water levels and discharge

The purpose of measuring discharge in a stream or river is to determine the volume of water that flows through a given cross-section in one second (see Fig. 5-1).

For practical reasons the discharge measured in different channel flows is often correlated with the water level observed at a given point. This correlation is called a discharge curve (see Fig. 5-2).

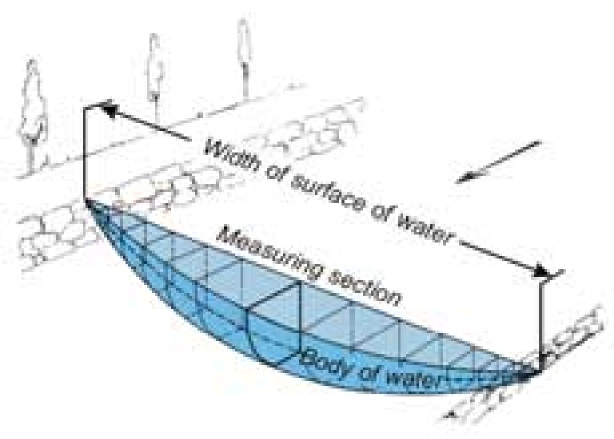


Fig. 5-1: Explanatory diagram of how discharge is measured: the volume of water that flows through the cross-section in one second (LH 1982).

Once the discharge curve has been established further discharge measurements must only be made periodically to verify the original curve and make changes if necessary. Using the discharge curve the volume of water discharged can be determined from the water level at any given time.

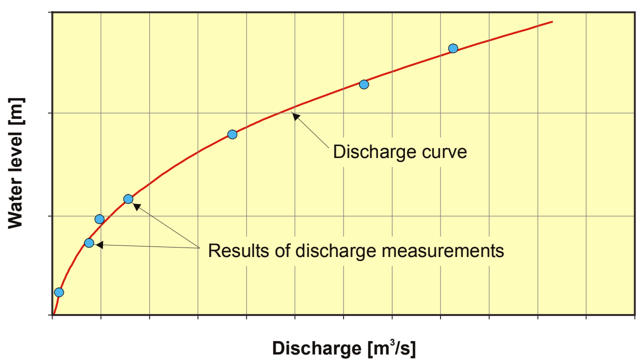


Fig. 5-2: Explanatory diagram of a discharge curve: correlation between discharge and water level (after LH 1982).

5.1.2 Measuring the water level

Both non-recording and recording instruments are used to measure water levels. Today the trend is towards apparatus with electronic data recording. The data are then transmitted and processed almost immediately. Digital instruments (shaft encoder, see Fig. 5-6) can be used alongside existing mechanical devices, such as limnigraphs with floats, for recording water levels.

The oldest method of measuring water levels involves a staff gauge that is permanently installed in a river or lake. Depending on their shape and the character of the river-bank and the flow conditions, staff gauges (see Fig. 5-3) are installed in measuring shafts, niches in the river bank, on jetties or directly on waterside walls or banks.

Maximum flood gauges (see Figs. 5-4 and 5-17) measure only the highest levels reached during a flood and are most frequently to be found on weirs. The levels measured can be used to estimate discharge by hydraulic calculations. A gauge is installed inside the pipe, which is open at the lower end, on to which is fixed a water-soluble coloured tape. The water that enters the pipe during a flood washes the colour away; the highest level reached can then be read off later.

The level is continuously recorded using floats, hydrostatic measuring apparatus or radar. Non-interventional radar systems (see Fig. 5-5) have the advantage of not needing to be installed in the water. At the same time the instruments and measurements are not harmed or impaired by floating branches, bed load, etc. Pneumatic installations and gauges with floats (see Fig. 5-6) are still widely used. It is relatively expensive to install and operate such measuring instruments, however. The measuring points have to be representative and at the same time they must be protected as far as possible from damage by plants, bed load, etc.

Fig. 5-3: Staff gauge, Riale di Pincascia – Lavertezzo (Tessin).

Fig. 5-5: Water-level gauge using radar sensor, Alp – Einsiedeln (Schwyz).

Fig. 5-4: Maximum flood gauge (diagram from Kan 2002).

Fig. 5-6: Gauge with float recorder, Inn – St. Moritz Bad (Grisons).

5.1.3 Measuring discharge

There is a selection of instruments that can be used for measuring discharge manually or electronically.

Hydrometric impellers (see Fig. 5-7) are the most commonly used. Flow velocity is measured over the entire gauge section of the river. The volume of water per unit of time can be calculated from a series of single measurements (see Fig. 5-1). The impeller is fixed onto a rod or a cable attached to the bank or a jetty. Impellers on cables can be used in places where it is too difficult to install other devices or where alternative measuring methods are too dangerous. An alternative to the impeller is a measuring device which uses magnetic induction (see Fig. 5-8).

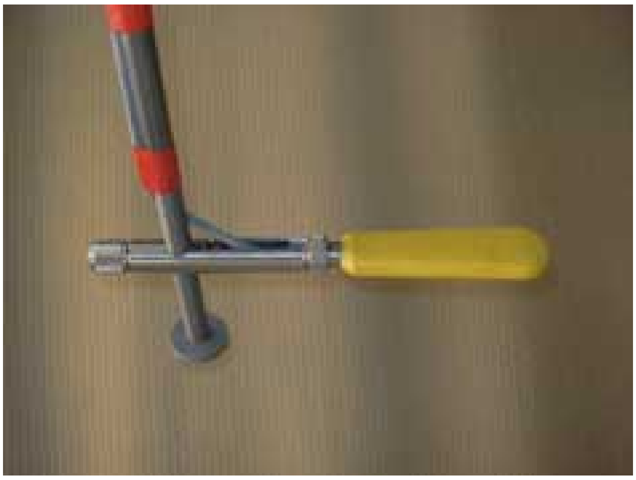


Fig. 5-8: Measuring device using magnetic induction.

The acoustic Doppler current profiler (ADCP, see Fig. 5-9) is a state-of-the-art instrument. Four acoustic sensors measure water depth, integral flow velocity over the total depth and the displacement of the instrument in relation to the bed of the river. This device can be used in similar circumstances to the hydrometric impeller. Since the ADCP does not have to be submerged, however, and enables measurements to be taken more quickly, it is ideally suited to measuring flood levels.

With Jens' submerged gauge (see Fig. 5-10) mean flow velocity can be measured in small rivers and streams. Measurements made in this way are generally

Fig. 5-7: Hydrometric impeller on a cable.

Fig. 5-9: Trimaran float with acoustic Doppler current profiler (ADCP).

not as accurate as those made using an impeller; they need far less time, personnel and material, however.

Fig. 5-10: The Jens' gauge: mean flow velocity can be deduced from the pressure of the water on the rod.

Fig. 5-11: Tracer-dilution method: the fluorescent tracer is fed into the river from a Mariott bottle.

Fig. 5-12: Man-made weir, Massa – Blatten (Valais).

Determining discharge using the tracer-dilution method (see Fig. 5-11) involves feeding a known amount of tracer into the river. Salt and fluorescent materials are normally used as tracers. By measuring the concentration of the tracer further downstream it is possible to calculate the volume of water needed to obtain that concentration. Depending on the method used, the dilution coefficient is calculated either immediately after the measurements have been taken or later in the laboratory.

Man-made features in rivers, such as Venturi flumes or weirs (see Figs. 5-12 and 5-18), cause a change in the flow with the result that the discharge can be clearly correlated to the water level. The discharge volume can then be directly determined from the water level.

5.1.4 Measuring stations

Today the Swiss network for measuring discharge comprises around 200 federal and 300 cantonal stations on small watercourses and 30 stations run by private bodies (see Fig. 5-20). Apart from the permanent discharge measuring stations, the maximum water level is recorded at 107 flood measuring stations after major floods (see Fig. 5-17). The construction and technical installations at discharge measuring stations are adapted to the river or lake in question (see examples on p. 51). In order to be able to measure low water levels in rivers with marked variations in channel flow, a low-water channel is installed if possible (see Figs. 5-13 and 5-14).

Fig. 5-13: Measuring station — Goneri – Oberwald (VS)
Water-level measurement — Radar
Discharge measurement (with low-water channel) — Impeller

Fig. 5-14: Measuring station — Orbe – Le Chenit (VD)
Water-level measurement — Float
Discharge measurement (with low-water channel) — Impeller

Fig. 5-15: Measuring station — Aare – Bern (BE)
Water-level measurement — Pneumatic gauge
Discharge measurement — Impeller on cable

Fig. 5-16: Measuring station — Gürbe – Burgistein (BE)
Water-level measurement — Pneumatic gauge
Discharge measurement — Impeller

Fig. 5-17: Measuring station — Bütschlibach – Bumbach (BE)
Water-level measurement — Maximum flood gauge
Discharge measurement — Hydraulic calculations

Fig. 5-18: Measuring station — Rotenbach – Plaffeien (FR)
Water-level measurement — Float
Discharge measurement — V-shaped weir, volumetric

5.1.5 Measuring networks

The systematic observation of water levels in Swiss lakes and rivers started in 1863 with the founding of the Swiss Hydrometric Commission. Originally only water levels were measured but in time discharge volumes were also determined. In the second half of the 20th century the federal measuring network was considerably expanded through the addition of cantonal and private measuring stations (see Figs. 5-19 and 5-20). The cantonal stations observe principally smaller rivers and streams (mean catchment area 26 km^2), while the measuring network run by the Swiss National Hydrological Survey covers all the major rivers (mean catchment area 210 km^2). Figure 5-21 shows the currently operational stations that are part of the federal measuring network.

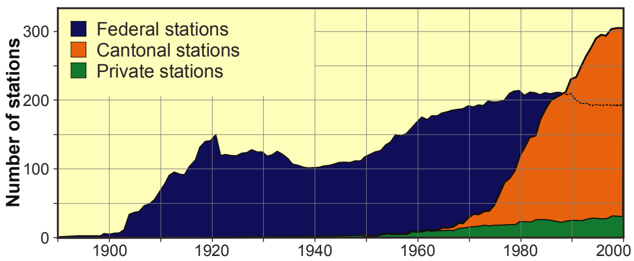


Fig. 5-19: Expansion of the discharge measuring network including federal, cantonal and private stations up to 2000 (after KAN 2002).

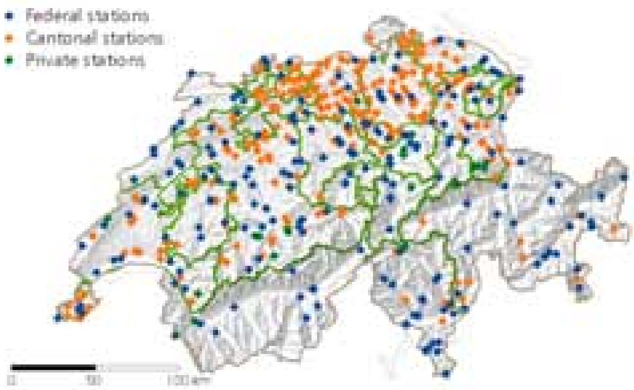


Fig. 5-20: Measuring network in 2000 (after KAN 2002).

5.1.6 Measurement error

The accuracy of discharge measurements depends on the type of river or lake, the measuring stations and the method and instrument used. Normally the measurements made at average discharge are more accurate than those made at flood discharge. The total random error in discharge measurements (e_Q) using a hydrometric impeller can be estimated using the following formula:

$$e_Q = \pm \sqrt{(e_V)^2 + \frac{1}{X}\left[(e_B)^2 + (e_D)^2 + (e_E)^2 + (e_p)^2 + (e_C)^2\right]}$$

In the case of a river with a natural course and at average discharge the following individual errors can be assumed for measurements made using an impeller:

e_V : Error in the mean flow velocity in the measuring section as a function of the number of vertical Xs
$e_V = \pm 3\%$ where $X = 20$

e_B : Error in determining the position of the measurement verticals
$e_B = \pm 1\%$

e_D : Error in determining the depth of the water in the measurement verticals
$e_D = \pm 1\%$

e_E : Error in determining the velocity with one measuring point (v_m)
$e_E = \pm 4\%$ where $v_m = 0.5$ m/s, duration of measurement 1 min

e_p : Error in the mean flow velocity in the verticals as a function of the number of measuring points per vertical
$e_p = \pm 2\%$ using the 5-point method

e_C : Error in the mean flow velocity depending on the calibration of the impeller
$e_C = \pm 1\%$

This gives a total random error of $e_Q = \pm 3.2\%$ for the example given. When flood water is measured the error can be far higher, depending on local conditions.

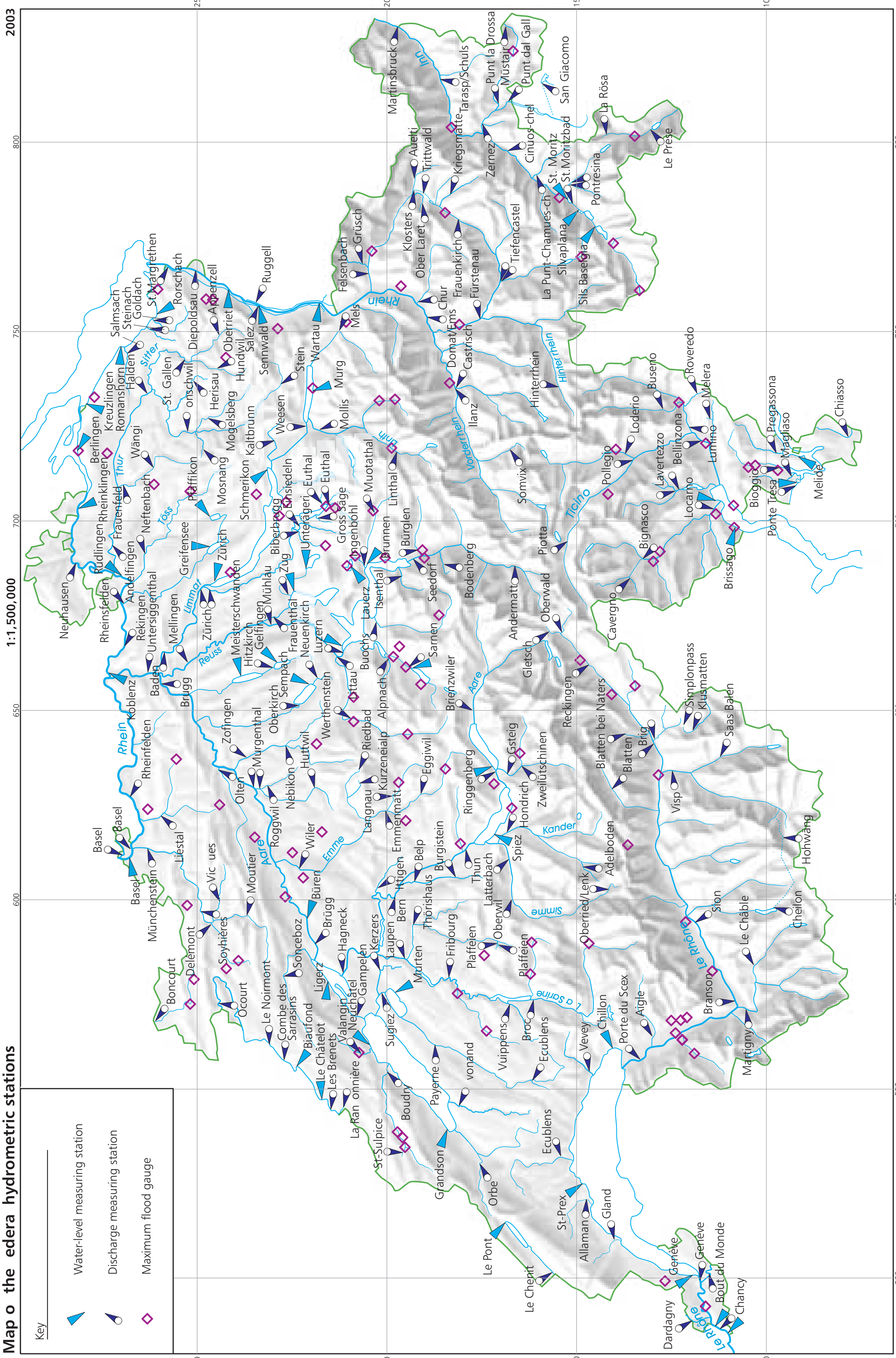


Fig. 5-21: Map of the federal hydrometric stations (data: FOWG).

5.2 Estimating discharge

Wherever it is not possible to measure discharge an attempt can be made to estimate it.

5.2.1 Estimating long-term mean monthly discharge

Regression ratios are often used to estimate monthly discharge in areas where no measurements are made. In mountainous areas, measuring and processing the essential climatic data is still so difficult, however, that such a procedure is not recommended. For this reason a method has been devised by which it is possible to estimate mean monthly discharge (MQ (month)) on the basis of the estimated mean annual discharge (MQ (year)) and the flow regime (Pardé coefficient) (see Section 5.3.2). Figure 5-22 shows the various stages of this method. Mean annual discharge is estimated using the regression ratios described by ASCHWANDEN (1985). The Pardé coefficients (PCs) for Swiss rivers and lakes are given in ASCHWANDEN & WEINGARTNER (1983). The procedure and all the necessary documentation can be found in WEINGARTNER & ASCHWANDEN (1992).

5.2.2 Estimating flood discharge

Figure 5-23 shows possible procedures for estimating flood discharge based principally on the availability of discharge data and knowledge of the area.

If discharge measurements are available for a given catchment they can be analysed using extreme value statistics. For example, the probability of flood discharge being above or below expectations can be estimated from the annual peak flood values using empirical and theoretical distribution functions. This method consists of the following steps:

– a measurement series of mean peak flood values that is as precise and as homogeneous as possible is set up;
– the distribution functions and the procedure for estimating the parameters are selected;
– the empirical distribution of the random values and the distribution functions are set out.

Figure 5-24 shows the result of extreme value statistics concerning mean peak flood values between 1972 and 2002 at the Mogelsberg station on the R. Necker. General extreme value distribution was chosen as an analytical distribution function and parameters were estimated using the moment method. A significance threshold of 90% was taken for the confidence interval. In general, estimations should be made for no more than three times the observation period (pale yellow zone). Extrapolation gives an HQ_{50} (flood discharge which occurs on average once every 50 years) of 327 m^3/s.

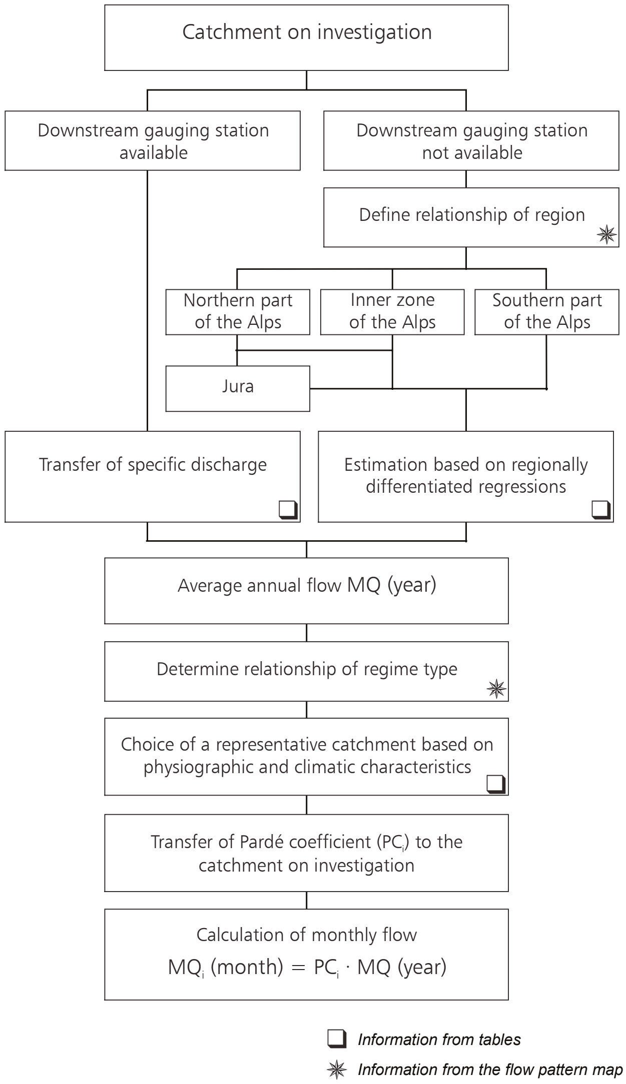


Fig. 5-22: Procedure for estimating long-term mean monthly discharge (WEINGARTNER & ASCHWANDEN 1992).

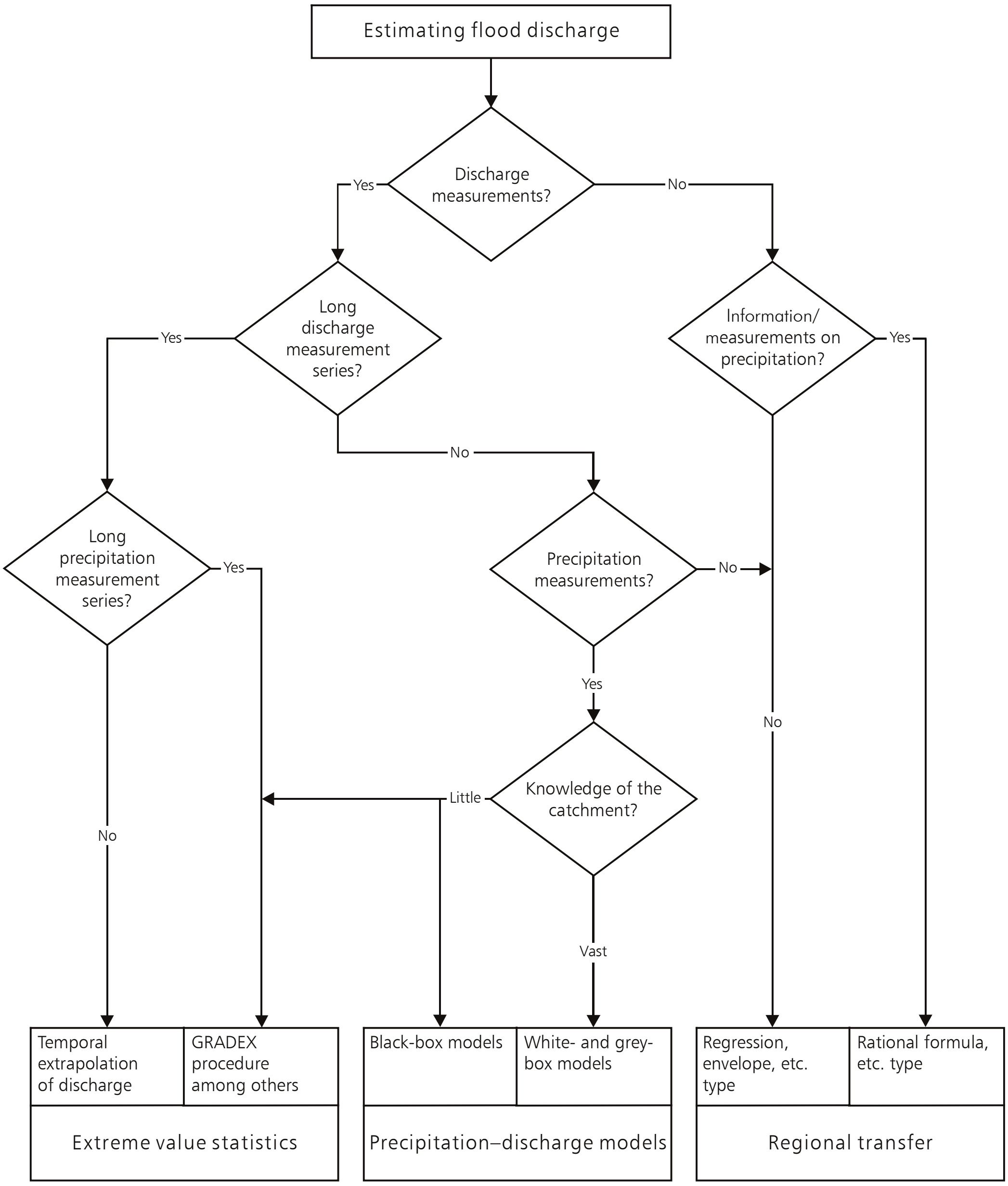


Fig. 5-23: Procedures for estimating flood discharge (SPREAFICO et al. 2003).

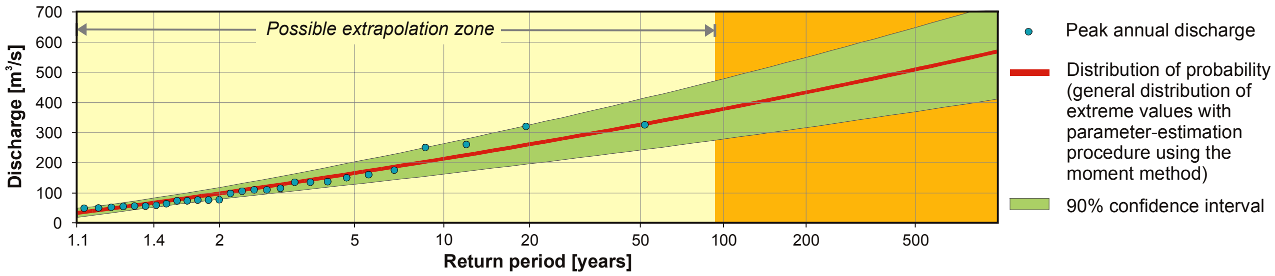


Fig. 5-24: Extrapolation of annual peak flood values to the Mogelsberg station on the R. Necker (1972–2002) (data: FOWG).

According to current estimations based on the confidence interval, the River Necker will probably carry between 240 and 420 m^3 of water per second once in 50 years.

Using the precipitation–discharge models precipitation can be converted mathematically into discharge. The degree of detail with which the series of physical processes is represented varies between the black-box, the grey-box and the white-box models. Since detailed information about the catchment and high-resolution measurement values (meteorology and discharge) are normally needed precipitation–discharge models are not an alternative to regional transfer in many cases.

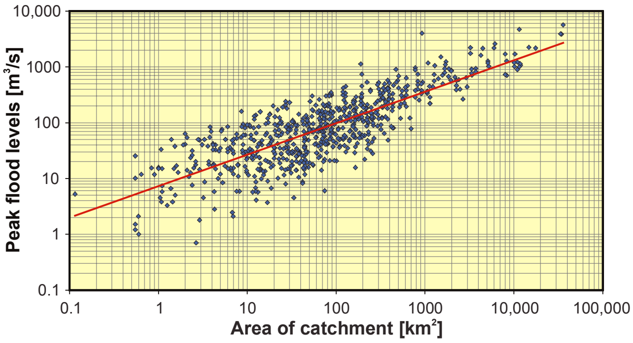


Fig. 5-25: The highest rates of discharge observed in Switzerland up to 1990 (after Weingartner 1999).

The process of transferring results to a region uses known correlations between the hydrological parameters and various characteristics of the region (climate, topography, soil, geology and landuse).

Figure 5-25, for example, shows the correlation between the highest rates of discharge observed in Switzerland and the area of the corresponding catchment. The resulting regression ratio shows that around 70% of the fluctuations in flood discharge can be attributed to the area of the catchment. The flood observations used in this case come from all over Switzerland. By combining regions with similar flood patterns (see Fig. 5-26) the marked heterogeneity of the landscape can be better taken into account, with the result that the regressions account for over 90% in certain regions.

Despite its simple structure, the flood estimation model based on these principles – GIUB'96 (Weingartner 1999) – provides comparatively good results (see Fig. 5-27). Out of the ten models that Barben (2003) examined, he considered only four as suitable, including two versions of the GIUB'96. It must be said, however, that no flood estimation procedure can guarantee reliable results in every case; detailed process-orientated investigations are needed in addition to estimate flood discharge.

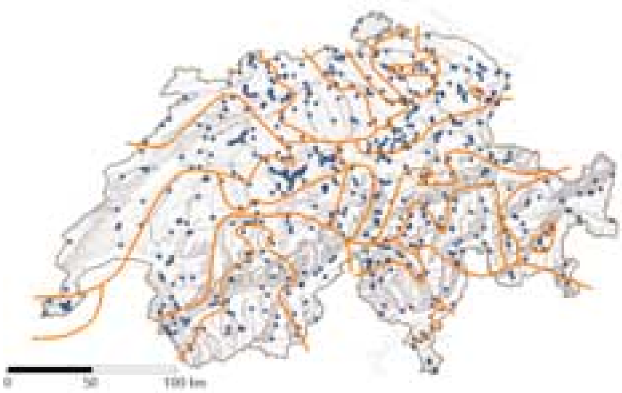


Fig. 5-26: Flood regions in Switzerland and location of flood discharge observed in Fig. 5-25 (after Kan 1995).

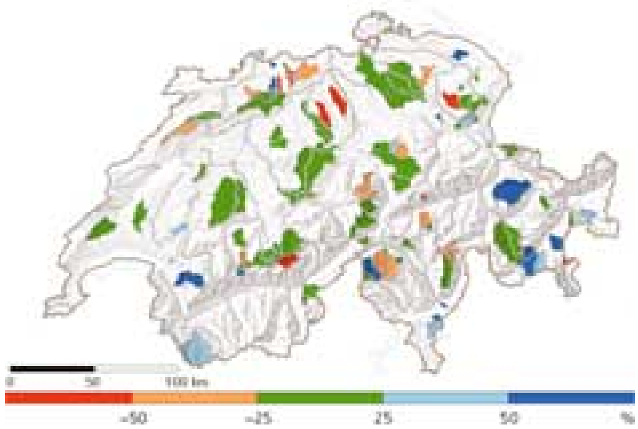


Fig. 5-27: Results of estimations of 100-year peak flood levels made using the GIUB'96 model (Fn). The colours indicate deviation of the results obtained using the model with reference values extrapolated from measurement results (in %). Over half the estimations can be considered "satisfactory" (green areas) (after Barben 2003).

The choice of an estimation method is influenced by various questions:

– What is the flood estimation needed for?
– Which flood parameter (peak, volume, etc.) is sought and with what degree of accuracy?
– What measuring stations lie within the area and what measurements are available?
– How big is the catchment?
– How much time and money is available for carrying out the estimation?

A practical aid with a description of selected models was drawn up (SPREAFICO et al. 2003) in order to make it easier to estimate flood discharge in practice. Two user-friendly computer programmes are available for using the models in small (< 10 km^2) and medium-sized (10–500 km^2) catchments (see Fig. 5-28).

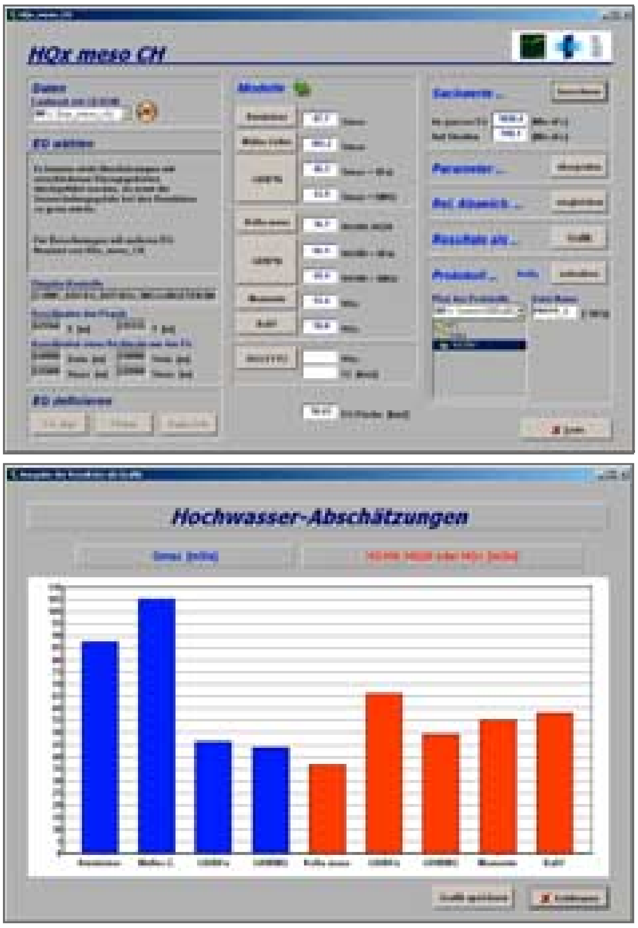


Fig. 5-28: Main screen (top) and diagram of results (bottom) of the HQx_meso_CH flood discharge estimation programme for catchments of between 10 and 500 km^2.

5.2.3 Estimating low-water discharge

In Switzerland many rivers, streams and lakes are influenced by a variety of water management or other structural features (see Section 5.4). As a resource, water is consumed more and more by the growing population and its needs and requirements. On the other hand, water reserves must be used in an ecologically responsible way. Fears generated by a rise in the frequency of extreme hydrological events – and connected with the threat of climatic change – have roused interest in low water levels, in view of possible scenarios regarding water management and protection.

Low water levels can be described in various ways (e.g. NMxQ = lowest mean discharge over x days within a year of low water levels). The Swiss parliament chose a discharge of Q_{347}, a value obtained from statistics and which is regularly given in annual hydrological reports. Art. 4 of the Water Protection Act defines Q_{347} as the discharge which, calculated over 10 years, is attained or exceeded on average during 347 days of the year and is not influenced to an important extent by the damming, diversion or addition of water. This definition implies that:

1. the discharge Q_{347} can be deduced from measurements,
2. the water course may not be subjected to undue unnatural influences, and
3. does not indicate a fixed observation period.

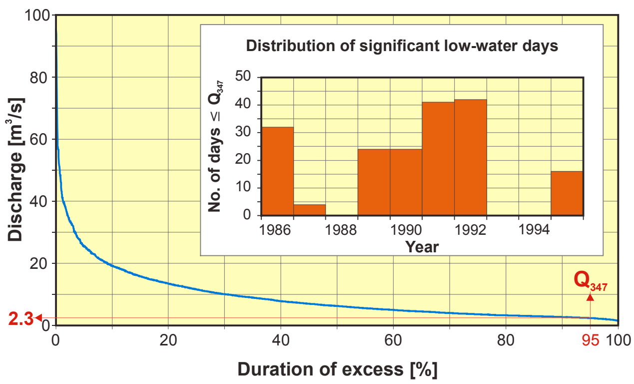


Fig. 5-29: Duration curve for the Thörishaus station on the R. Sense (1986–1995) and number of days in the calendar year when the Q_{347} 10-year mean of 2.3 m^3/s is not attained (after ASCHWANDEN & KAN 1999).

The discharge Q_{347} is obtained using a duration curve which corresponds to the volume of water that is reached or exceeded in 95% of all cases and therefore not reached in only 5% of cases (see Fig. 5-29). Figure 5-31 shows that the Q_{347} for individual years may be considerably more or less than the ten-year mean.

If there are no measurement series available or only very short ones, the Q_{347} has to be estimated. Federal offices have issued technical instructions to be followed in this case. The Swiss National Hydrological Survey has drawn up procedures for roughly estimating the Q_{347}, which it has published together with the SAEFL (ASCHWANDEN & KAN 1999, OFEFP 2000). A Q_{347} map has been created as a practical aid. Figure 5-30 describes the procedure for estimating the Q_{347}.

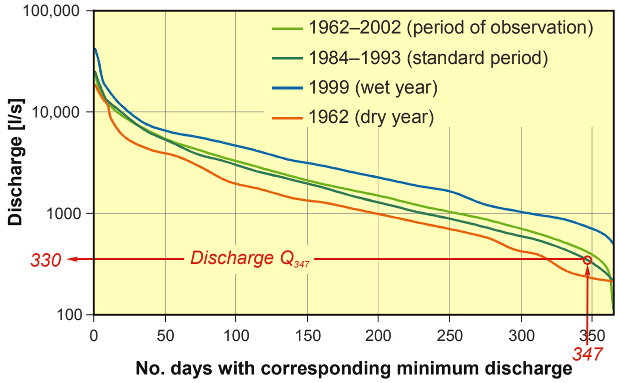


Fig. 5-31: Duration curve for the Hundwil station on the R. Urnäsch, canton of Appenzell Ausserrhoden (data: FOWG)

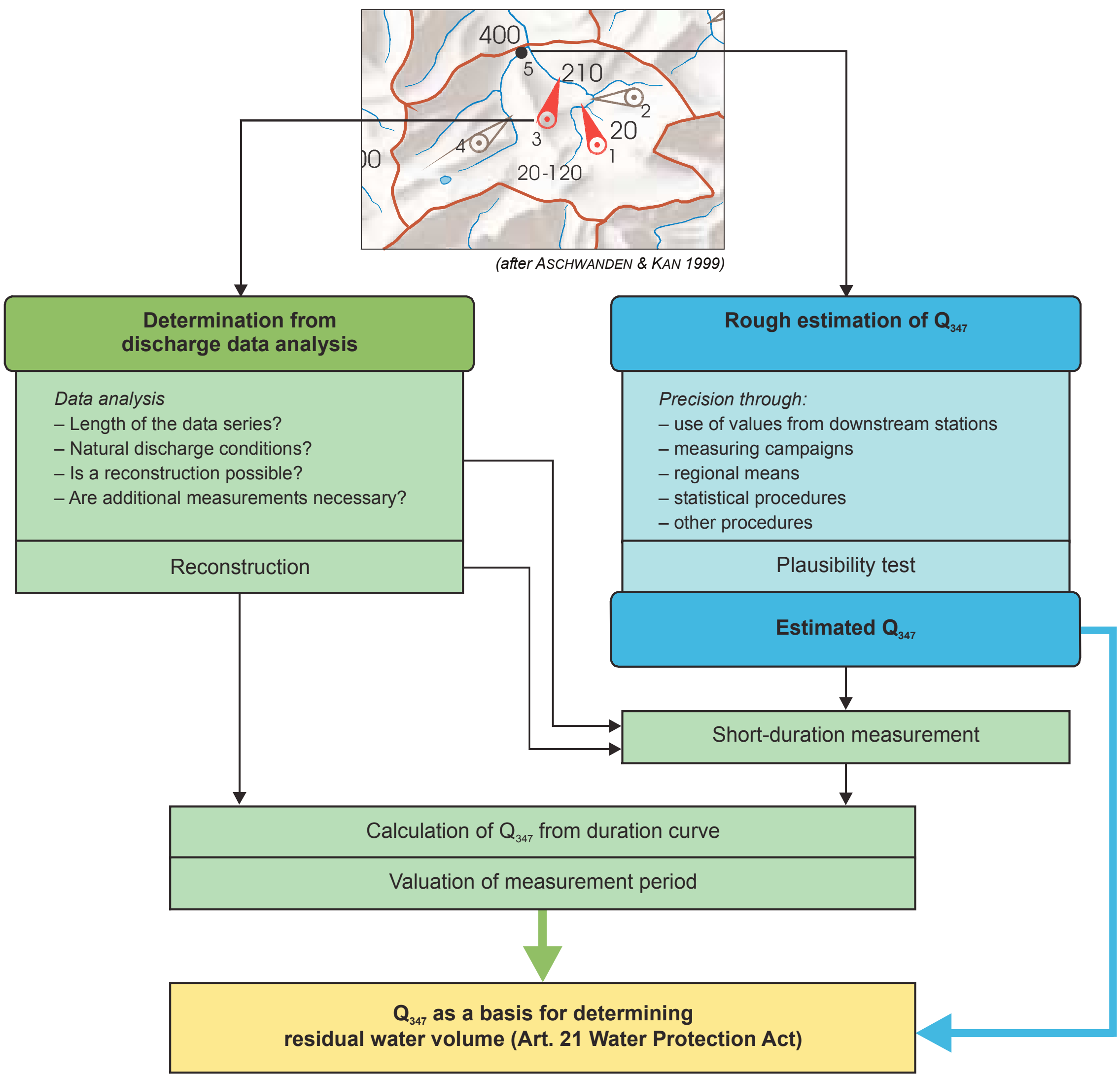


Fig. 5-30: Procedure for determining the discharge volume Q_{347} (after ASCHWANDEN & KAN 1999).

5.3 Discharge conditions in Switzerland

There is considerable natural variation in discharge from one year to another and from one area to another. There is, however, a degree of regularity that correlates with the altitude of the catchment.

5.3.1 Annual discharge

Each year 54,460 million m^3 of water flow out of Switzerland; at the same time 13,575 million m^3 of water flow into Switzerland from other countries. The balance of 40,885 million m^3 represents Switzerland's own contribution to the water cycle (figures for 1961–1990) (SCHÄDLER & WEINGARTNER 2002a).

Excluding inflow into Switzerland, the mean annual Swiss discharge is 1296 m^3/s (see Table 5-1). If this volume were distributed evenly across the 41,285 km^2 surface of the country it would correspond to a layer of 991 mm of water. This principle is used to compare discharge from different regions. Figure 5-32 shows area discharge from Swiss water balance areas.

Catchment	Area [km^2]	Area discharge [mm/y]	Discharge vol. [m^3/s]
Rhine	27,823	952	840
Rhone	7691	910	222
Ticino	3352	1458	155
Inn	1818	964	56
Adda	475	1360	20
Adige	126	836	3
Total Switzerland	41,285	991	1296

Table 5-1: Mean annual discharge from various catchments in Switzerland (1961–1990) excluding inflow from other countries (SCHÄDLER & WEINGARTNER 2002a).

Discharge is highest along the main ridge of the Alps with volumes of over 2000 mm per year. It is lower in the inner-Alpine valleys and the Central Lowlands. Discharge is below 300 mm per year along the Jura Mountains and in northern Switzerland.

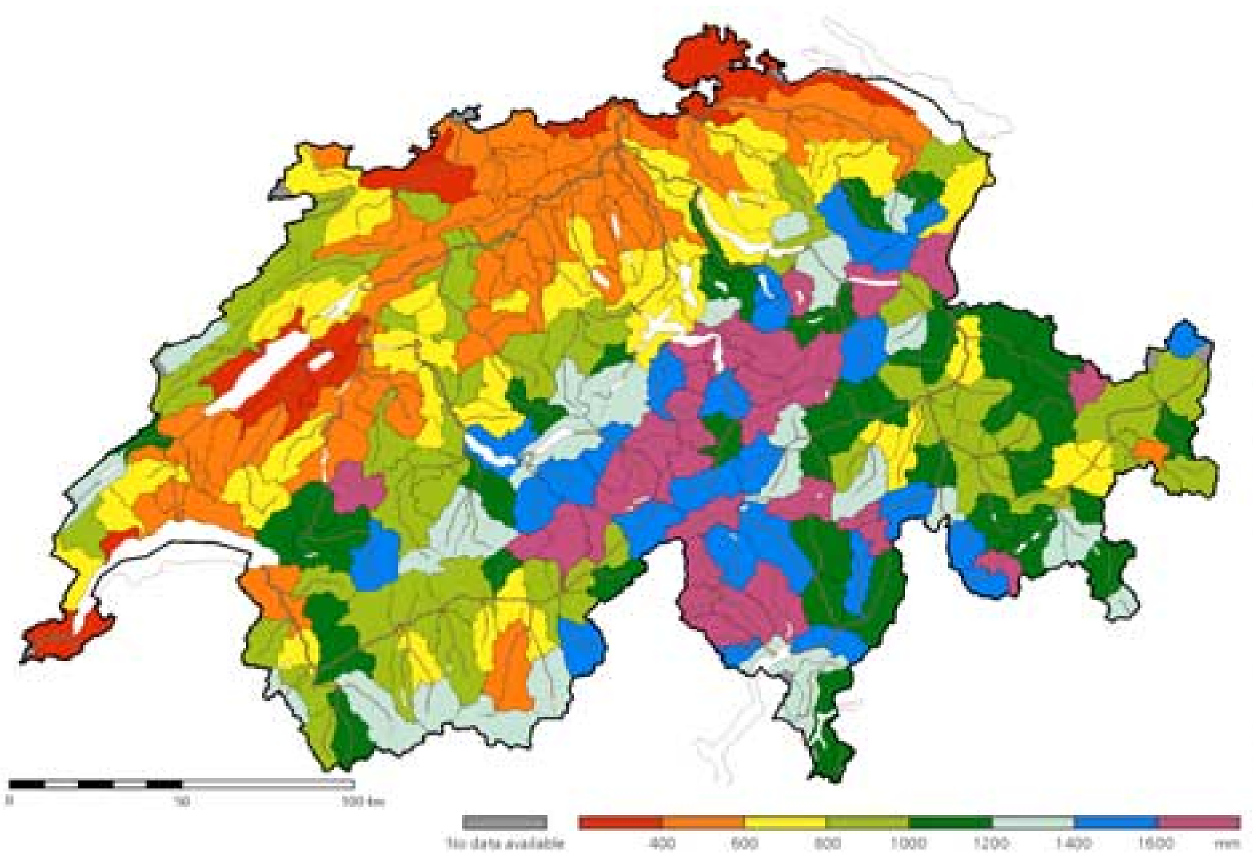


Fig. 5-32: Mean annual area discharge for the period 1961–1990 (after SCHÄDLER & WEINGARTNER 2002a).

5.3.2 Seasonal variation in discharge

The complex process of the formation of discharge can be determined through seasonal distribution. In the case of rivers whose catchments are largely in mountain areas, discharge formation is determined by accumulation and melting snow or glacier ice. The minimum discharge of the R. Massa in the Valais (mean altitude of the catchment 2945 m), for example, is in winter, when the majority of precipitation is retained; maximum discharge can be observed in summer, when melt waters account for a large part of the flow (see Fig. 5-33, left). In contrast the discharge of the R. Venoge (Vaud; mean altitude of the catchment 700 m) decreases gradually over the summer months, despite generally higher rainfall. The reason for this is that the vegetation consumes more water. In spring, when processes that increase discharge (high rainfall, contribution of melt-water, low rate of evaporation) are dominant discharge is at its maximum (see Fig. 5-33, right).

The monthly discharge rates are subject to characteristic seasonal variations that are described by so-called discharge regimes (WEINGARTNER & ASCHWANDEN 1992). The entire range of Swiss rivers and streams can be categorised under 16 different types of discharge regimes. Regimes with a single maximum are typical of the Alpine areas, where snow and ice dominate the seasonal variation. Regimes with more than one peak reveal the changing influence of snow, precipitation and evaporation. These types of regime are typical of catchments north of the Alps and below an altitude of 1500 m. On the southern side of the Alps the climatic particularities can be summarised in four distinctive types of discharge regime. In the case of longer rivers, the discharge regime may vary more than once between the source and the estuary (see Fig. 5-34).

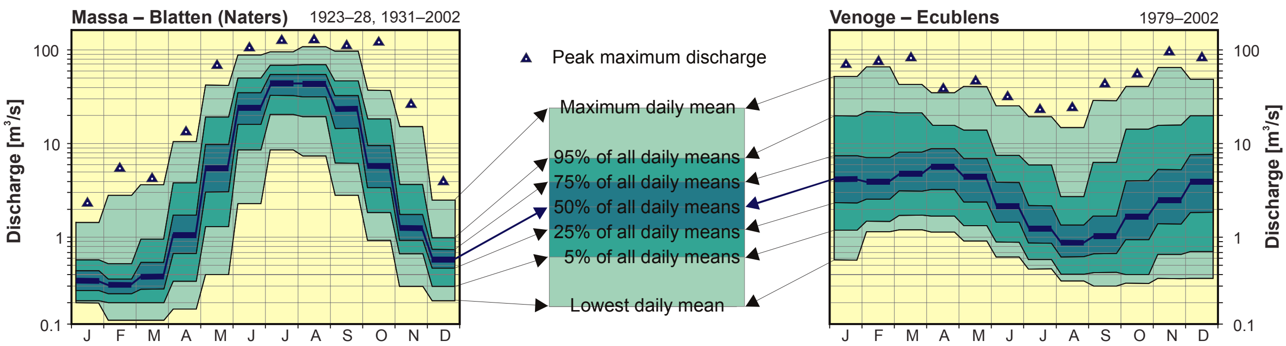


Fig. 5-33: Monthly distribution of mean daily discharge and peak maximum discharge (after OFEG 2003).

Fig. 5-34: Section of the discharge regime map (after WEINGARTNER & ASCHWANDEN 1992).

The regime is defined by determining the Pardé coefficient (PC_i) for each month. The Pardé coefficient shows the ratio of mean discharge in the month in question (MQ_i (month)) to mean annual discharge (MQ (year)).

$$PC_i = \frac{MQ_i\ (\text{month})}{MQ\ (\text{year})}$$

The Pardé coefficient of Swiss rivers varies between around 0.02 and 3.4.

5.4 Modification of the discharge pattern

Rivers have been used as communication routes and to drive machinery for many centuries and have been altered accordingly.

The major modifications to river systems and lake levels were carried out in the 19th century (see Figs. 5-35 and 5-36). In many places work to drain valley floors and dam tributaries was continued into the 20th century. Out of the largest lakes, Lake Constance, Lake Walen, Lake Sempach and Lake Hallwil still remain unaltered today. Rivers were dammed and straightened and the level of the lakes was controlled for several purposes:

- to improve protection against flooding,
- to reclaim areas of potential development,
- to reduce the risk of epidemic diseases,
- to optimise and use rivers as communication routes.

In the case of many rivers and lakes, harnessing to obtain drinking water and for other purposes including

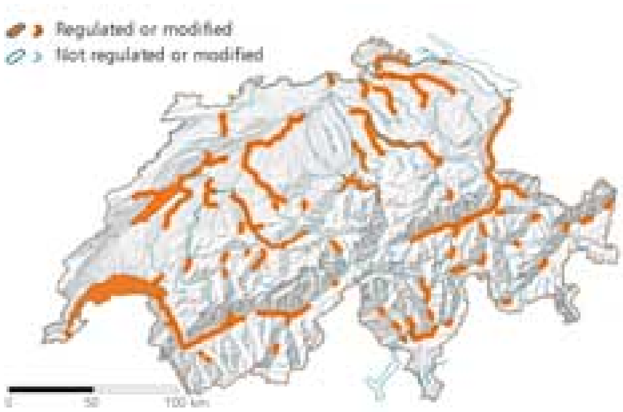


Fig. 5-36: Modification of rivers and lake levels during the 19th century (after GÖTZ 1988).

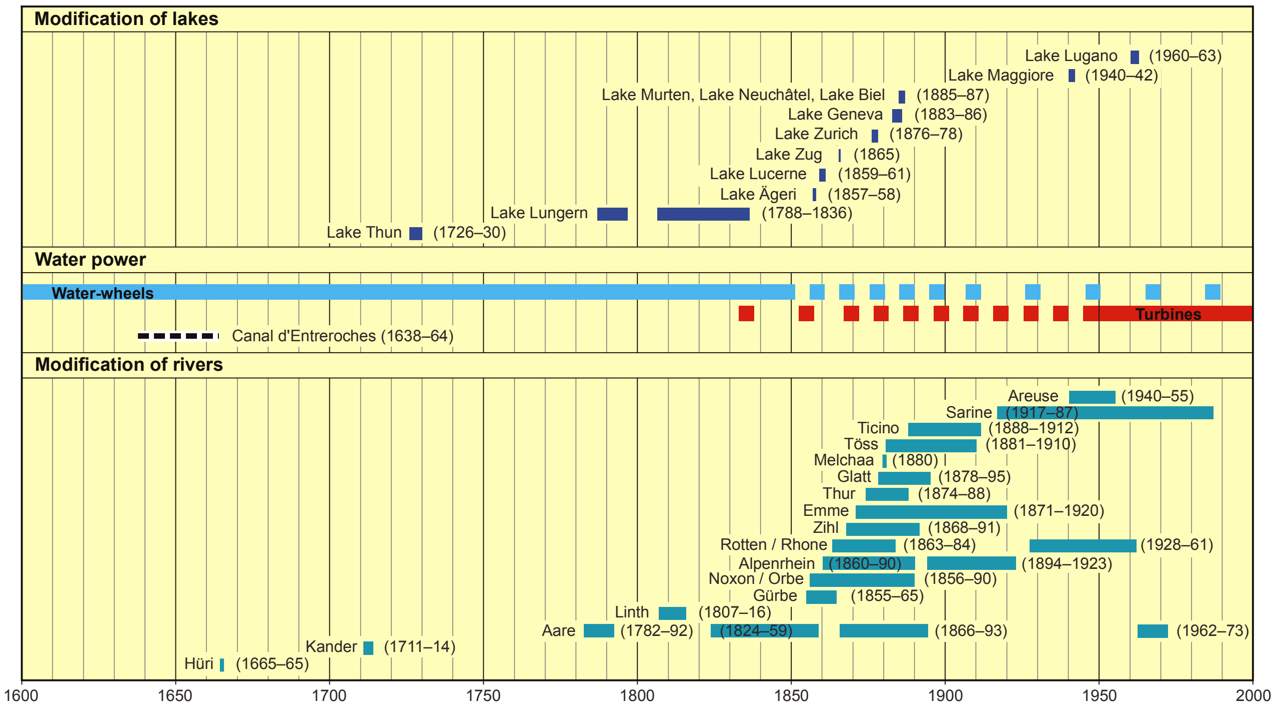


Fig. 5-35: Radical modification of the discharge patterns of Swiss rivers and lakes between 1600 and 2000 (sources: HÜGLI 2002, SCHNITTER 1992, VISCHER 1986).

water power accounts for the most important modification as far as water volume is concerned. Harnessing of rivers for hydro-electric power in the Alps and foothills expanded considerably between 1950 and 1970. An important aspect of how this influences discharge patterns is that water is taken out of the mainstream and fed back in later. Figure 5-37 shows the degree of influence observed after hydro-electric power stations have gone into operation.

The large rivers in the Central Lowlands show a slight shift in discharge from summer to winter (type D in Fig. 5-37) as a result of the storage of up to 3500 million m^3 of water in the main reservoirs and compensating reservoirs (useful capacity 1990). Above the lakes along the edge of the Alps this pattern shift is even more noticeable (type C). In places where the water is fed back into the river downstream from measuring points or into a different river (types B and A) there is a marked influence on the discharge pattern.

The fact that hydro-electric power stations operate to satisfy demand also affects daily discharge patterns. When there is a surge in demand for electricity, short-term changes in water level of up to 1 metre can be observed in some rivers downstream of the point where the water is fed back in from the power station.

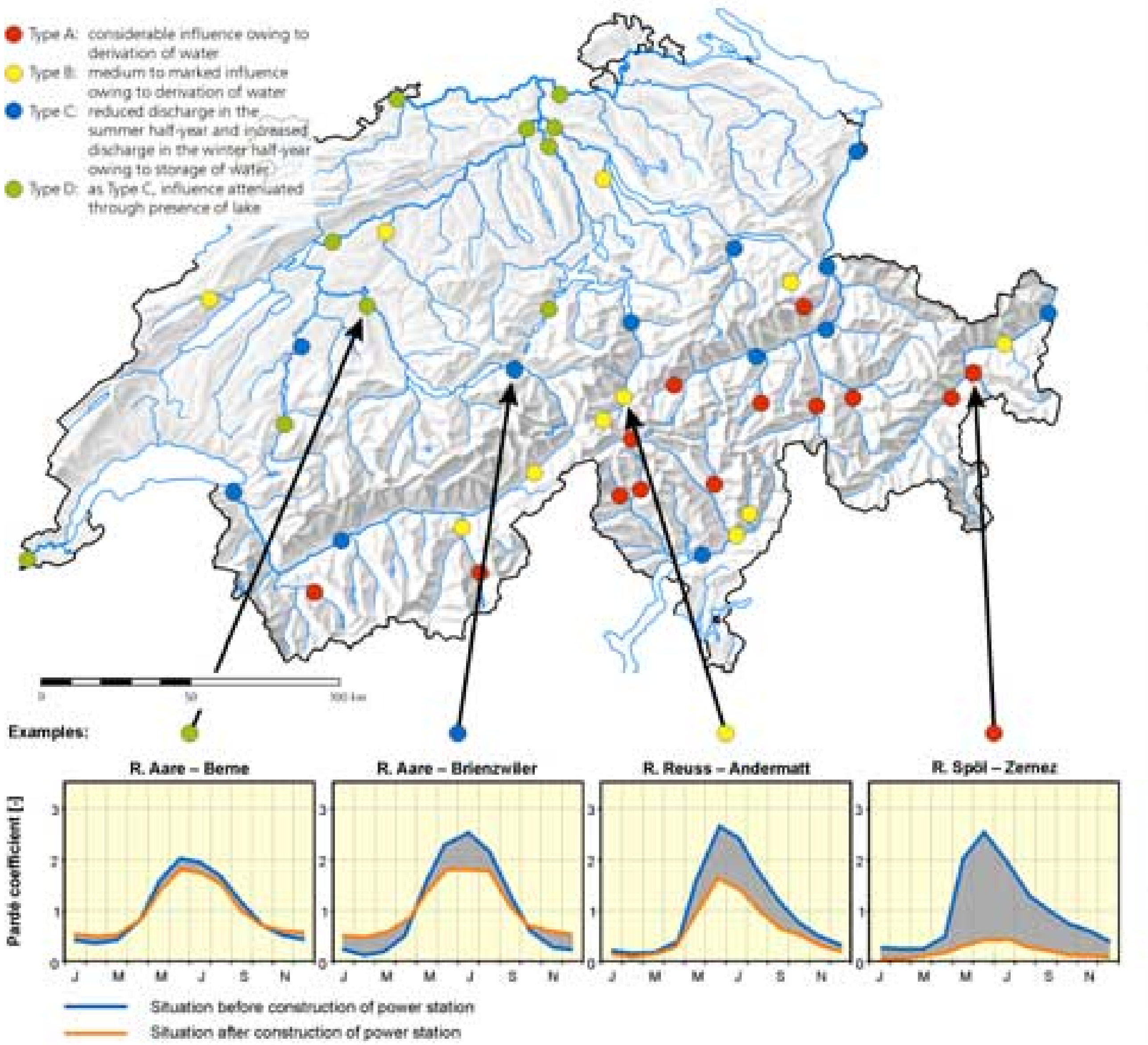


Fig. 5-37: Influence of power stations on river discharge patterns (after MARGOT et al. 1992).

5.5 Floods

In extreme situations the mean discharge rates are massively exceeded. It is essential that extreme events are taken into account when hydro-engineering measures are planned. In Switzerland extreme flood levels can be traced back over several hundred years.

5.5.1 Information about flood discharge rates

Information about flood discharge rates is an essential basis for communities that live near rivers and engineering works carried out along rivers. Flood level markers (see Fig. 5-40) and a large number of historical reports are evidence of attempts to ensure that information about extreme events is not lost and to prepare future generations for the possibility of rare flood levels (see Fig. 5-38). Since the 19th century empiric formulae have been used to estimate maximum discharge that can be expected (Q_{max}) in any given catchment. Figure 5-39 shows a selection of such envelope curves which all give the Q_{max} for a catchment area (Fn). Out of all these “traditional” approaches, Hofbauer’s envelope curve formula (1916) would appear to be most appropriate for describing conditions in Switzerland:

$$Q_{max} = 42 \cdot Fn^{0.5}$$

Further statistical characteristic values for flood probability can be calculated or estimated within the framework provided by Q_{max} (see Section 5.2.2). The longer the measurement series the greater the probability that it includes extremely rare events. The HQ_{100} calculated using extreme value statistics from the 99-year measurement series (1897–1995) for the R. Emme at Emmenmatt was 396 m^3/s (GEES 1997). This figure was exceeded twice during the 20th century (see Fig. 5-38). If later flood discharge rates are taken into account (1897–2003) the HQ_{100} rises to a more plausible figure of around 450 m^3/s.

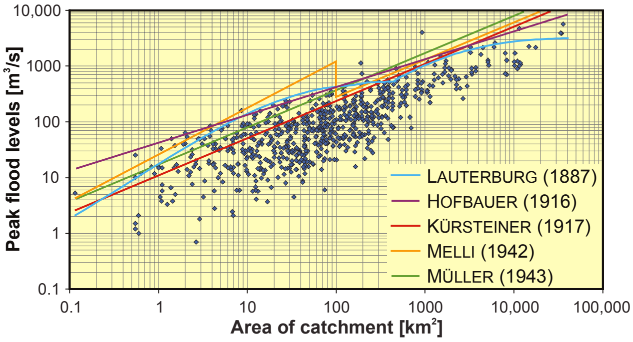


Fig. 5-39: Envelope curves for maximum expected peak flood levels (Q_{max}) according to various authors in comparison with summarised peak discharge levels observed in Switzerland (after WEINGARTNER 1999).

Fig. 5-40: Flood level marker on the shore of Lake Lucerne.

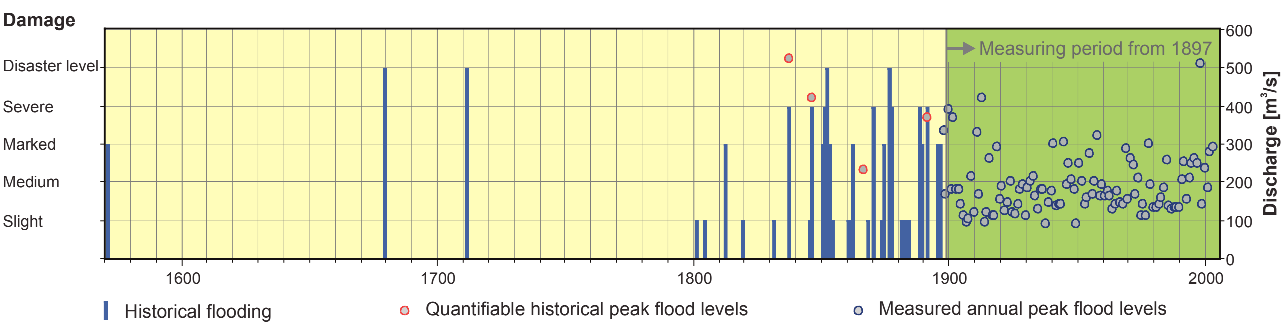


Fig. 5-38: Flooding of the R. Emme: historical flooding with recorded extent of damage within the catchment or known peak discharge rate and peak annual flood maxima measured at the Emmenmatt station (data: FOWG, GEES 1997).

5.5.2 How major flooding comes about

With the exception of abrupt waves that are created when stored water is released, for example, natural flooding is a reaction to precipitation. Whether high rates of precipitation will lead to flooding depends to a large extent on the development pattern and the consequent hydrological situation in a catchment, however.

In the case of large rivers, flooding is normally caused by intensive precipitation over a long period of time. An impressive example was the 100-year flooding of the R. Aare in May 1999 (see Fig. 5-41). The continuous rainfall from 11 to 15 May 1999 along the northern side of the Alps led to exceptional levels in many rivers and lakes, the like of which is only seen every 20 years or more. New record levels were observed at 32 measuring stations; discharge of the R. Aare in Thun, for example was 40% above the previous record, namely 570 m^3/s.

The development pattern was a decisive factor in the flooding of May 1999. In April it rained for 20 days and 50 to 100% more precipitation was recorded than the long-term mean. This caused the ground to become saturated. Between 25 April and 10 May the dominant factor in the discharge rate was the snowmelt, which was marked even at higher altitudes. When the rain started on 11 May the ground was already saturated and certain lakes were already full to bursting point (BWG 2000).

The discharge from small and medium-sized catchments is more susceptible to intensive but short rainstorms. The flooding of the R. Biembach (canton of Berne) on 1 July 1987 was also caused by a combination of unfavourable factors. As a result of storms during the previous week the storage capacity of the ground in the catchment was already almost at its limit. It could retain only a small part of the intensive rainfall that started shortly before 2 pm when two thunderstorm cells met over the Biembach catchment (around 10 km^2). There was an immediate reaction in the Biembach and the discharge rate reached a peak of about 50 m^3/s before 3 pm (see Fig. 5-42) (GEMEINDE HASLE BEI BURGDORF 1992).

5.6 Formation of discharge

The ground is of key importance in the formation of discharge. The distribution of soils with dominant discharge processes (see Section 5.6.1) is a decisive factor in how the discharge from a catchment will react (see Section 5.6.2). In a water channel the discharge hydrograph is affected by the roughness of the surface (see Section 5.6.3) and retention (see Section 5.6.4).

In general, the first few millimetres of precipitation cling to vegetation and never reach the ground (see Section 2.5.1). As much as 5 mm of rainfall are needed to moisten the soil under a dry conifer in the summer. In order to fill the storage capacity of the surface soil and deeper layers to such an extent that they no longer retain water a certain volume of water is needed. This depends on the intensity of the precipitation and the hydrological condition of the catchment at the time, as well as its characteristics (KÖLLA 1987). If more water is available than plants, surface soil and deeper layers can store, the excess is discharged.

Fig. 5-41: Flooding in Berne in May 1999.

Fig. 5-42: Flooding of the Biembach (BE) on 1 July 1987.

5.6.1 Discharge processes

The main discharge processes can be differentiated using diagrams of ground profiles (see Fig. 5-43). Hortonian surface discharge occurs when precipitation exceeds the infiltration capacity of the ground. Where the ground is covered with vegetation this rarely occurs, except where it has been compacted or is hydrophobic and therefore absorbs very little water. Saturation surface discharge occurs when the ground is saturated. This happens particularly fast in flat or marshy areas that have low storage capacity. As far as concerns subterranean discharge, a distinction must be made between the slow movement of water determined to a large extent by capillary action (general seepage) and the faster discharge along macropores (e.g. tunnels dug by fauna or hollows created by roots) that is dependent on gravitational forces. Subterranean discharge is also faster when highly porous strata lie above an impermeable layer.

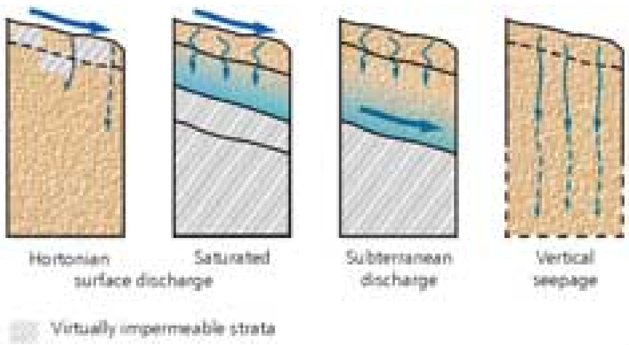


Fig. 5-43: Discharge processes and different types of reaction to intense rainfall (after SPREAFICO et al. 2003).

If the soil is porous and lies above a permeable geological structure a large amount of water can seep down vertically and be stored. After a certain time this water can then come to the surface in springs or groundwater eruptions.

5.6.2 Reaction of catchment discharge

In a catchment the various discharge processes occur simultaneously and overlap one another. Moreover, the hydrological status of the soil changes during rainfall with corresponding effects on the discharge process that is dominant at the time. The further formation of discharge will be affected by raindrop size, intensity and duration. Test zones are used to quantify the relative importance of each process, which can then be illustrated in discharge reaction curves.

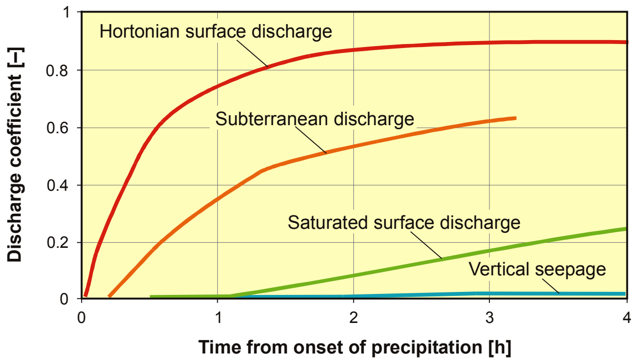


Fig. 5-44: Discharge reaction curves at four locations with typical discharge reactions (after NAEF et al. 1999).

Figure 5-44 shows discharge reactions from four test zones with the dominant process. The discharge coefficient indicates the ratio of discharge to precipitation. A coefficient of 0.6 indicates that 60% of the precipitation is discharged.

- Hortonian surface discharge: extremely fast reacting surface with low retention, as observed in wet areas along rivers.
- Subterranean discharge: fast discharge reaction and moderate retention, occurs for example in steep slopes above rivers.
- Saturated surface discharge: delayed reaction with high level of retention, typical of slopes away from rivers.
- Vertical seepage: greatly delayed reaction with high level of retention; typical of almost flat areas with deep soil layer far away from rivers.

By extrapolating discharge reactions observed in test zones to larger areas the discharge reaction can be estimated for whole catchments (see Fig. 5-45).

5.6.3 Flow resistance

Hydraulic calculations must take into account the degree of roughness of the water channel. In contrast to man-made channels, for which roughness coefficients can be found in tables, it requires years of experience to estimate the roughness of natural water channels. As far as Switzerland is concerned, the

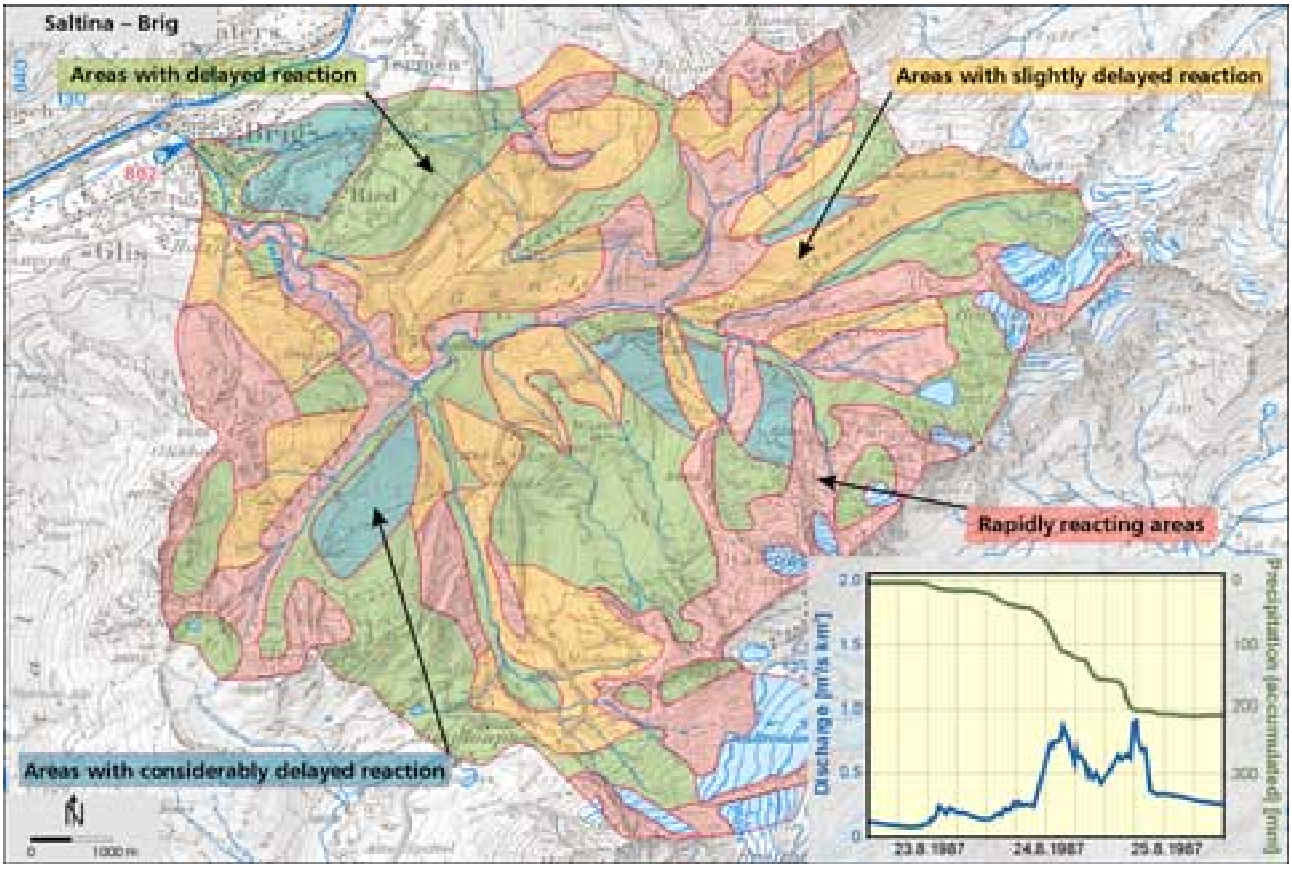


Fig. 5-45: Areas of varying discharge reaction within the Saltina catchment near Brig (Valais). The discharge reaction of the whole catchment is delayed and moderate (see diagram of measured flooding in August 1987) (after NAEF et al. 1999).

roughness coefficient (k_{St}) was determined for a series of selected sample stretches of river in 2001. Eight small rivers and 4 stretches of mountain streams were studied (see Fig. 5-46). The banks along the 8 test stretches on the small rivers were sloping, with no flat riverbanks. In most cases the banks had been artificially strengthened and were partially covered with vegetation. The gradient, the modification of the banks and the composition of the bed load varied. Stretches were chosen where flow conditions were similar and there was no local loss of flow due to bridge piers or widening out, for example.

High flow resistance is expressed in low k_{St} values. The resistance coefficient in one and the same river may vary depending on the discharge volume (see Table 5-2). In rivers with a mountain character k_{St} values rise as discharge rises, which implies a lessening of the flow resistance. In rivers with little gradient the k_{St} values fall when discharge rises, however (greater flow resistance).

Test stretch	**Discharge [m^3/s]**	**k_{St} [m$^{1/3}$/s]**
Minster – Euthal	30	36
	60	38
	100	38
	140	38
Suze – Sonceboz	10	29
	20	29
	40	36
Emme – Burgdorf	100	32
	250	31
Gürbe – Belp	4.3	32
	20	33
	30	31
	40	30
	50	28
Lütschine – Gsteig	60	24
	90	26
	120	27

Table 5-2: Examples of flow resistance with different discharge volumes (SPREAFICO et al. 2001).

Fig. 5-46: Rivers where stretches were used to study flow resistance (after SPREAFICO et al. 2001).

5.6.4 Retention

The retention of part of the discharge within the catchment leads to a reduction in the peak discharge rate. A typical type of retention is the flooding of the valley floor (see Fig. 5-47), but under certain circumstances the channel itself can have an attenuating effect on peak flood levels.

Flooding of the valley floor is the most effective type of retention; its effect should not be overestimated, however (NAEF & THOMA 2002). Large rivers can flood for several days. Effective retention over such a period requires floodplains of a size that cannot be found in Switzerland.

Effective retention within the channel is possible in the following cases:

– Gradient < 1%: in steep channels a reduction in the flow velocity can only be observed at the front of the flood. The velocity of the following water is accelerated and if the water channel is long enough a vertical flood wave will form.
– Roughness coefficient (k_{St}) < c. 25: the rougher the channel the greater the retention.
– Increase in volume of up to 1 hour: the faster the discharge volume rises the more the peak discharge within the channel is attenuated.

These prerequisites are fulfilled in surprisingly few catchments, with the result that natural retention rarely plays an effective role in reducing major flooding (NAEF & THOMA 2002).

An exception was the flooding of the R. Gürbe (canton of Berne) on 29 July 1990. Within only a few hours 240 mm of rain fell in the upper section of the Gürbe catchment. In the steep upper reaches of the river discharge increased immediately (see Fig. 5-48, Burgistein measuring gauge). In the flatter lower reaches between Burgistein and Belp there was a degree of channel retention, with the result that maximum discharge as far down as Belp dropped. In July 1990 large areas were flooded too, which also helped to reduce the maximum discharge. It was estimated that of the total attenuation of 51 m^3/s, 5 m^3/s could be accounted for by channel retention, and 46 m^3/s by flooding.

Fig. 5-47: Flooding of the floodplain: the R. Doubs near Ocourt (canton of Jura) on 13 March 2001.

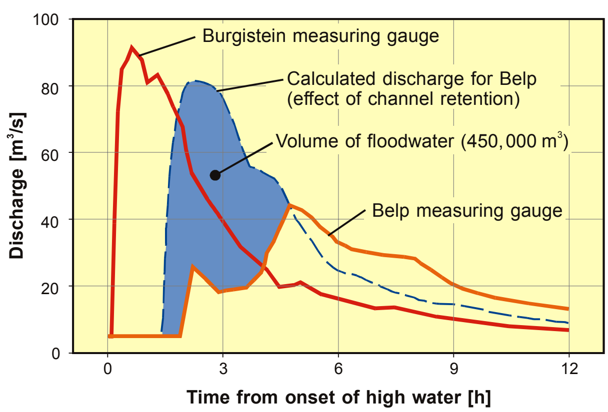


Fig. 5-48: Attenuation of maximum discharge on 29 July 1990 in the lower reaches of the R. Gürbe (canton of Berne) (after NAEF & THOMA 2002).

5.7 Predicting floods

Today hydrological predictions are an important basis for planning the economic exploitation of the River Rhine for hydro-electric power as well as for planning and organising the transport of important commodities. The countries downstream use the results of Swiss predictions as basic parameters for their own prediction models.

The Swiss National Hydrological Survey uses the HBV3-ETHZ model to predict discharge for the Rhine catchment downstream from the lakes along the perimeter of the Alps. At present work is being carried out on extending this to cover the whole Rhine catchment. No predictions are published for smaller river catchments and streams.

Measured mean hourly discharge rates, hourly temperatures and precipitation measured by the MeteoSwiss automatic network and hourly data obtained from high-resolution, numerical weather forecasting models constitute the database for these predictions. This is the first time that an operational discharge prediction model has been coupled with a numerical weather forecasting model in Switzerland.

All data are entered into a database, checked, monitored for plausibility and processed for input into the model (see Fig. 5-49). Discharge rates are normally calculated daily. In situations of extreme flooding new forecasts are drawn up every two hours for the Rheinfelden and Rekingen stations on the R. Rhine, the Andelfingen station on the R. Thur, the Mellingen station on the R. Reuss and the Brugg and Murgenthal stations on the R. Aare.

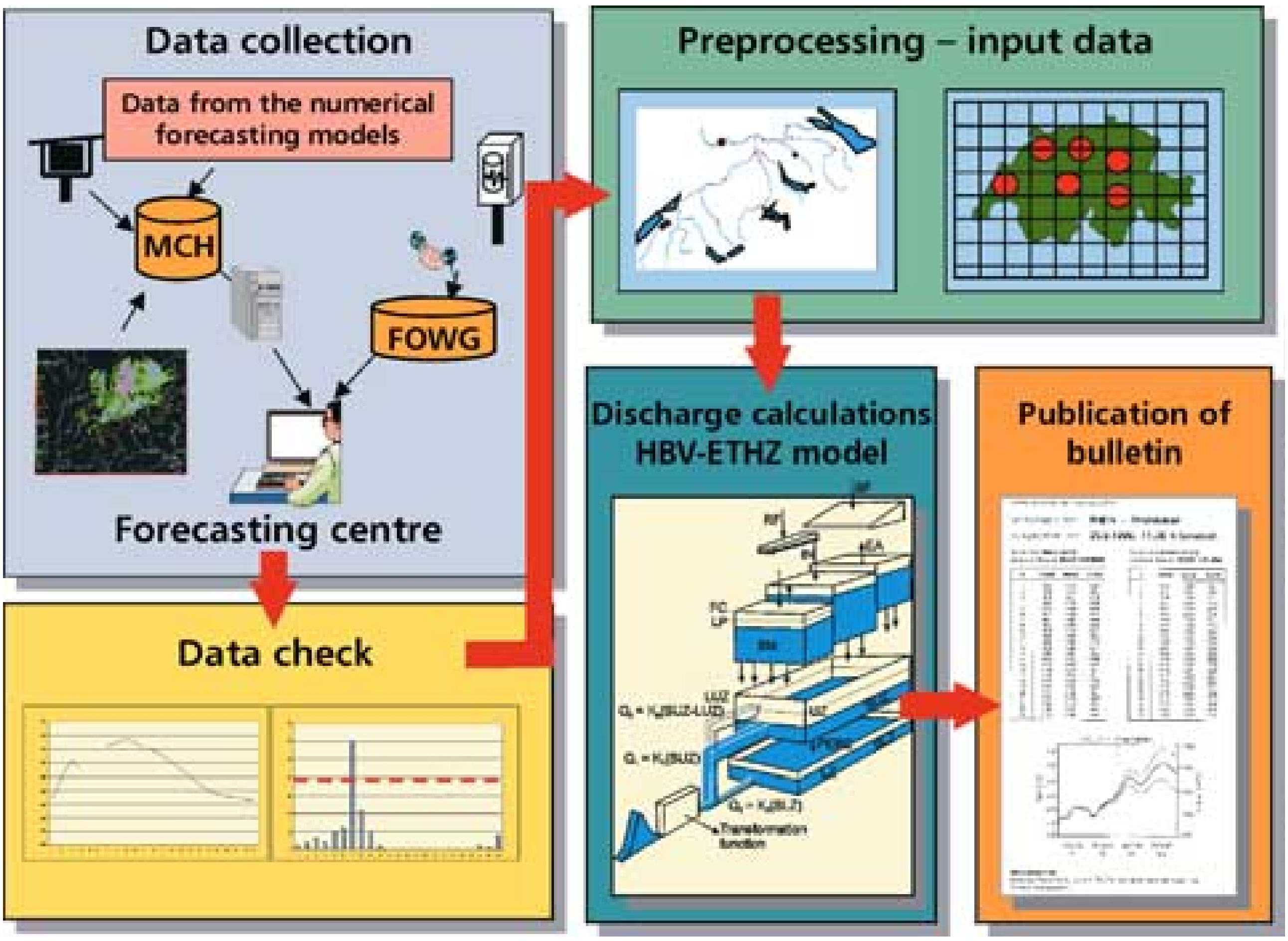


Fig. 5-49: Operational discharge predictions (graph: T. Bürgi, FOWG).

The bulletins concerning water level and discharge predictions provide a numerical and graphical overview of the river data measured over the previous hours and of the expected changes in water level and discharge. This information is drawn up in the form of hourly means for three calendar days (see Fig. 5-50). Forecast bulletins are available to the public at www.bwg.admin.ch.

Bundesamt für Wasser und Geologie - Landeshydrologie, 3003 Bern-Ittigen

Vorhersage für: **RHEIN - Rheinfelden**

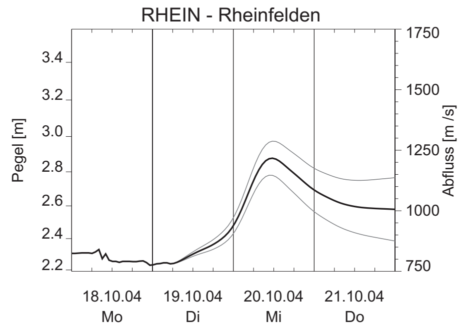
ausgegeben am: 19.10.2004, 8.16 h Lokalzeit

Stundenmittel **Abfluss [m /s]**
gemessene Werte bis **19.10.04, 6.00 MEWZ**

H	19.10.04	20.10.04	21.10.04
1	777	950	1079
2	781	977	1071
3	782	1008	1063
4	785	1042	1056
5	785	1076	1049
6	781	1110	1043
7	783	1142	1037
8	788	1169	1032
9	794	1191	1027
10	801	1206	1024
11	809	1215	1021
12	816	**1217**	1018
13	824	1213	1016
14	830	1205	1014
15	837	1194	1012
16	843	1182	1011
17	849	1170	1010
18	856	1158	1010
19	864	1146	1009
20	873	1134	1008
21	883	1122	1008
22	895	1110	1007
23	910	1098	1006
24	928	1088	1006

Stundenmittel **Wasserstand [m]**
gemessene Werte bis **19.10.04, 6.00 MEWZ**

H	19.10.04	20.10.04	21.10.04
1	2.23	2.50	2.68
2	2.24	2.54	2.67
3	2.24	2.58	2.66
4	2.25	2.63	2.65
5	2.25	2.68	2.64
6	2.24	2.73	2.63
7	2.24	2.77	2.62
8	2.25	2.81	2.62
9	2.26	2.84	2.61
10	2.27	2.86	2.61
11	2.28	2.88	2.60
12	2.30	**2.88**	2.60
13	2.31	2.87	2.59
14	2.32	2.86	2.59
15	2.33	2.85	2.59
16	2.34	2.83	2.59
17	2.35	2.81	2.59
18	2.36	2.80	2.58
19	2.37	2.78	2.58
20	2.38	2.76	2.58
21	2.40	2.75	2.58
22	2.42	2.73	2.58
23	2.44	2.71	2.58
24	2.46	2.70	2.58



Wetteraussichten
19.: Stark bewölkt oder bedeckt und zeitweise Regen. Schneefallgrenze von 2000 bis gegen 2500 Meter steigend.
20.: Vor allem im Westen gelegentlich Regen, im Osten föhnige Aufhellungen.
21.: Wechselnd bewölkt und am Vormittag etwas Regen.
---------------------normaler Vorhersagedienst-----------------

Fig. 5-50: Example of a weather forecast bulletin (www.bwg.admin.ch).

6 Lakes

Statistics				
Largest lake (surface area)	581.3	km^2	Lake Geneva	Source: FOWG
Deepest lake	310	m	Lake Geneva	Source: FOWG
Greatest volume	89,900	million m^3	Lake Geneva	Source: FOWG
Largest reservoir (volume)	401	million m^3	Grande Dixence (VS)	Source: FOWG
Longest theoretical time water remains in place	15	years	Lake Sempach	Source: LIECHTI 1994
Oldest sluice	1592		Lake Zug	Source: VISCHER 2003

6.1 The characteristics of lakes

Lakes are non-flowing water bodies in which layers of water of stable temperature occur over a longer period during the summer months. This is generally true if the mean depth of the lake is about 14 m or more. Relatively shallow natural lakes are called ponds, artificially dammed lakes reservoirs. Layers of water of different temperatures can also occur in reservoirs in the summer.

6.1.1 Lake zones

Figure 6-1 shows the different zones of a lake: the lake shore (littoral), the open water (pelagic) and the bed of the lake. The shore is a transitional zone between land and water and fulfils an important function owing to the shallowness of the water. It is here that biodiversity is at its greatest. At the same time this zone is extremely vulnerable owing to stabilisation measures, exposure to artificial waves and overuse by bathers.

The open-water zone includes those parts of the lake where there is no bed vegetation owing to the depth of the water. A large number of minute organisms (plankton) live in the uppermost layer of open water, which is perfused with light. This plankton is the basic food of many fish. A certain amount of dead plankton will sink to the bed of the lake where it is broken down by microorganisms and creatures that live on the bed of the lake. The mineralised nutrients are then released for primary production or are absorbed into the sediment.

6.1.2 Layers of water and circulation

Water is heaviest at a temperature of 4°C (see Fig. 6-2). While in the spring the temperature is normally the same at all levels in a lake, the uppermost layer (epilimnion) is quickly warmed by the sun and floats on the cooler water below (hypolimnion). A third, transitional layer forms between the epilimnion and the hypolimnion which is called the metalimnion, where there is a marked reduction in temperature from top to bottom. There is very little exchange of gases between the epilimnion and the hypolimnion (stagnation) (see Fig. 6-3).

As the air temperature falls in autumn the lake starts to lose heat from its surface. Strong winds help to mix the cooling water masses. It is only when the temperature throughout the lake is similar that full circulation is possible. The whole bed of the lake is then supplied with oxygen and nutrients once again.

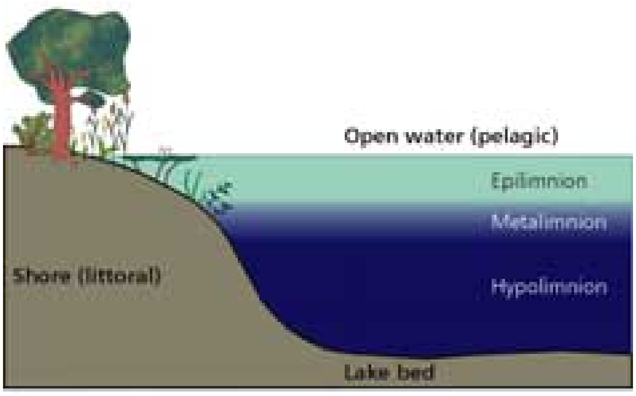


Fig. 6-1: Diagram of the different vertical zones in a lake (after LIECHTI 1994).

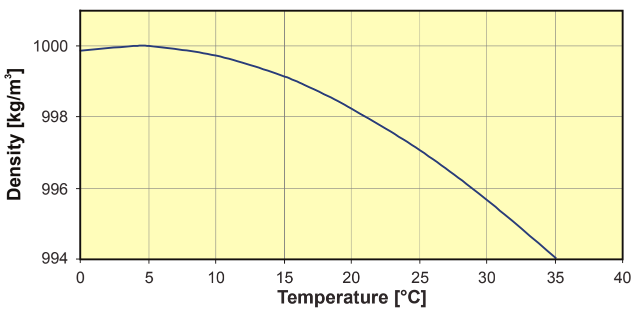


Fig. 6-2: Water density.

If the cooling process continues an inverse temperature layering occurs: water with a temperature of below 4°C is lighter and will float above the warmer water. If the surface water reaches a temperature of 0°C the lake will start to freeze from the surface down (see Fig. 6-5). This happens relatively rarely in lakes at lower altitudes. The temperature of the water on the lake bed will stay at +4°C, thus enabling flora and fauna to survive. With the arrival of spring and the warming process, the cycle will start all over again (LIECHTI 1994).

Not all lakes experience full circulation of water every year (see Section 6.5.3). The last full circulation of water in Lake Geneva, for example, was observed in 1986 (CIPEL 2004). Figure 6-4 shows the marked seasonal influence on the layers of water of different temperatures in the upper 60 m or so of Lake Geneva.

Apart from layers of different temperature, there can also be layers of water with a different chemical composition. The chemical composition of two layers of water can be so different that they will not mix. It is for this reason that in the northern basin of Lake Lugano only the upper 100 m of water at the most circulates; there is no oxygen input into the water beneath (see Fig. 6-13) (LIECHTI 1994).

6.2 The formation of lakes

Various factors may cause the formation of lakes. Often various factors are combined. The creation of a lake signifies the start of silting up by sedimentation.

6.2.1 The creation of a lake

Most of the lakes in the Swiss Central Lowlands were formed by advancing glaciers during ice ages. During this process, existing depressions were deepened and enlarged through erosion by the ice mass. The longer dimension of the lakes normally indicates the direction of flow of the glacier. When the glaciers started to melt these depressions filled with melt-water. Further water was retained behind the terminal moraine, as we can see in the present-day Lake Constance and Lake Sempach, for example (LIECHTI 1994).

There are lakes within the Alps that have been formed by water collecting behind a mass of rubble brought down by a rockfall. Lake Derborence, for example, formed after the largest rockfall in the modern history of Switzerland (23 June 1749).

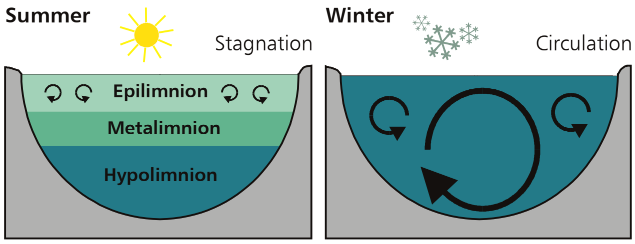


Fig. 6-3: Explanatory diagram of water cirulation and temperature layers (after www.gewaesserschutz.zh.ch).

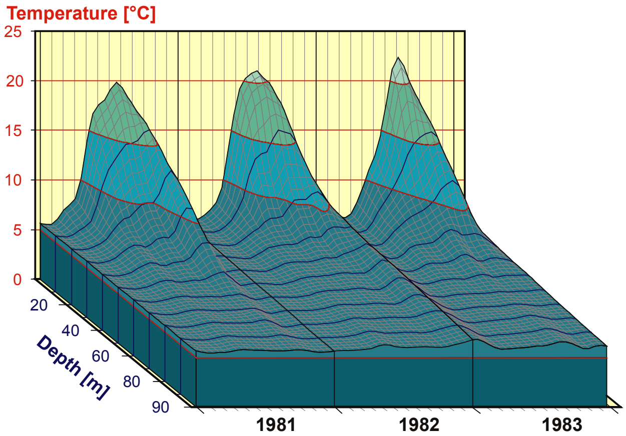


Fig. 6-4: Temperature profile of Lake Geneva 1981–1983 (after DE MONTMOLLIN & JAKOB 1995).

Fig. 6-5: Frozen lake 2002 (L. Pfäffikon).

The oldest lakes in Switzerland came into being some 10,000 years ago; most lakes were formed much more recently, however. In contrast, it is estimated that Lake Baikal in Siberia dates from between 20 and 25 million years ago. Table 6-1 shows a selection of possible causes and corresponding examples of the formation of lakes.

Factor	Example
Tectonic processes	
Lake on a tectonic fault line	L. Baikal (Siberia)
Syncline valley lake	L. de Joux (Switzerland)
Volcanic activity	
Crater lakes	L. Albano (Italy)
Crater caused by a meteorite	
Crater lake	L. Manitoba (Canada)
Dissolving of rock	
Subterranean lake	L. St. Léonard (Switzerland)
Glacial processes	
Eroded basin	L. Thun (Switzerland)
Erosion and retention by terminal moraine	L. Greifen (Switzerland)
Retention behind lateral moraine	L. Übeschi (Switzerland)
Dead ice	L. Burgäschi (Switzerland)
Accumulation of debris	
Rock fall	L. di Poschiavo (Switzerland)
Man-made	
Reservoir	L. Gruyères (Switzerland)
Gravel pit	Meienried pit (Switzerland)

Table 6-1: Factors leading to the formation of lakes and some examples (after DOKULIL et al. 2001, with additions).

6.2.2 Silting up

When a lake is formed it automatically entails the start of a process of silting up. Where tributaries flow into the lake, bringing sediment and suspended particles (cf. Chapter 8), they create deltas; the lake becomes smaller and shallower. For example, at the end of the last Ice Age (around 10,000 years ago) one single lake stretched from Meiringen to beyond Thun, covering what are today Lake Thun and Lake Brienz. Since then, tributaries flowing into the lake have brought sediment with them that has filled up large areas of the original lake, and in around 36,000 years' time Lake Thun will be totally silted up (cf. Table 6-2).

In the case of naturally dammed lakes, erosion of the lake bed around the outflow can lower the level of the lake quite suddenly, thus reducing the overall area of the lake. Figure 6-6 shows the morphological development of Lake Greifen over the last 11,000 years or so.

The successive shrinkage of the surface area of the lake has been caused by:

– erosion of the lake bed by 18 m around the outflow; the terminal moraine of a lateral arm of the Ice-Age Rhine–Linth glacier was eroded,
– deposit of debris by streams flowing into the lake, and
– artificial lowering of the level of the lake by 40–90 cm as part of the Glatt hydroengineering works carried out in 1890/91 (MEIER BÜRGISSER & KELLER 2004).

Lake	Volume of lake [million m³]	Annual increase in sediment [million m³]	Duration of silting [1000 years]
L. Constance	48,000	3.3	14–15
L. Geneva	89,900	1.8–3.0	30–50
L. Thun	6500	0.18	36
L. Walen	2490	0.2	12–13
L. Biel	1240	0.36	3–4
L. Pfäffikon	58	0.0038	15
L. Oeschinen	37	–	2.6

Table 6-2: Estimated silting time. Only sediment brought in by main tributaries has been taken into acocunt (data: FOWG, GUTHRUF et al. 1999, IGKB 2004, LIECHTI 1994).

Apart from the fact that bed load and suspended particles are brought into the lake by tributaries, organic material produced in the lake itself is incorporated into

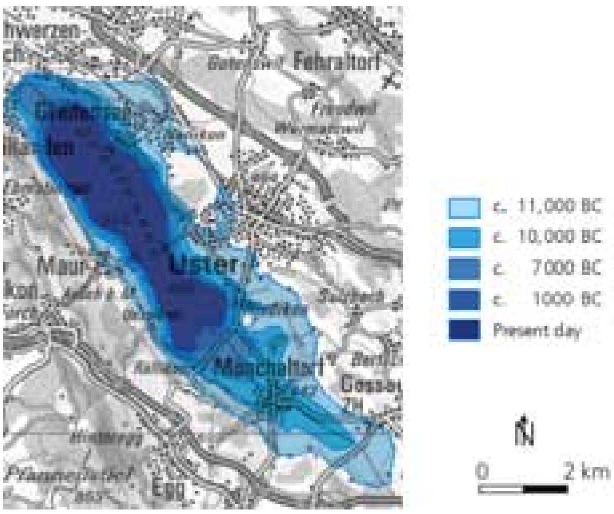


Fig. 6-6: Change in the shape of L. Greifen over time (after MEIER BÜRGISSER & KELLER 2004).

the sediment and thus contributes to the filling process. Towards the end of its existence, the lake is taken over by vegetation growing along the shoreline and in the lake itself. It is considered filled in when the entire area of the lake has become a bog (BINDERHEIM-BANKAY 1998).

6.2.3 Lakes in Switzerland

Switzerland has 70 natural lakes with a surface area of over 0.1 km^2. Lakes account for a total area of 1422 km^2 or around 3.5% of the country (www.statistik.admin.ch). Figure 6-7 shows the largest natural lakes listed in Table 6-3. Total phosphorus content is used as a parameter for assessing the quality of the water (cf. Section 6.5.1).

No.	Lake	Surface area [km^2]	Volume [million m^3]	Max. depth [m]
1	L. Geneva	581.3	89,900	310
2	L. Constance (upper and lower)	536.0	48,000	254
3	L. Neuchâtel	217.9	14,170	153
4	L. Maggiore	212.3	37,100	372
5	L. Lucerne	113.6	11,800	214
6	L. Zurich (upper and lower)	90.1	3900	143
7	L. Lugano (north and south)	48.7	6560	288
8	L. Thun	48.4	6500	217
9	L. Biel	39.8	1240	74
10	L. Zug	38.3	3210	198
11	L. Brienz	29.8	5170	261
12	L. Walen	24.1	2490	150
13	L. Murten	23.0	600	46
14	L. Sempach	14.5	660	87
15	L. Hallwil	10.3	215	47
16	L. Greifen	8.6	161	34
17	L. Sarnen	7.5	244	52
18	L. Ägeri	7.2	357	82
19	L. Baldegger	5.3	178	66
20	L. Sils	4.1	137	71
21	L. Pfäffikon	3.3	58	35

Table 6-3: The 21 largest natural lakes in Switzerland (after BWG; IGKB 2004). See Fig. 6-7 for location.

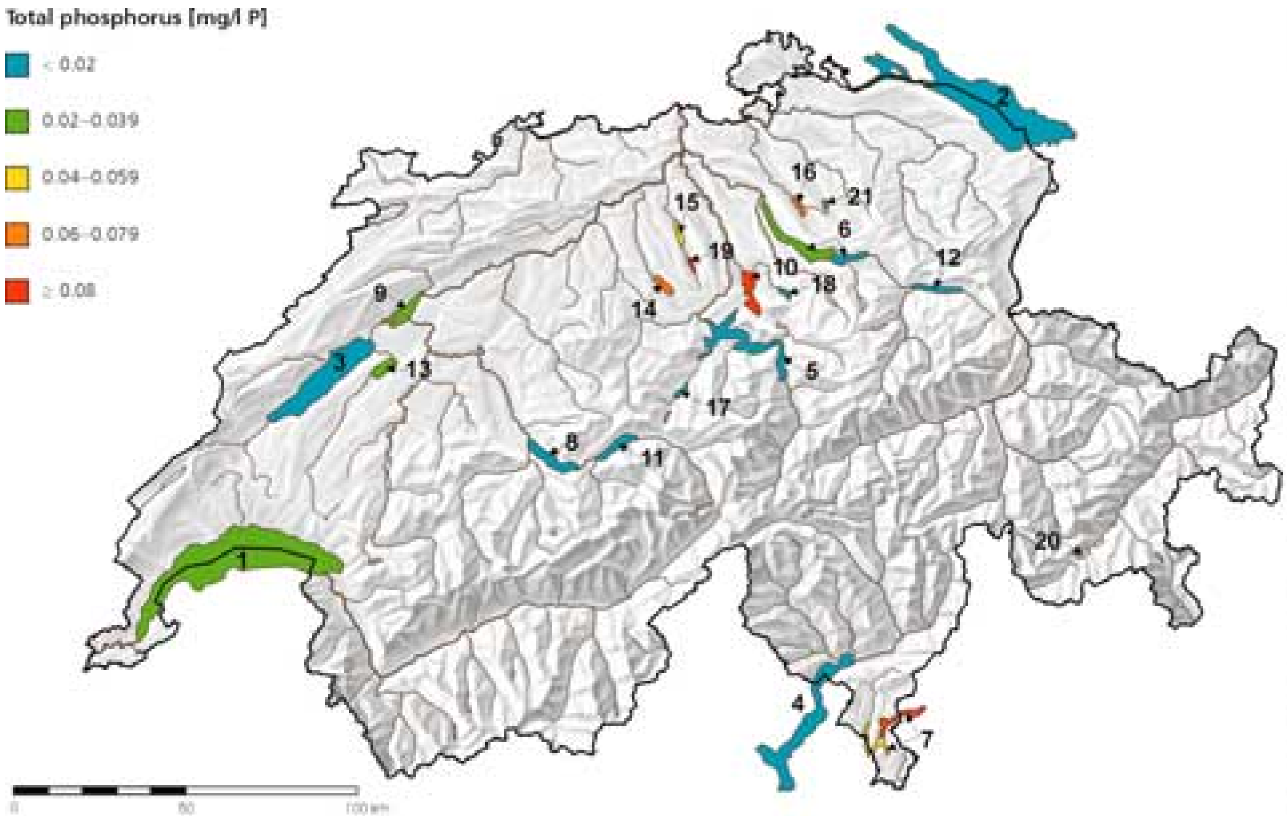


Fig. 6-7: Map of the 21 largest natural lakes in Switzerland (cf. Table 6-3) with total phosphorus content for the period 1996–2000 (after JAKOB et al. 2004).

6.3 The functions of lakes

Lakes have been used by man since the beginning of time.

Fishing

Fishing is one of the very oldest uses of lakes. Protection regulations and fishing restrictions already existed in the Middle Ages (DOKULIL et al. 2001). Although the importance of fresh-water fishing has been falling since the 1970s there are still 349 professional fishermen who work on some 20 lakes in Switzerland (figures for 2004; www.umwelt-schweiz.ch).

Communication

Until the construction of the railways in the 19th century, rivers and lakes were busy communication routes. Today traffic on lakes consists almost exclusively of ferry services, passenger boats used mainly by tourists and boats that transport building material obtained by dredging or along the shoreline.

Energy

Most of the water retained in reservoirs (cf. Fig. 6-8) is used to produce electricity. Hydro-electric power stations generate 16,700 GWh or around 30% of Switzerland's annual electricity production (www.bwg.admin.ch).

Flood retarding basins

Lakes are natural flood retarding basins. Between 10 and 15 May 1999, for example, the largest lakes at the foot of the Alps in the Rhine catchment together retained 950 million m^3 of water, corresponding to a discharge rate of some 2200 m^3/sec in Rheinfelden. This was a natural process since on the one hand Lake Constance is not regulated (i.e. has no sluices on the outflow) and on the other the effect of regulation on the other lakes is negligible since the sluices were fully open at the time (BWG 2000). Where there are no natural lakes protection against flooding can in some cases be improved by creating artificial flood retarding basins.

Drinking water

Drinking water is supplied by a number of natural lakes (www.trinkwasser.ch). Some 20% of the total volume of water consumed in Switzerland (corresponding to 200 million m^3) is obtained from around 30 waterworks on lakes.

Fig. 6-8: The Gebidem reservoir (canton of Valais) holds 9.2 million m^3 of water.

Leisure activities

The use of lakes for leisure pursuits has increased drastically over the past few decades. Activities on the shore as well as on or in the water have become an important aspect of the tourism industry.

Climate

The tempering effect of lakes on the local and regional climate has been used by farmers for many centuries: vineyards will only flourish on the northern side of the Alps if they are in climatically favourable locations – in particular along lakes. Neat rows of vines are still typical of many sunny slopes above lakes in the Alpine foothills and the Central Lowlands.

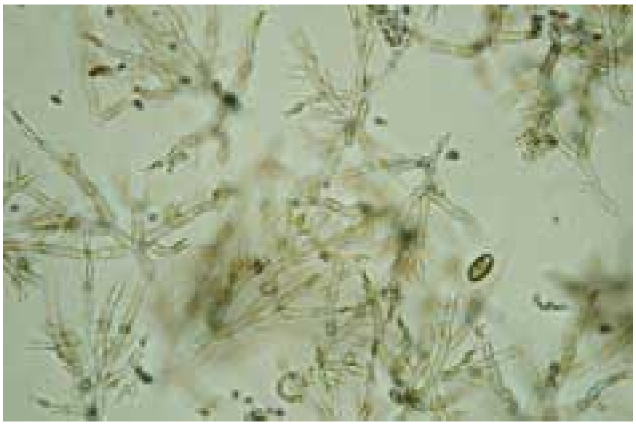


Fig. 6-9: Phytoplankton (Dynobrion).

6.4 Balance of nutrients and water quality

The status of nutrients in a lake is a reflection of the activities in its catchment (GSA 2003). Lakes whose catchments include relatively few settlements and are in a more or less natural state have a low nutrient count while those whose catchments are well populated or intensively farmed have more nutrients. The overall condition of most Swiss lakes can once again be qualified as good. Nevertheless, there is still room for improvement in many places.

6.4.1 Phosphorus and oxygen

Under natural conditions the level of phosphorus in lakes is so low that it is the limiting factor for primary production. The vast majority of primary production consists of suspended algae, also called phytoplankton (see Fig. 6-9).

In the summer months vast quantities of algae are produced close to the surface and release oxygen as a product of their metabolism. The oxygen level in the epilimnion thus rises through the summer. Part of the dying phytoplankton is broken down in the metalimnion. The remaining dead biomass sinks to the bed of the lake where it uses oxygen to decompose, thus reducing the concentration of oxygen in the lower water (cf. Fig. 6-10). Since it is not possible to replace the oxygen from the epilimnion owing to the vertical layering of the water, the oxygen supply may be totally exhausted. This results in organic materials being broken down without oxygen, whereby deoxidised compounds (ammonium, hydrogen sulphide, methane, etc.) are formed, some of which are poisonous. Moreover, phosphorus that has been absorbed into the sediment may be rereleased, which is equivalent to fertilising the lake. The lowest depths of the lake will only receive oxygen again when the water next circulates. At the same time, phosphorus will once again be distributed throughout the whole lake.

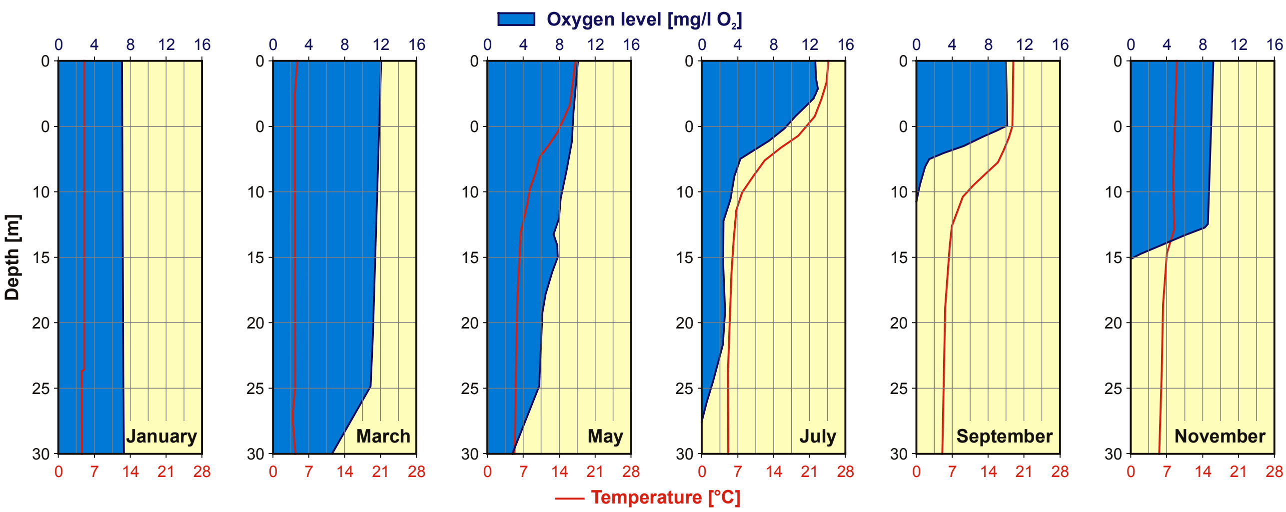


Fig. 6-10: Oxygen and temperature profile of L. Greifen in 2003 (after www.gewaesserschutz.zh.ch).

6.4.2 Phosphorus content in lakes – A success story for water protection

From the 19th century on the population of Switzerland started to rise, lavatories were being installed in houses and waste water was channelled into surface waters, the country was slowly becoming industrialised and the land was being farmed more intensively. These factors led to an increase in nutrients in many Swiss lakes. The quality of the surface water became steadily worse under the increasing burden of pollution and it became necessary to take legal measures to protect the lakes. In 1953 an article on water protection was enshrined in the federal constitution (see Chapter 9).

The rich supply of nutrients led to increased primary production in certain lakes. In summer extensive carpets of algae formed on the surface of many lakes (see Fig. 6-11). This development reached its height in the 1970s (see Fig. 6-12). Since then it has been possible to reduce the quantity of phosphates that enter Swiss lakes, mainly through the following measures on the land:

- Thanks to the construction of sewage treatment plants the proportion of household and industrial waste water that is fed into lakes untreated has been continually reduced.
- Phosphate traps have been installed in sewage treatment plants as an additional processing stage. These retain a large part of the phosphate in the sludge.
- The ban on phosphates in washing powders, which came into force in 1986, has had a marked effect.

At the same time, efforts are being made to ensure that nutrients from agricultural zones do not drain into lakes unintentionally. At present this source accounts for the larger part of nutrients in lake water.

Today the level of phosphorus in most of Switzerland's larger lakes can be considered satisfactory. There is still a problem with lakes in areas of intensive farming. In some lakes, for example L. Baldegger and L. Sempach, flora and fauna can only survive thanks to measures that involve the water itself, such as an artificial air supply and aided water circulation.

6.4.3 Oxygen supply in deep waters

Owing to the layers of water at different temperatures in the summer, oxygen is supplied naturally to the lowest layer only in winter. The water in lakes that are exposed to strong winds and are located in a flat, wide basin regularly goes through a total circulation process, while the water in relatively protected lakes that are narrow and deep often circulates only down to a certain depth. For example, the water in L. Brienz does not circulate completely every year. In such cases the warmth of the earth has some influence on the temperature of the deeper water. The gradual warming of the deepest water, even if only slight, will reduce the stability of the different layers, with the result that after a few years the water will circulate right down to the lake bed during a cold winter. In the case of L. Brienz, after 1991 such a phenomenon was observed again only in winter 1998/1999 (GSA 2003).

With the reduction of total phosphorus levels, many Swiss lakes have seen an improvement in the oxygen level during the stagnation period. Figure 6-13 shows the trend in oxygen content in selected Swiss lakes

Fig. 6-11: Carpet of algae in L. Baldegger (canton of Lucerne), May 1982.

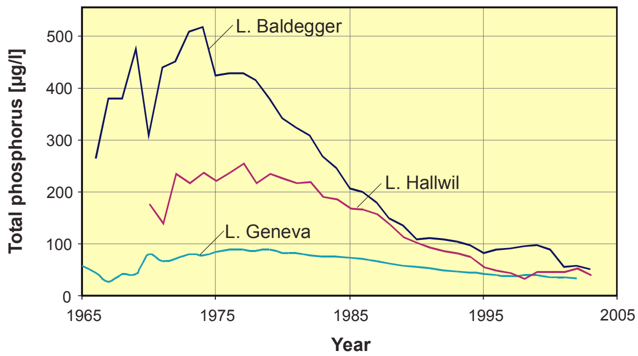


Fig. 6-12: Changes in total phosphorus content of selected lakes. Target level 10–25 µg/l P (data: P. Liechti, BUWAL).

between 1979/80 and 1999/2000. Alongside a positive trend (e.g. L. Geneva, L. Neuchâtel) there are also lakes whose oxygen content is still far from the legally required level (4 mg oxygen per litre, conditional on specific natural conditions). The northern basin of L. Lugano shows only a slight improvement owing to the chemical layering in its deeper waters. In the case of Lake Sempach and L. Baldegger, the positive effects of measures taken involving the lake itself are clearly recognisable.

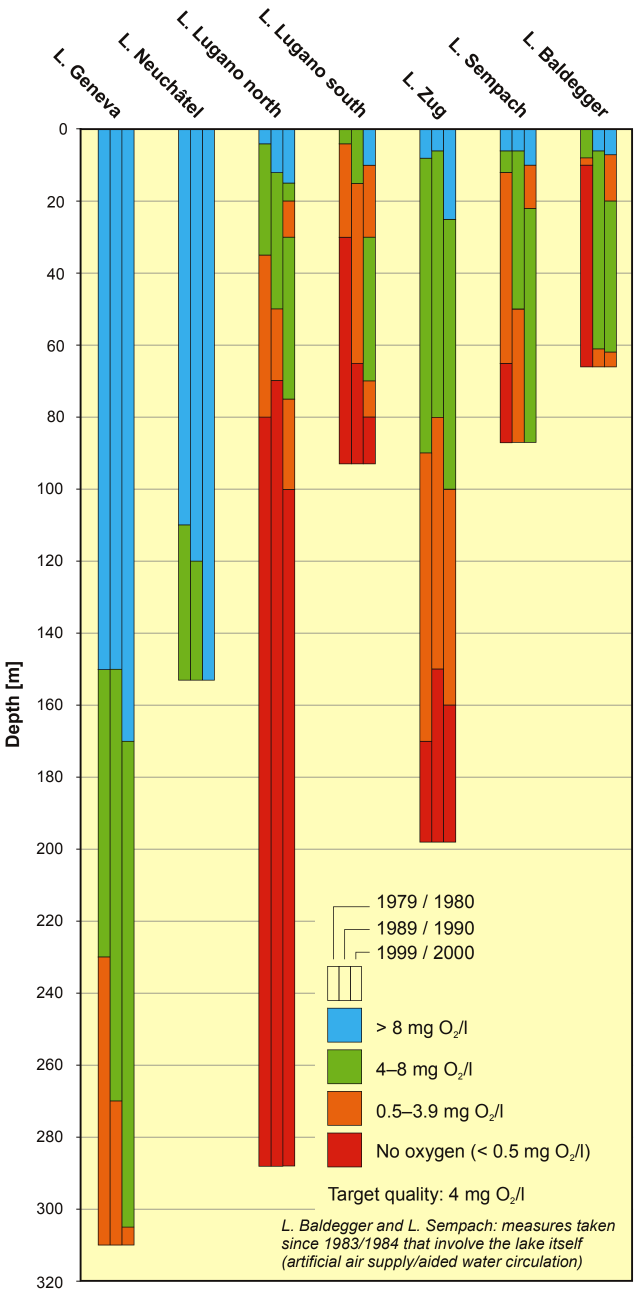


Fig. 6-13: Changes in oxygenation in selected lakes at the end of the summer period of stagnation (after Jakob et al. 2004).

7 Groundwater

Statistics

Exploitation of drinking and industrial water in Switzerland in 2001			Source: SSIGE 2004
Source	**Volume**	**Percentage**	
Groundwater from water supply wells	377 million m^3	36 %	
Groundwater from springs	491 million m^3	48 %	
Lake water	168 million m^3	16 %	
Total	1036 million m^3	100 %	

Groundwater resources in Switzerland Sources: BITTERLI et al. 2004, DOERFLIGER & ZWAHLEN 2000, GUILLEMIN & ROUX 1992, POCHON & ZWAHLEN 2003, SSIGE 2004

Aquifer	Area	Proportion of total water supply	Time to travel 1 km
Unconsolidated porous aquifer	c. 6 %	36 %	6 months–2 years
Karstic aquifer	c. 16 %	18 %	5 to 50 hours
Fissured aquifer	c. 78 %	30 %	2 days to 1 year

7.1 Subterranean water

Being subterranean, groundwater is by far the least visible part of the natural water cycle; the science of groundwater is called hydrogeology. Rock series that will absorb water and allow it to pass freely through are called aquifers.

7.1.1 Groundwater and hydrogeology

Groundwater is water that occupies and saturates pores, discontinuities, fissures and other spaces in the rocks. It forms mainly through infiltration of rainwater and water from rivers and streams. It moves only by gravitational force and can be found at depths of several thousand metres. Groundwater flows from where it infiltrates into the soil towards where it flows out (see Fig. 7-1). Groundwater can be discharged directly into surface water, come to the surface naturally (springs) or be artificially retained (water supply well). In this respect, springs are a special aspect of groundwater. It is impossible to measure the characteristics of groundwater and the corresponding aquifer directly at any point on the Earth's crust. Hydrogeological studies therefore mainly use indirect methods and interpretation.

Hydrogeology addresses the geological and hydrological conditions and the physical laws concerning the origin, occurrence, movement and characteristics of groundwater. It also applies and uses the knowledge obtained to investigate, exploit and protect groundwater (CASTANY & MARGAT 1977, GHO 1982, PRICE 1996, PFANNKUCH 1969, GARY et al. 1977).

7.1.2 Aquifers

Many types of rock may absorb water and allow it to pass freely through. There are three main types of aquifer: unconsolidated, karstified and fissured rock (OFEFP 2004).

In unconsolidated aquifers (e.g. gravel or sand) the groundwater flows through the pores of the rock, generally reaching speeds of only a few metres per

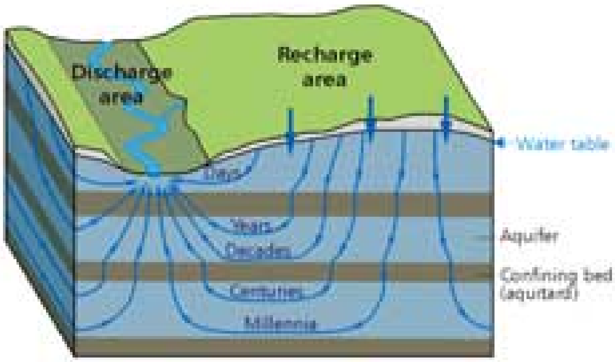


Fig. 7-1: Explanatory diagram concerning groundwater: Infiltration or recharge area, discharge area, directions of flow and residence times (after BOUZELBOUDJEN et al. 1997).

	Hydraulic conductivity	
Type of rock	**K-value**	**Description**
Coarse gravel/sand	10^{-2}–10^{-3}	high
Coarse gravel, sandy to silty	10^{-4}	medium
Loamy gravel	10^{-5}	medium to poor
Fine sand, silt, clay, loam	$< 10^{-5}$	medium to very poor

Table 7-1: Hydraulic conductivity of unconsolidated rocks: order of magnitude (K-value) in m/s and description (after SGTK from 1972 on).

day. The ability of the rock to allow water to pass freely through can be defined according to Darcy's law (see PRICE 1996). The decisive factors are the hydraulic gradient and the hydraulic conductivity (K-value) (see Table 7-1 and Fig. 7-2).

$$Q = K \cdot S \cdot i$$

where: Q is the flow through a groundwater cross section [m^3/s]
S is the area of cross section [m^2]
i is the hydraulic gradient [–]
K is the hydraulic conductivity [m/s]

PFIFFNER et al. (1997) and BOUZELBOUDJEN et al. (1997) both provide a summary of the estimated hydraulic conductivity of the geological series between the Jura and the Alps and under the molasse basin.

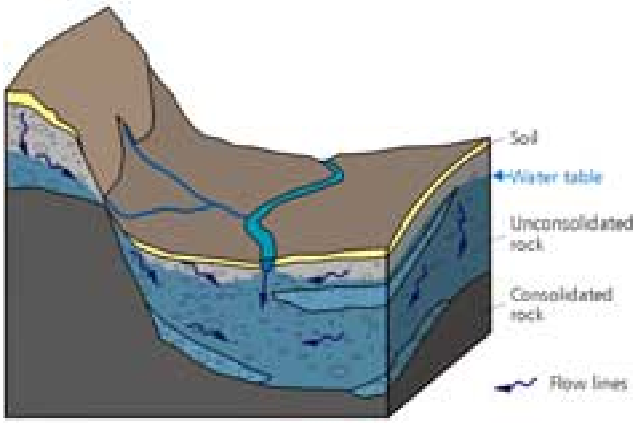


Fig. 7-2: Unconsolidated porous aquifer.

Certain rocks (e.g. limestone) can be karstified, i.e. existing discontinuities can be extended through solution of the rock and finally form a three-dimensional network of open fissures, tubes and caves (see Fig. 7-3). In this type of karstic aquifer the flow velocity can vary considerably both locally and over time, reaching several tens of metres per hour. For this reason, groundwater resources in karstic aquifers are especially sensitive to pollution.

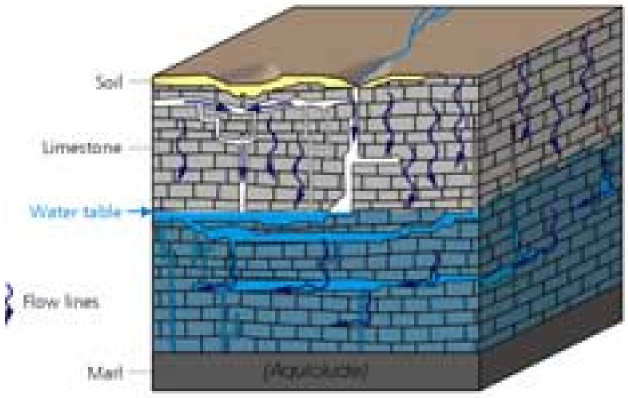


Fig. 7-3: Karstic aquifer (diagram after DEMATTEIS et al. 1997).

In the case of fissured aquifers (e.g. molasse sandstones, flysch, granite) the groundwater flows through discontinuities such as fissures and bedding joints, or even through pores, depending on the type of rock (e.g. sandstone) (see Fig. 7-4). The speed of the water depends on the size of the discontinuities and the degree of connection of the network of fissures, ranging from a few metres to several hundred metres per day.

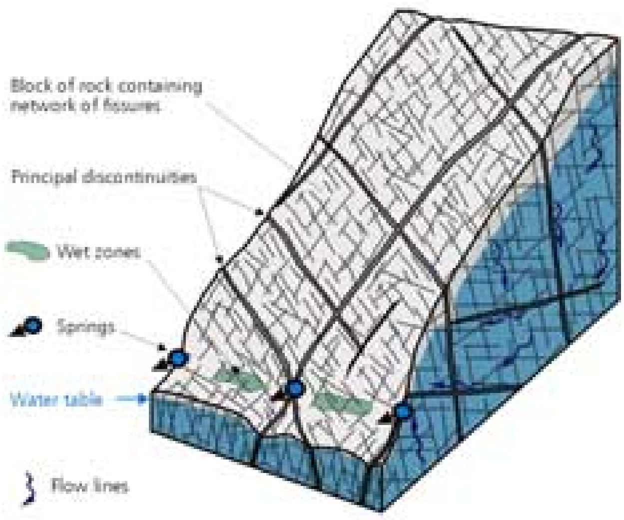


Fig. 7-4: Fissured aquifer (after POCHON & ZWAHLEN 2003).

7.2 Measuring the groundwater level and spring discharge

Long-term quantitative observation of the groundwater is necessary in order to identify at an early stage changes in the volume of groundwater resources due to natural causes or human activity. This represents the basis for a sustainable water supply throughout the country. The national network for the observation of groundwater levels and spring discharge was set up in 1975 for this very purpose.

In general, the groundwater level is measured using a perforated tube (observation or water supply well) that is installed in the aquifer manually (using a manual water-level meter) or automatically (see Fig. 7-5).

Automatic measurements are carried out with the help of a float, a bubble gauge or a pressure probe. The data obtained are either printed out using a recording cylinder or stored digitally in a module. Observation wells are generally used to measure the undisturbed groundwater level while in a water supply well the level of the water is influenced by the operation of the well itself.

The spring discharge is measured as close as possible to the spring using a natural cross section or with the help of an artificial overflow. The water level is measured just as for discharge measurements in surface waters; the spring discharge is determined using a rating curve (see Chapter 5).

At present, the national network for the observation of groundwater levels and spring discharge (NABESS) comprises 41 observation wells and 2 springs and enables experts to maintain an overview of the situation throughout the country (see Fig. 7-6). In BUTTET & EBERHARD (1995) a first summary is published of the results obtained through the NABESS measuring network. Daily means are available to the general public (see www.bwg.admin.ch, as well as the Swiss Hydrological Yearbook, e.g. OFEG 2004). Quantitative data on groundwater are also collected by cantonal authorities, universities and private organisations to meet their specific requirements; some 1,000 measuring stations (springs, observation and water supply wells) are included in the national inventory (SCHÜRCH et al. 2004; see also www.bwg.admin.ch).

Apart from measuring quantities of groundwater, its quality is of decisive importance with regard to drinking water. Issues concerning water quality in general

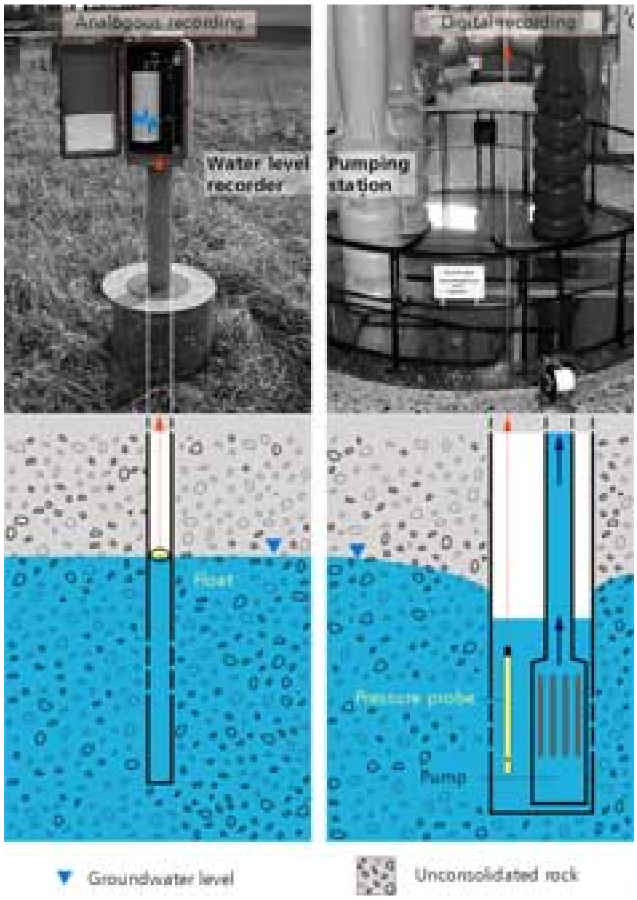


Fig. 7-5: Measuring principle and data collection using an observation well (left) and a water supply well (right) (after SCHÜRCH et al. 2004).

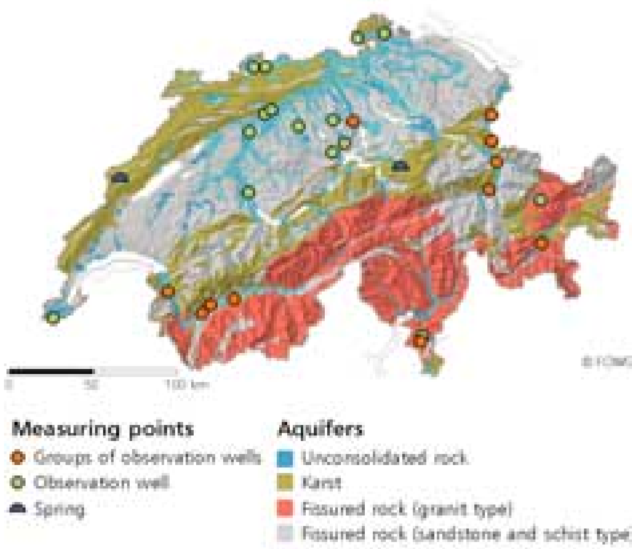


Fig. 7-6: Federal stations that measure groundwater level and spring discharge (as at 2003) and principal types of aquifer (Hydrogeological Sketch of Switzerland).

are addressed in Chapter 9 while the quality of groundwater in particular is dealt with in Section 7.4.

7.3 The groundwater regime

The groundwater recharge is characterised by a seasonal rhythm. This leads to variations in the level of groundwater and spring discharge. In the case of highly productive groundwater resources in the permeable gravels of extensive river valleys, for example, groundwater is recharged principally through infiltration from rivers, with maximum groundwater levels mostly in spring and summer.

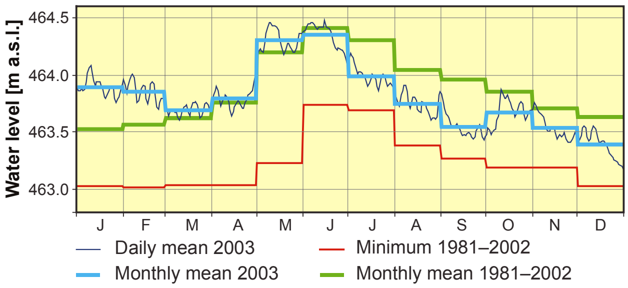


Fig. 7-9: Seasonal groundwater levels in river gravel: R. Rhine at Wartau Weite B (canton of St. Gallen) (after BUWAL/BWG/MeteoSchweiz 2004).

In the case of the large Alpine rivers – the Aare, the Reuss, the Rhine, the Rhone and the Inn – groundwater is recharged mainly in spring and summer through melt water from snow and glaciers. For this reason in the particularly dry summer of 2003 the groundwater levels in the valley gravels of these rivers were in general low but still above the long-term minimum, as for example at Wartau (BUWAL/BWG/MeteoSchweiz 2004) (see Fig. 7-9).

Discharge and groundwater recharge in small catchments in the Central Lowlands (Swiss Plateau, midland area) are determined by the pattern of precipitation and evapotranspiration. In these catchments above-average dry periods can result in a lack of groundwater recharge, as can be seen from a comparison of the hydrograph of monthly means with the long-term mean annual regime of groundwater at Nebikon (Wiggertal, canton of Lucerne) (see Fig. 7-7).

In a karstic aquifer the groundwater moves within a network of karst tubes (karst network) as well as along fissures and in masses of rock with low permeability. Karst groundwater comes to the surface mostly

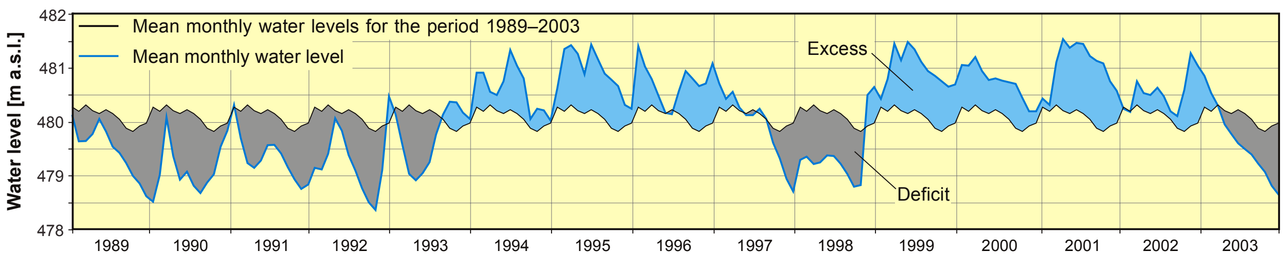


Fig. 7-7: Groundwater balance Nebikon – Winkel (canton of Lucerne). Comparison of mean monthly groundwater levels for individual years with those for the period 1989–2003 (after SCHÜRCH et al. 2004).

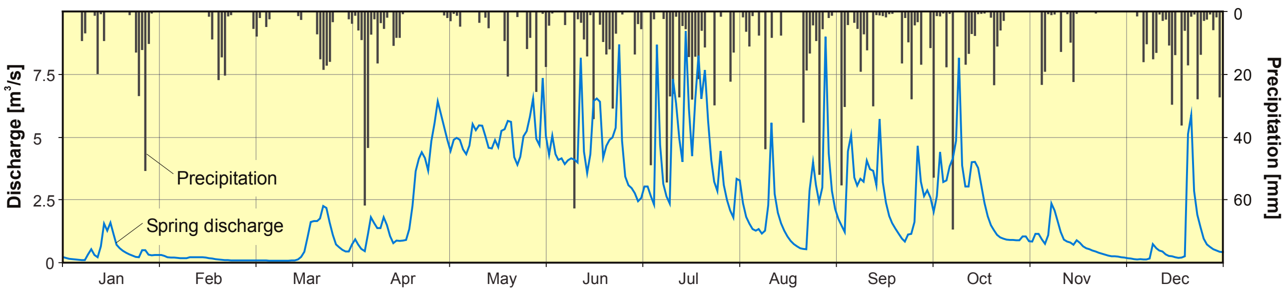


Fig. 7-8: Spring discharge from a karstic aquifer in 1993: Schlichenden Brünnen, Muotathal (Schwyz) with precipitation measured at the Bisisthal station (after SCHÜRCH et al. 2004).

through springs whose discharge can vary considerably, depending on weather conditions. The hydrograph of daily means for the Schlichenden Brünnen spring in the canton of Schwyz (Fig. 7-8) is typical of these springs with a rapid and marked increase after rain and a fast decrease in discharge afterwards as well as a slow decrease during periods of low rainfall (cf. period from 9 October to 21 December 1993 in Fig. 7-8).

7.4 The quality of the groundwater

Over 80% of drinking and industrial water in Switzerland is obtained from groundwater. For this reason, not only the quantity but also the quality of the groundwater has to be monitored throughout the country to ensure supplies over the long term. It is the responsibility of the National Groundwater Quality Observation Network to fulfil this task.

7.4.1 Tools used for national monitoring

The implementation of measures aimed at protecting the groundwater requires adequate and long-term data series concerning the state of the groundwater. Until now, such data have been collected by cantonal laboratories, water companies and increasingly cantonal water protection offices to meet their specific requirements. Data series have also been collected by universities (KILCHMANN 2001).

Since a national overview too has to be guaranteed, the national network for the observation of groundwater quality (NAQUA) was set up in 1997. When it is completed, the NAQUA$_{TREND}$ module will comprise 50 measuring points throughout the country that are as representative as possible and will be used for long-term observations; at the end of 2003 48 points were already in operation (see Fig. 7-10). The NAQUA$_{SPEZ}$ module is used at around 500 measuring points for specific investigations concerning particular aspects of the quality of the groundwater.

7.4.2 The process of collecting data

The choice of NAQUA measuring points, taking samples and analysis must all meet stringent requirements (OFEFP/OFEG 2002, 2004, GREBER et al. 2002). Existing water supply wells, tapped springs and observation wells are taken into account in the selection of measuring points. The measuring programme is made up of modules according to the building-block system (see Fig. 7-11). It is centred around a basic programme plus additional programmes that can be adapted at any time. The use of the additional programmes depends on potential man-made pollution (e.g. agriculture, traffic), the natural factors that play a role at each station and the results of previous analyses. The analysis results provided by the laboratory in charge are immediately evaluated so that the additional programmes to be used for future measurements can be adapted without delay. Groundwater samples are taken from wells only after sufficient water has been pumped up and constant values are obtained for the field parameters, which are continuously recorded.

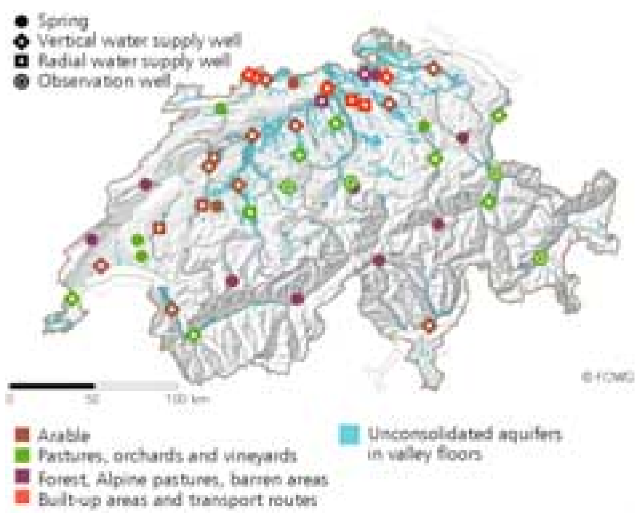


Fig. 7-10: NAQUA$_{TREND}$ measuring points (as at 2003) with principal landuse in the hydrogeological catchment (data supplied by NAQUA$_{TREND}$ measuring network).

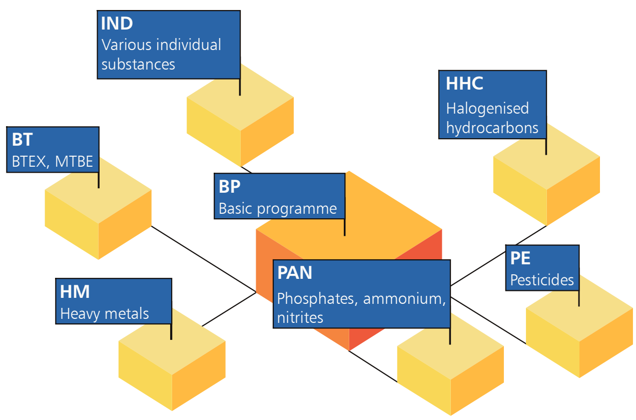


Fig. 7-11: NAQUA modules – The basic programme can be combined with up to six additional programmes (after GREBER et al. 2002).

7.4.3 Presentation of selected measurement series

The effects of the dense population of Switzerland and the intensive use of the land can be seen in the groundwater. Findings show that Swiss groundwater, and therefore drinking water, is of excellent quality since, according to what we know today, the values obtained indicate that it presents no danger to human health. The values do indicate clearly, however, that concerted efforts to protect groundwater resources will still be needed in the future (OFEFP/OFEG 2004).

From among the principal chemical compounds found in groundwater, nitrates are the clearest indicator for determining the influence of landuse. Agricultural landuse is the main source of nitrates in groundwater. They are leached out of the soil and carried into the groundwater by rain. Figure 7-12 gives an example of mean and maximum nitrate levels for all NAQUA measuring points in 2002 and 2003, grouped according to the principal type of landuse. This bar chart shows that landuse has a marked effect on the level of nitrates in groundwater and thus on its quality. Furthermore, the available data imply that the mean nitrate level in Swiss groundwater resources fell between 1989–1991 (cantonal data) and 2002–2003 (NAQUA data).

An important factor behind the mean decrease is the general changes that have come about in agricultural practices. Since 1999 the federal authorities have also been funding renovation projects aimed at reducing the undesired process of nitrates being leached out of the soil into the groundwater. To obtain such funding, farmers must undertake to adopt production methods that do not affect the groundwater (e.g. changing from arable to cattle farming with extensive pastures) (MEYLAN 2003). The two hydrographs shown in Figure 7-13 show typical observed trends in nitrate levels depending on local conditions. While the measuring point included in the nitrate project has shown a clear drop in nitrate levels since around 1995, a marked rise was observed until 1996 at the measuring point not in the nitrate project; subsequently the level has been brought back down to that of 1989, largely owing to radical changes in agricultural practices.

As part of the 2002 phase of the special NAQUA$_{SPEZ}$ programme herbicides (most frequently the blanket herbicide atrazin and its degradation product desethylatrazin) were identified at a large number of measuring points (see Fig. 7-14). According to

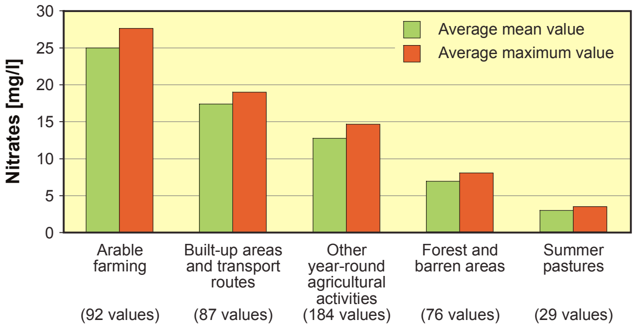


Fig. 7-12: Average mean and maximum nitrate content in relation to principal landuse for the NAQUA measuring points used (2002–2003) (after OFEFP/OFEG 2004).

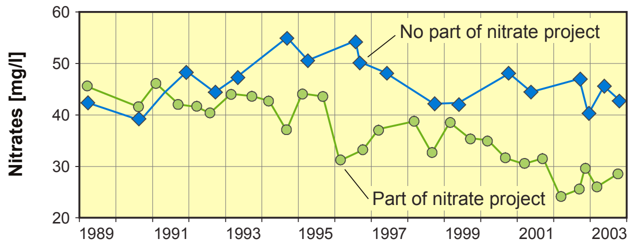


Fig. 7-13: Two water supply wells in the eastern Central Lowlands (gravels outside the zone of influence of a river). Principal type of landuse arable farming (after OFEFP/OFEG 2004).

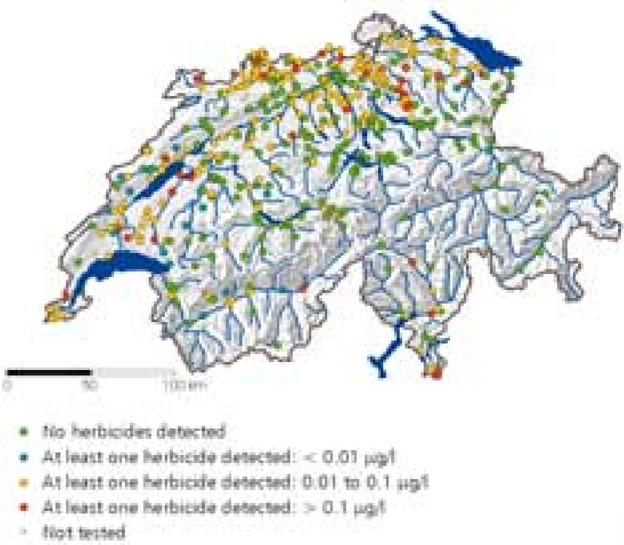


Fig. 7-14: Maximum level of herbicides in groundwater in 2002. For groundwater that is used as drinking water the Water Protection Ordinance (WPO 1998) stipulates a maximum concentration of herbicides of 0.1 µg/l for each individual substance (after OFEFP/OFEG 2003).

present-day knowledge the trace amounts that were observed do not represent a health risk. Their presence in the groundwater needs to be carefully monitored, however (OFEFP/OFEG 2003, 2004).

The trace element boron can be of geogenic and/or anthropogenic origin. It occurs naturally in many minerals, among other things. On the anthropogenic side, it is found in Switzerland in communal waste water (washing powders, medicines) but also in many industrial products, fertilisers and insecticides. For this reason it can be used as an indicator of general human influence such as seepage from refuse tips. A comparison of boron and sodium – a principal chemical compound that can be of geogenic or anthropogenic origin – shows a positive correlation between the two (see Fig. 7-15). If high concentrations of both boron and sodium (GREBER et al. 2002, MATTHESS 1994, MERKEL & SPERLING 1996) are found, it is highly probable that man-made pollution is the cause.

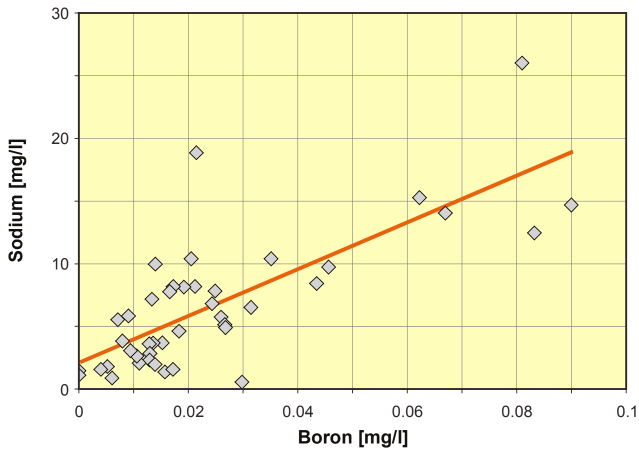


Fig. 7-15: Correlation between boron and sodium as an indicator of possible anthropogenic influence (data from NAQUA$_{TREND}$ measuring network, 1999–2002).

7.5 Groundwater as a habitat

A multitude of different single-cell microorganisms such as bacteria and protozoa live in aquifers. Small multicell animal organisms can also be observed in special groundwater habitats. This fauna consists mostly of micro-crustaceans. All autochtonous microbial species are harmless and these naturally occurring animal communities (biocoenoses) help to purify the aquifers. According to the Water Protection Ordinance of 28 October 1998 biocoenoses in subterranean water should live "close to nature and appropriate to the location" as well as being "specific to unpolluted or slightly polluted bodies of water". Studies are being carried out to define evaluation criteria for natural biocoenoses in groundwater.

7.5.1 Living organisms in groundwater

So far studies of microoganisms in groundwater have concentrated mostly on two aspects: the occurrence and transport of pathogenic microorganisms and the role played by bacteria in degrading toxic substances. Thanks to the rapid progress in methods used in molecular microbiology it is being increasingly recognised, however, that a multitude of different microorganisms live in unpolluted aquifers, in particular bacteria but also archibacteria, protozoa and bacteriophages (GIBERT et al. 1994, GRIEBLER & MÖSSLACHER 2003, HUNKELER et al. in prep.). Like the bacteria, the archibacteria constitute an important group of primitive single-cell organisms whose cells have no nucleus; genetically both groups are basically different. Protozoa are also single-cell organisms but their cells have a nucleus. Bacteriophages are viruses that infect bacteria; viruses need a living host in which to develop. The size of a bacterium normally varies between 0.5 and 2 μm, while protozoa are normally between 2 and 200 μm in size, depending on the species.

These microorganisms can live naturally and permanently in groundwater or may originate elsewhere, i.e. they are either autochtonous or allochtonous. The origin of all allochtonous species can be anthropogenic or natural and many are harmless. The significance of the pathogenic species has recently been analysed (AUCKENTHALER & HUGGENBERGER 2003). It would seem that all autochtonous species are harmless, while all pathogenic species are allochtonous (HUNKELER et al. in prep.).

Apart from microorganisms, fauna can also be observed in karstic groundwater and in certain unconsolidated porous aquifers. With few exceptions these organisms are extremely small (< 3 mm) and can also be autochtonous or allochtonous. The species that are known in Switzerland and live only in groundwater are mainly crustaceans, insects, nematodes and molluscs, the majority of known species being crustaceans (HUNKELER et al. in prep., personal communication from P. Moeschler). In Switzerland there are certain species that only occur in a restricted area (endemic species) and therefore need particular protection, e.g. the microcrustacean Gelyella monardi (see Fig. 7-16).

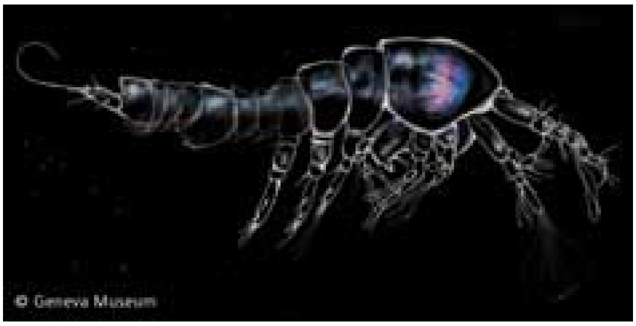


Fig. 7-16: The microcrustacean Gelyella monardi was identified for the first time in the karstic aquifer that feeds the Combe-Garot spring (canton of Neuchâtel). It lives exclusively in groundwater and is 0.3 mm long (drawing by C Marendaz, after MOESCHLER & ROUCH 1988).

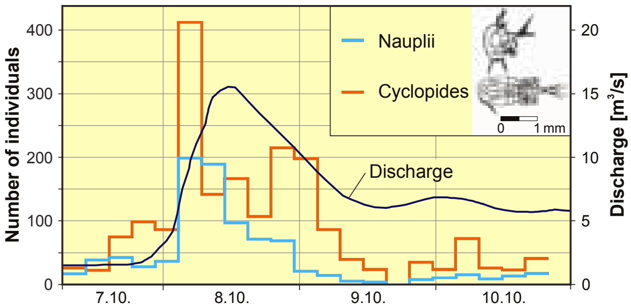


Fig. 7-17: Occurrence of various microcrustaceans in the source of the R. Areuse (canton of Neuchâtel) during the floods on 8 October 1980 (after MOESCHLER et al. 1982).

Groundwater fauna can be used as a natural indicator for hydrogeological studies. MOESCHLER et al. (1982, 1988), for example, used this fauna, in particular microcrustaceans, for analysing the hydrodynamic conditions in karstic aquifers. They continually took samples of spring water, counted the number of microfauna individuals and subsequently compared their numbers with the hydrograph for the spring discharge and interpreted their results (Fig. 7-17).

7.5.2 Groundwater as an ecosystem

Federal legislation requires the preservation of natural habitats for native flora and fauna (Water Protection Act of 24 January 1991) and stipulates that in subterranean water biocoenoses should live close to nature and appropriate to the location as well as being specific to unpolluted or slightly polluted bodies of water (Water Protection Ordinance of 28 October 1998). Consequently, present legislation not only sets standards for the chemical and microbiological quality of the water but also defines the ecological targets for groundwater, thus opening up a new direction for groundwater protection. This situation is at the same time a challenge to science: clear criteria and methods for defining and demonstrating natural biocoenoses in groundwater need to be devised first of all. Corresponding studies are underway (HUNKELER et al. in prep.). This interdisciplinary issue will involve joint projects in the fields of earth, water and life sciences.

HUNKELER et al. (in prep.) list the characteristics of microbial communities in groundwater. As a habitat, groundwater is characterised by the absence of light

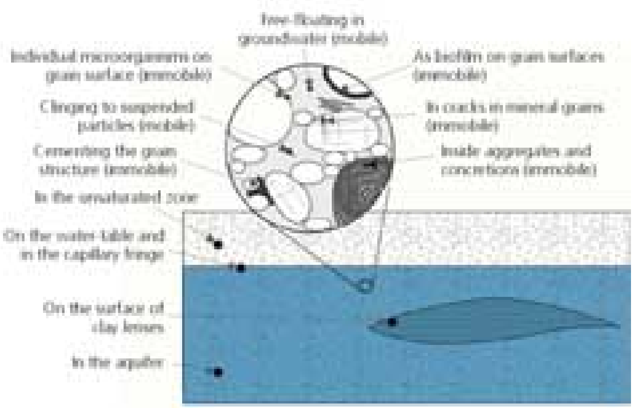


Fig. 7-18: Occurrence of microorganisms (habitats and microhabitats) in an unconsolidated porous aquifer (after HUNKELER et al. in prep.).

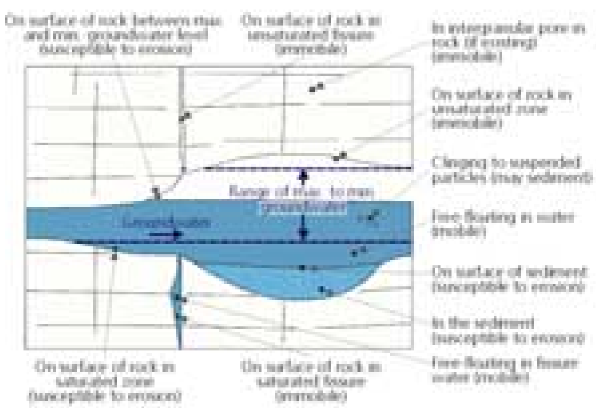


Fig. 7-19: Karstic aquifers offer many different habitats for microorganisms (after HUNKELER et al. in prep.).

and frequently a lack of organic carbon and nutrients. The microorganisms that live there are partly in a state of reduced activity. In groundwater bacteria can find the elements that are essential to their survival such as hydrogen, oxygen and carbon, as well as nutrients, e.g. nitrogen, phosphorus, potassium or sulphur. There are many interactions between the bacteria and the grains of minerals in the rock or the dissolved or undissolved substances transported in the groundwater. Bacteria can settle on the surface of the mineral grains. This natural living community helps to purify the aquifer. Organic carbon is consumed by certain bacteria that are destroyed by protozoa, which in turn form the basic food of the microfauna. The spatial geochemical heterogeneity of the aquifer is reflected in the heterogeneity of the microbial communities that live there. The boundaries between the different areas of the aquifer (e.g. the capillary fringe between saturated and non-saturated zones, boundaries between different lithological units such as clay lenses and gravel or aquifer and aquiclude) are often characterised by a particularly high number of species and are known as ecotones.

Typical habitats for microorganisms in groundwater are shown in Figures 7-18 and 7-19. Marked temporal variations in populations of microorganisms can be observed in some groundwater habitats.

7.6 Using tracers in groundwater

Various methods are used in applied hydrogeology such as geological mapping, geophysical studies, drilling and tracers in groundwater. Artificial or natural tracers are used to mark groundwater. The progress made in tracer methodology corresponds to the high demands that are made today regarding the study of the transport of substances underground and groundwater protection in general.

7.6.1 The use of artificial tracers

The principle is simple: the water is marked using a tracer that can still be identified at high dilutions in order to follow its movement (see Fig. 7-20). The emergence of the tracer is observed at possible exit points using suitable sampling methods. It is then analysed in the field or quantitatively measured in the laboratory. The most commonly used substances are water-soluble fluorescent tracers and salts (Bäumle et al. 2001, Schudel et al. 2002).

Marking the water enables scientists to answer the following questions:

– Where does the water flow to?
– Where does it come from?
– Is there a link between two given points?
– How do certain substances spread through the water?
– How long does the water remain underground?
– How fast does the water flow underground?

These methods can be used to determine the limits of the hydrogeological catchment of a spring or the hydraulic parameters of an aquifer, for example. The tracer hydrographs, also known as breakthrough

Fig. 7-20: Tracer test in a karst system, Covatanne Gorge (Vaud).

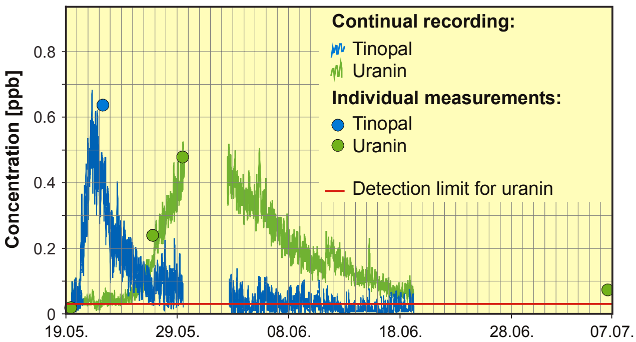


Fig. 7-21: Tracer test at the Livurcio spring (Tessin). Distance between the tracer injection point and the spring: 25 m (tinopal), 80 m (uranin), tracer injected on 19 May 2000 (after POCHON & ZWAHLEN 2003).

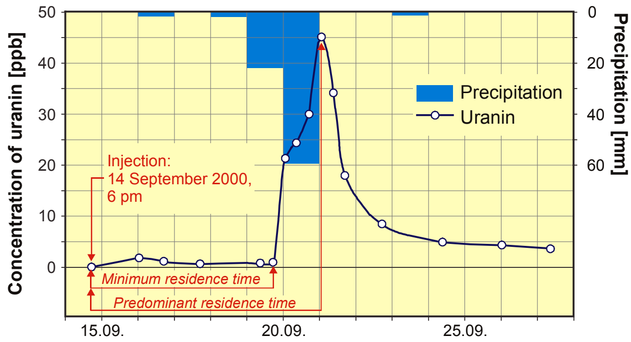


Fig. 7-22: Tracer test at the Borgnone spring (Tessin), 14 to 27 September 2000. Distance between the tracer injection point and the spring: 90 m (after POCHON & ZWAHLEN 2003).

curves, shown in Figures 7-21 and 7-22 show the results of tracer tests carried out to delineate groundwater protection zones in fissure aquifers in the Tessin.

Since INFO-TRACER, the coordination centre for tracer tests in groundwater (www.bwg.admin.ch), came into operation in 1984, between 100 and 500 tracer tests have been reported in Switzerland each year.

7.6.2 The use of natural tracers

Artificial tracers are particularly suitable for studying groundwater with limited residence time (e.g. a few hours to a few weeks), while natural tracers (e.g. soluble substances, water temperature, electrical conductivity, microbiology, isotopes) provide information over a longer period or a larger area.

The isotopes that occur naturally in the water cycle without the need for artificial enrichment for a study are called environmental isotopes and are often used as a natural tracer in applied hydrology and hydrogeology. In this respect, as natural components of water molecules oxygen-18, deuterium and tritium are ideal tracers. They do not interact with the environment and they are transported in exactly the same way as the water. Oxygen-18 and deuterium are stable isotopes, their concentration varies with the different water phases. Tritium is radioactive. It is thanks to these characteristics that isotopes can be used as tracers for a variety of purposes (ETCHEVERRY 2002, PARRIAUX et al. 2001, SIEGENTHALER et al. 1983) (see Section 10.5).

Figure 7-23 gives an example of the use of oxygen-18 as a natural tracer for the quantitative analysis of groundwater recharge through river infiltration near Kappelen (Seeland). Part of the groundwater is recharged direct from local precipitation while part is supplied from river infiltration. The catchment area of the infiltrating surface water is far higher than the Seeland. This means that the oxygen-18 "fingerprint" is different in rainfall and in the R. Aare. By using a mixed model with two components it is possible to determine the proportion of water from the R. Aare in the groundwater (WEA 1989).

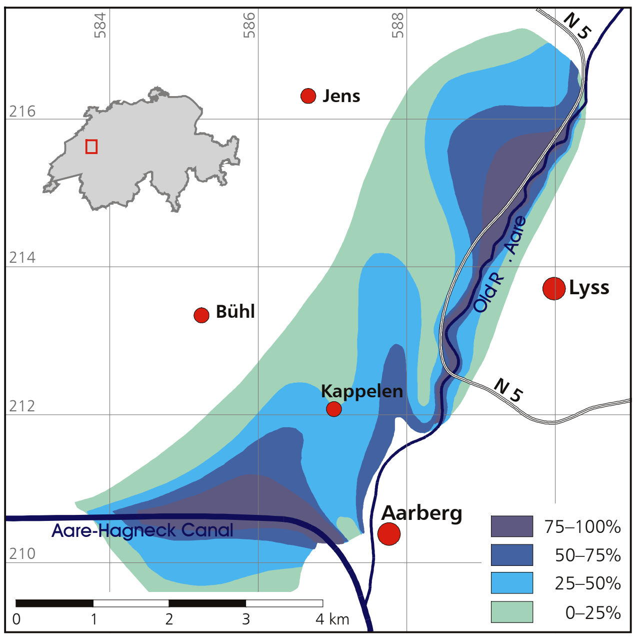


Fig. 7-23: Proportion of Aare water in groundwater determined using oxygen isotopes (sampling points – observation wells – not shown) (after WEA 1989).

7.7 Water in low-permeability rock series

Studies of low-permeability rock series present a challenge for current hydrogeology, especially since the 1980s. It has become necessary to gain more knowledge in this field in view of the issue of conventional waste disposal and the final storage of radioactive waste. Over the past few years new underground engineering projects and drilling in Switzerland have been used to collect important hydrogeological data about this rock type. The Mont Terri Rock Laboratory, for example, has been set up in the branch of a motorway tunnel.

7.7.1 Low permeability and measuring requirements

Low-permeability media occur in sedimentary (e.g. clay formations) and crystalline rocks (e.g. granite). They are not in fact aquifers since they do not allow sizeable quantities of groundwater to pass freely through. They are generally water-saturated, however, and although it moves extremely slowly, the water they contain is part of a groundwater flow system. It can be seen from Figure 7-24 and Table 7-2 that the permeability (hydraulic conductivity) of these types of rock, e.g. Opalinus Clay, can be merely a billionth of that of a high-yield aquifer. This means that the relevant values from a hydrogeological point of view are extremely small, and that measuring the characteristics of these rocks and taking water samples presents a real technological challenge. The effect of investigation procedures (e.g. drilling) on the natural characteristics of the rock and the distortion of the measuring equipment (e.g. through mechanical or thermal stress) have to be carefully taken into account in the design and implementation of the experiments.

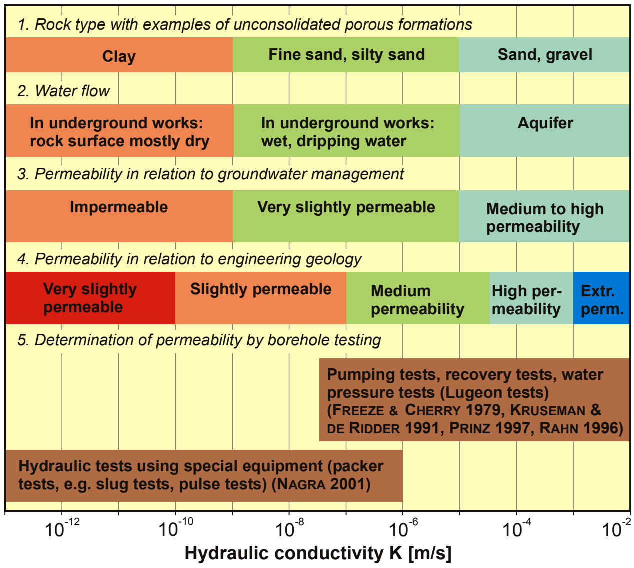


Fig. 7-24: Permeability: ranges and descriptions (after TRIPET et al. 1990).

7.7.2 Types of groundwater circulation – An example

The principal parameters that are relevant to the hydrogeological characterisation of low-permeability media include lithology (type of rock), hydraulic conductivity (see Table 7-2), porosity, pore geometry, groundwater characteristics, transport processes

Type of rock	Location	K-value [m/s]	References
Lower Fresh-water Molasse			
Medium and coarse sandstone (Meander belt type)	Borehole, Burgdorf (canton of Berne)	$4 \cdot 10^{-8}$–$4 \cdot 10^{-6}$	AMMANN et al. 1993
Fine to medium sandstone (Crevasse splays type)	Grauholz Tunnel (canton of Berne)	$< 5 \cdot 10^{-10}$–$5 \cdot 10^{-6}$	DOLLINGER 1997
Palfris formation (Lower Cretaceous)			
Marly-clayey Schist	Wellenberg (Nidwalden) near surface	10^{-11}–10^{-8}	NAGRA 1997
Marly-clayey Schist	Wellenberg (Nidwalden) > 300 m deep	10^{-13}–10^{-11}	NAGRA 1997
Opalinus Clay (Aalenian)			
Claystone	Mont Terri Rock Laboratory (Jura)	2–$9 \cdot 10^{-13}$	PEARSON et al. 2003
Unconsolidated rocks in valley floor			
Sandy gravel (very productive aquifer)	Aare aquifer between Thun and Berne	$2 \cdot 10^{-3}$–$2 \cdot 10^{-2}$	PASQUIER et al. 1999
Gravel (partly with silt) and sand (productive aquifer)	Gürbetal upper aquifer (canton of Berne)	$3 \cdot 10^{-5}$–$5 \cdot 10^{-3}$	PASQUIER et al. 1999

Table 7-2: Permeability (hydraulic conductivity, K-value): selected examples of low-permeability sedimentary formations (top). In comparison, K-values of two unconsolidated, porous aquifers (bottom).

(e.g. gravity, diffusion), and the origin and age of the water. Figure 7-25 shows an example of a chloride profile in a series of clay formations (Opalinus Clay and Liassic claystones).

The samples were taken in the Mont Terri Rock Laboratory (Jura). The clay formations lie between two water-bearing limestone series that dip to the south–east at an angle of around 45°: underneath the Gryphaea Limestone (Fig. 7-25, left), on the top the Dogger limestones (Fig. 7-25, right). The chloride content can be interpreted as a "fingerprint" of the original sea-water that covered the area when the sediments were laid down around 180 million years ago. The highest concentration of chloride, namely about 14,000 mg/l, is around two thirds of the concentration in sea-water. The drop in the chloride level towards the lower and upper formation boundaries is caused by the diffuse transport of NaCl from the Opalinus Clay into the neighbouring permeable limestone strata. This reduction in salinity probably started some 2.5 million years ago when erosion of the Jura Mountains allowed water to infiltrate into the overlying Dogger limestones (BOSSART & WERMEILLE 2003); the drop in salinity has not yet reached an equilibrium and still continues today. The present-day slow water circulation in the clay formations in the direction of the rock laboratory (tunnels and boreholes) can be explained, however, by the drainage effect of the tunnel system. A summary of the hydrogeological conditions of the Opalinus Clay at the Mont Terri can be found in HEITZMANN (2004).

7.8 Groundwater as a potential hazard

Groundwater can also represent a potential hazard. Regular measurement of the relevant parameters is essential for planning appropriate preventive measures to reduce potential damage.

7.8.1 Groundwater and flooding

As the disastrous flooding in Switzerland in 1999 and 2000 showed, the groundwater conditions before and during floods is often a decisive factor governing their intensity. Depending on local conditions a rise in the water table can be responsible for flooding and damage. In Locarno the extremely high level of the lake between 14 and 15 October 2000 caused the water table to rise; this resulted in fuel-oil tanks being ripped out and causing oil pollution (see Fig. 7-26). Structural measures can be taken to avoid such situations arising in the future (fixing down the tanks more firmly, design of buildings).

The results of a study carried out in the Rhone valley (Valais) showed how the zones threatened by a rise in the water table can be delineated (FAGERLUND 2001). If necessary, appropriate landuse planning measures can be taken in these zones. For these studies the data from the 100-year flood that occurred in October 2000 were also evaluated (see Fig. 7-27). The analysis was based on the dense measuring network for observing the groundwater level in the Rhone valley between Lake Geneva and Visp (www.crealp.ch).

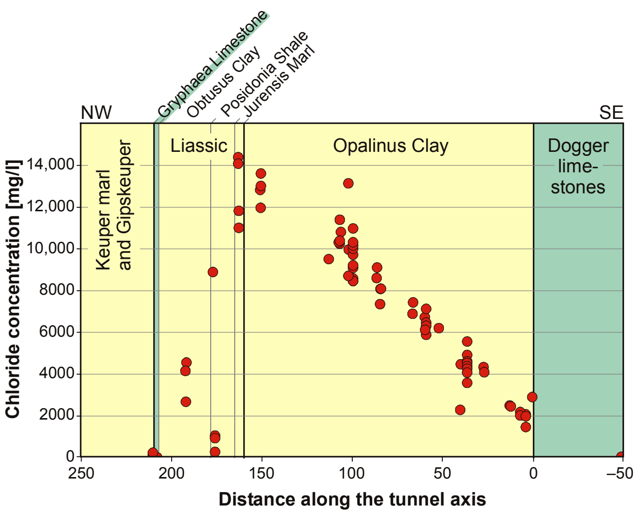


Fig. 7-25: Profile of chloride concentration in pore water in Opalinus Clay (after PEARSON et al. 2003).

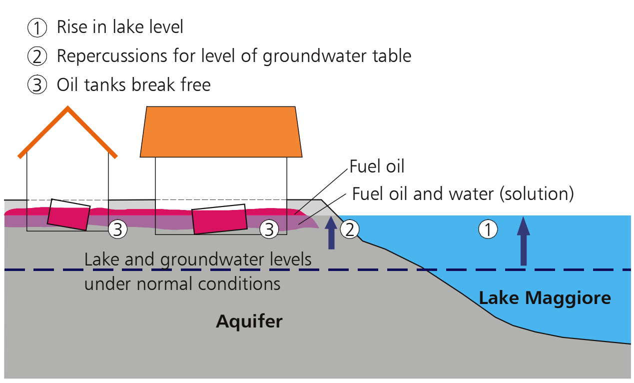


Fig. 7-26: Diagram of flood situation in Locarno, October 2000 (after DUPASQUIER & PARRIAUX 2002).

7.8.2 Groundwater and mass movement

Groundwater is one of the decisive factors in the initiation and pattern of mass movements such as landslides, rock falls and mudflows. It has an adverse effect on hydraulic conditions as well as rock and soil mechanics within an unstable mass. In the case of the landslide that occurred at La Frasse (north–east of Aigle in the canton of Vaud) the displacement was compared with precipitation on the one hand and groundwater inflow on the other (NCG+EPFL 2004). No direct connection was found between the mass movement and precipitation; the same applies to most landslides where the shear plane is deep-seated. There appears to be a close link, however, between mass movements and the inflow of groundwater along the sides of the moving mass (see Fig. 7-28).

The landslide lies in an area of flysch, is approximately 2 km long and between 500 and 1000 m wide. Mass movement was first measured in the middle of the 19th century in connection with the construction of the cantonal road. The first preventive measures, namely installing a drainage system, were taken in the early 1920s.

Lowering the water pressure can be an effective long-term way of stabilising this landslide, since this pressure is the decisive factor governing its movement. Accordingly a drainage system is recommended with a drainage gallery of about 1 km in length beneath the shear plane plus drilled holes going up vertically from the drainage gallery. A similar system was installed between 1993 and 1996 to prevent mass movement at Campo Vallemaggia (Tessin) (see Fig. 7-29). Measurements taken since indicate that the water pressure has been considerably lowered and the landslide significantly stabilised.

The Campo Vallemaggia landslide lies in an area of crystalline (metamorphic) rock and covers an area of over 5 km^2 with a depth of up to 250 m and a total volume of some 800 million m^3 (Bonzanigo 1998 and 1999, Lombardi 1996). It is one of the largest landslides in Europe. The first boreholes were sunk to examine the landslide in 1962.

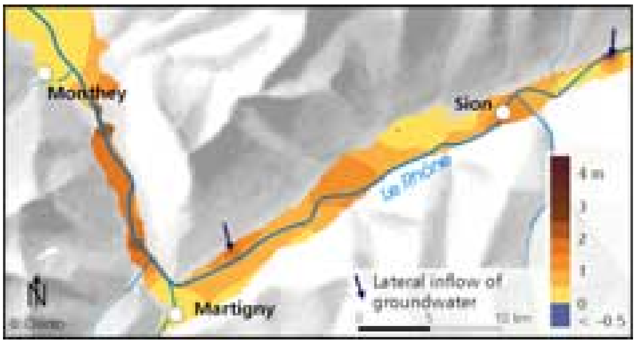


Fig. 7-27: Flooding in the Rhone valley in October 2000: section from map of maximum amplitude of the groundwater table, situation on 16 October 2000 (after Fagerlund 2001).

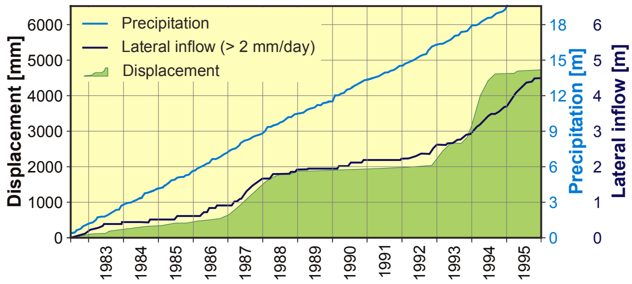


Fig. 7-28: La Frasse landslide, relationship between lateral inflow of groundwater and displacement, accumulated from July 1982 to December 1995. Congruence improved by excluding low daily inflow values (< 2 mm/day) from the accumulated values (after NCG+EPFL 2004).

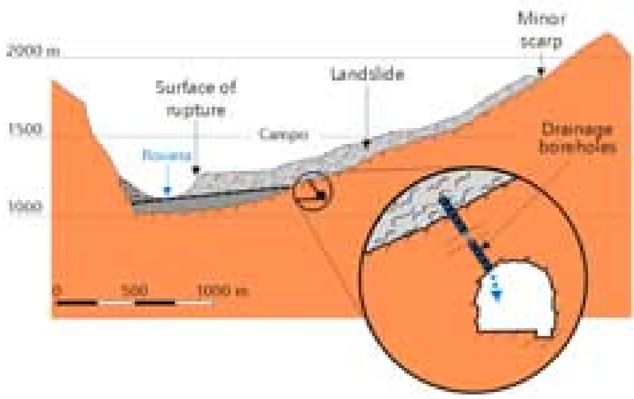


Fig. 7-29: Landslide at Campo Vallemaggia, diagram of cross section with detail of drainage system (after Lombardi 1996).

7.9 Use of groundwater

Groundwater is our most important natural resource. The greater part of the drinking and industrial water that is used in Switzerland is supplied from groundwater. The water thus obtained is of good quality, most of it being supplied to end-users after only basic treatment or none at all. Groundwater is also an extremely good source of heat, however, that can be used for various purposes. It is thus an indigenous and environmentally friendly source of energy.

Fig. 7-30: Inside view of a water supply well in an unconsolidated porous aquifer (Lenzburg pumping station at Niederlenz, canton of Aargau).

Fig. 7-31: Gallery for spring catchment facility, karstic aquifer (Les Moyats spring serving La Chaux-de-Fonds, canton of Neuchâtel).

7.9.1 Groundwater for water supply

In Switzerland water companies, which number around 3000, supply over 1000 million m^3 of drinking water each year, over 80% of which is obtained from groundwater. In 2001 48% of the water consumed was supplied from springs, 36% from wells and 16% was produced by treating lake water (SFSO 2002, SSIGE 2004). In localities with fewer than 10,000 inhabitants, where in fact 54% of the population of Switzerland live, 98% of drinking water is obtained from groundwater (MEYLAN 2003, SSIGE 2002). Around 46% of the groundwater obtained from springs and wells can be supplied direct to the consumer without being treated or disinfected, while 40% requires only basic treatment (e.g. with chlorine, UV light or ozone) (BUWAL 1993).

Groundwater is collected in installations designed specifically to suit local hydrogeological conditions and adapted for water requirements. These installations are mostly water supply wells (vertical and radial wells) (see Fig. 7-30), spring tapping facilities (see Fig. 7-31) (OFEFP 2004) or artificial recharge plants for water supply (e.g. in Geneva, Basle and Zurich; see Section 7.11.2). A radial well consists of several sections of screen collector pipe that are drilled horizontally into the aquifer from a vertical collecting well.

Around half of the groundwater used comes from water supply wells in alluvial valley floors that are mostly fed by major rivers, including the principal Alpine rivers. Since the water level in aquifers that are influenced by the Alpine climate normally reaches its maximum in spring and summer, snow melt accentuating this pattern, the natural recharge of ground water is in principle sufficient, even during long dry periods.

On the other hand, half the groundwater consumed in Switzerland is supplied from springs. If they are fed by groundwater from near the surface, a long period of dry weather can lead to a marked fall in discharge. For this reason, it is advisable for villages and towns where such a situation regularly occurs to link up with larger water company networks (BUWAL/BWG/MeteoSchweiz 2004).

7.9.2 Groundwater as a heat source

Energy in the form of heat is stored under the surface of the earth. On average the temperature of the earth rises by about 3°C per 100 m of depth. This geothermal energy is stored in the groundwater and in the rock and can be used for various heating purposes. There are three different methods of exploiting this phenomenon (OFEN 1998), excluding subterranean heat exchangers where no groundwater is used (e.g. geothermal heat probes that sometimes extend down into the groundwater).

The first method is to use the heat in shallow groundwater, i.e. to a maximum depth of 400 m (BURGER et al. 1985). In Switzerland the mean temperature of the shallow groundwater (between 5 and 20 m deep) lies between 8 and 12°C and varies very little with the seasons. This method involves pumping off groundwater through a pumping well and extracting the heat from it via a heat pump (see Fig. 7-32). In the canton of Berne alone, for example, over 900 such installations are in operation and produce a total of over 50 MW (SSG 2002b).

The second method involves subthermal or thermal springs (temperature from 15° to 20°C or even > 20°C) or deep groundwater which is exploited by single or deep boreholes. In Switzerland six deep-level installations (between c. 550 and 1550 m, temperature of the water at surface level 23 to 69°C) with a total thermal production of over 10 MW provide warm groundwater for heating purposes such as the geothermal heating system in Riehen (Basle-Land) or thermal baths. Thirteen thermal resorts use warm groundwater obtained from springs, shallow wells or deep boreholes (OFEN 1998, SSG 2003, VUATAZ & FEHR 2000) (see figs. 7-33 and 7-34).

The third method uses warm water in tunnels. The total geothermal potential of fifteen tunnels that have been studied amounts to some 30 MW, which corresponds to the heating requirements of around 4000 households; of these 15 tunnels, 5 road and rail tunnels, e.g. the Ricken Tunnel in the canton of St. Gallen, the Mappo-Morettina Tunnel in the Tessin and the Furka Tunnel in the Valais, have already been linked up to a geothermal heating system (SSG 2002a).

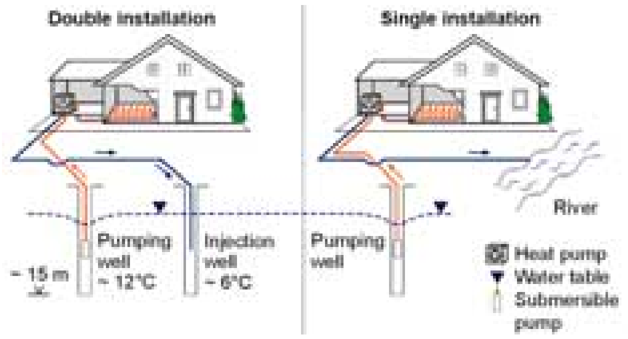


Fig. 7-32: Heating a house using groundwater heat (after SSG 2002b).

Fig. 7-33: Pumping test in deep well at Lavey-les-Bains (Vaud). Temperature of water at emergence: 68°C.

Fig. 7-34: Thermal springs in Val d'Illiez (Valais). Temperature of water at emergence: max. 30°C.

7.10 Protection of groundwater

Over 80% of the Swiss population's requirements regarding drinking and industrial water are covered by groundwater from permeable unconsolidated and consolidated rocks. At the same time, groundwater is an important element in the natural water cycle and many ecosystems, however. One of the aims of the revised legislation on water protection that came into force in the 1990s is to ensure the quantitative and qualitative protection of groundwater from adverse influences while allowing for sustainable use within a framework of ecological objectives.

7.10.1 Risks to groundwater

Under natural conditions the quality of the groundwater depends largely on the substrate through which it flows (DEMATTEIS et al. 1997). Certain characteristics that are not desirable with regard to water for human use, such as a high mineral content or a low level of oxygen (BITTERLI et al. 2004), may result from particular local geological conditions. The natural quality of the groundwater can also be changed by human activity, however, or at least put at risk. Examples are the infiltration of nutrients (e.g. nitrates) and herbicides from agricultural zones, gardens and sports fields, microbial pollution resulting from the inappropriate use of liquid manure, seepage from leaky waste water pipes and manure pits or leaks from fuel-storage depots (OFEFP 2004). Figure 7-35 shows the various pollution sources. From the point of view of quantity, certain undesirable human elements also pose a threat, including engineering works below the water table (which may drain off the water or reduce the groundwater flow profile) or dense settlement (creating large areas of impermeable ground surfaces).

7.10.2 Basic principles of groundwater protection

In view of the possible negative environmental influences the groundwater is to be given blanket protection throughout the country under the terms of the Water Protection Ordinance of 28 October 1998. On the other hand, the continual supply of drinking water is to be ensured at all times and on a long-term basis through special (user-specific) protection of groundwater that is currently being used and that may be used in the future (see Fig. 7-36) (OFEFP 2004).

Origin of pollution	***Diffuse occurrence***	***Concentrated occurrence***
Agriculture, gardens	Spreading of manure and pesticides	Leaky manure pit
		Emptying of manure pits, incorrect or illegal disposal of dangerous substances
Built-up areas	Diffuse leakage from defective waste water pipes	Leaks from fuel-oil tanks
		Overflow from fuel-oil tanks
Industry, trades	Continuous leakage of dangerous substances in large industrial zones	Unsafe storage of dangerous substances
		Incidental release of dangerous substances, incorrect or illegal disposal of dangerous substances
Transport routes	Salt-spreading in winter, draining off of oil and metal compounds, evaporation of fuel particles, use of herbicides on weeds along railway track	Road and rail accidents
Polluted sites		Former industrial sites and tips, firing ranges, sites of accidents

Fig. 7-35: Occurrence of continual (yellow) and occasional (orange) pollution (after DUPASQUIER & PARRIAUX 2002).

	Qualitative	**Quantitative**
Blanket protection	To ensure water quality and biocoenoses are as natural as possible	To preserve natural hydraulic conditions in aquifers
User-specific protection	To guarantee quality of drinking water	To ensure sufficient supplies of drinking water

Fig. 7-36: Objectives of water protection (OFEFP 2004).

The principal tools used for eliminating threats to the quality of the groundwater are:

- quantifiable groundwater quality requirements; if these physico-chemical indicator levels are exceeded it normally implies the possibility of man-made pollution and the need for action (investigation and taking measures);
- water protection areas, groundwater protection zones and areas (tools to be invoked at the landuse planning stage, see Section 7.10.3);
- technical, structural and organisational measures, for example in the storage, transport and use of substances that may pollute the groundwater (DUPASQUIER & PARRIAUX 2002) and when engineering works are carried out such as quarrying in water protection areas and groundwater protection zones.

With regard to the protection of groundwater against reductions in quantity, measures are stipulated in the following areas among others:

- use and management of groundwater (e.g. prevention of over-use);
- engineering works that may affect groundwater (e.g. special conditions concerning underground structures and dams).

The strategy already mentioned is based principally on prevention, for all types of aquifers, in unconsolidated porous as well as karstic or fissured rock, and is aimed at ensuring sustainable groundwater protection.

7.10.3 Protection at the landuse planning stage

The principal elements regarding landuse planning measures are as follows (see figs. 7-37 and 7-39; OFEFP 2004):

- water protection area A_u contains the main groundwater resources;
- surface water for special use can be protected through water protection area A_o;
- area of contribution Z_u provides protection from virtually undegradable substances (targeted protection of the quality of the water);
- groundwater protection zones S1, S2 and S3 serve to protect the catchment facility and the groundwater immediately before it is used as drinking water;
- groundwater protection areas ensure preventive protection wherever it is planned to use the groundwater in the future.

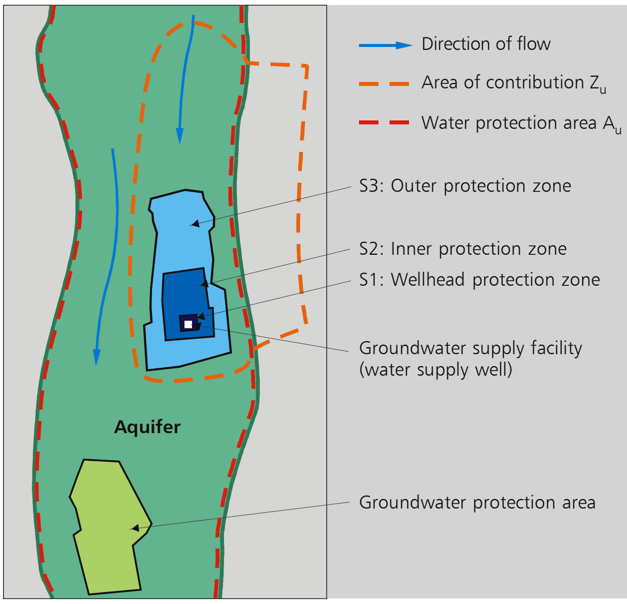


Fig. 7-37: Planning tools regarding groundwater protection (after DUPASQUIER & PARRIAUX 2002).

A list of protective measures or limitations on landuse, depending on the protection needed, exists for each one of the above mentioned elements.

In the case of aquifers in unconsolidated porous formations the S protection zones are arranged concentrically around the catchment facility (source), the criterion for delineating zone S2 being the residence time of the groundwater: the residence time from the outer edge of zone S2 to the source must be at least 10 days. For delineating the protection zones S in karstic and fissured aquifers, the decisive factor is vulnerability (groundwater susceptibility to natural and human impacts, see EUROPEAN COMMISSION 1995, ZWAHLEN 2004) in the catchment area of the source according to the Water Protection Ordinance. The corresponding criteria, which are based on hydrogeological knowledge and are verifiable, are listed in new guidelines (DOERFLIGER & ZWAHLEN 2000, POCHON & ZWAHLEN 2003); they are aimed at ensuring standardised and sustainable groundwater protection throughout the country. For strongly heterogenous aquifers (karstic aquifers and certain fissured aquifers) the need for protection does not decrease gradually with distance from the source, so that the protection zones are not concentric (see Fig. 7-38).

The cantonal authorities produce water protection maps, normally with a scale of 1:25,000, that provide an overview of the protection areas and zones to be invoked for landuse planning, as well as the catchment facilities (water supply wells, exploited springs) (see Fig. 7-39). A digital map of water protection covering the whole of Switzerland has been created as part of a geographical information system (GIS) and is partly accessible to the general public through the internet (overview map of groundwater protection zones and water protection areas, www.ecogis.admin.ch or www.umwelt-schweiz.ch).

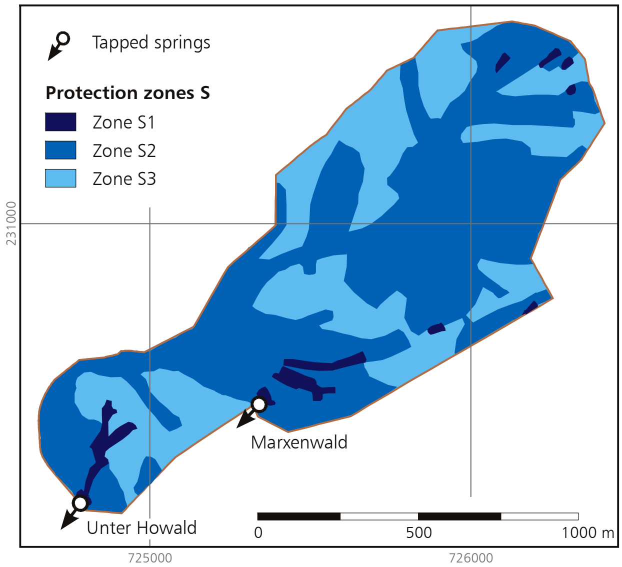


Fig. 7-38: Proposed delineation of protection zones for two exploited springs in Rieden (canton of St. Gallen). Aquifer: sub-Alpine Molasse conglomerate, sandstone and marl (after Pochon & Zwahlen 2003).

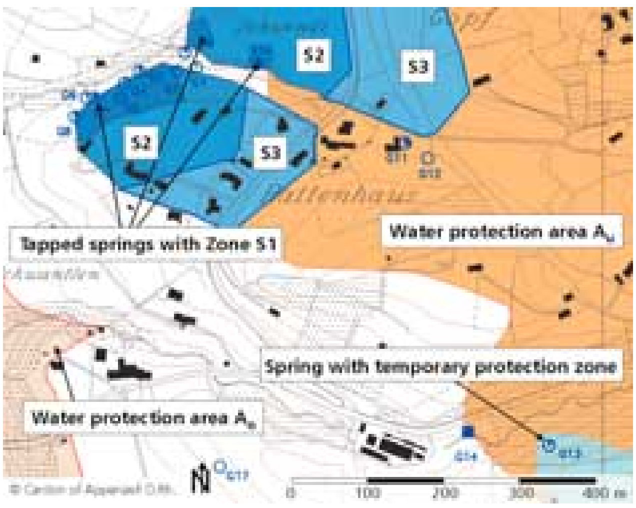


Fig. 7-39: Section of the Canton of Appenzell Ausserrhoden water protection map (1:100,000) (additional labelling).

7.11 Groundwater and forest

Results of observations of groundwater quality and statistics concerning groundwater protection zones underline the major importance of forested catchment areas for the supply of drinking water. The presence of the forest ensures that the groundwater is clean. The sustainable management of forests as sources of drinking water requires not only careful implementation of legislation concerning water protection but also efficient preservation of clean air and appropriate use of forests, however.

7.11.1 Low levels of pollutants and optimal cleaning processes in forests

In contrast to land used for agriculture, almost no pollutants enter the ground directly in forested areas. The use of fertilisers such as mineral supplements, liquid manure, dung or compost is not necessary and is in fact severely limited or even forbidden. In contrast to built-up areas, there are not likely to be any waste water pipes running through forests from which faecal bacteria and other undesirable substances can seep into the groundwater. Moreover, in forests the risk of other types of pollution through accidents or negligent handling of dangerous substances such as fuels or chemicals is minimal. Owing to the limited commercial activities in forests, any springs or water supply wells they contain are exposed to far less risk of contamination than groundwater supply facilities in agricultural zones or built-up areas (see Fig. 7-12). In addition the high level of humus in many forest floors, the corresponding biodiversity in the soil and the dense network of roots ensure that water in the forest floor is purified. Even with its special micro-climate a forest provides optimal conditions for water to be biologically cleaned as it passes through the soil. Most of the mineral and organic substances that do not belong in drinking water will be filtered out or degraded (IWB undated, Meylan 2003, Schürch et al. 2003a).

7.11.2 Forests as sources of drinking water

Owing to the advantages that forests offer as sources of drinking water many groundwater supply facilities (springs or water supply wells) are located in forested

Fig. 7-40: NAQUA measuring station at a public tapped spring with a forest catchment (Freienstein–Teufen, canton of Zurich).

areas (see Fig. 7-40). In Switzerland around 42% of all groundwater protection zones are in forests. This figure is well above the proportion of the total surface area of the country that is forested, namely around 27% (MEYLAN 2003).

Wherever possible, large plants for artificial groundwater recharge to provide drinking water use forest floors to filter the water. At the Lange Erlen groundwater supply plant in the canton of Basle-Stadt, for example, water from the R. Rhine is channelled to fourteen forested areas totalling some 22 hectares and allowed to seep through the forest floor to artificially recharge the groundwater (IWB undated). The seepage installations and the water supply wells that are part of the groundwater recharge system of the city of Basle at Hard near Muttenz are located in a forest of 240 hectares (see Fig. 7-41) where a rich tree diversity is maintained (HARDWASSER AG undated). The groundwater obtained at both sites is of excellent quality.

7.11.3 Air pollutants and nitrate pollution: Potential risks and solutions

The advantages of forests in relation to drinking water are increasingly under threat today from excessive levels of air pollution and general acidification. Frequent high levels of nitrogen in the forests are mainly caused by agriculture, but in addition by road traffic emissions and fires. Through the filtering effect of high tree canopies which catch dust particles as well as pollutant gases, forests are more affected than other types of landscape, deciduous trees generally showing more favourable characteristics than conifers. Moreover, the high rate of evaporation in a forest helps to raise the concentration of soluble substances in the portion of rainwater that reaches the forest floor. Meanwhile, excessive nitrogen supplies lead to higher nitrate leaching; this increases the risk of added nitrate pollution of the groundwater, from forest catchments too.

Fig. 7-41: Infiltration canal for the Hard groundwater recharge plant (Basle-Land).

Although the first target in the battle to protect the groundwater must be the sources of nitrogen compounds (including ensuring clean air) an important contribution can be made by forest management specifically aimed at groundwater protection in order to reduce the level of nitrates and other unwanted foreign substances in infiltrating water. In this connection the choice of tree species, rejuvenation measures, reafforestation and reasonable use of large-scale felling in catchments which supply drinking water are particularly relevant (COMBE & ROSSELLI 2002, MEYLAN 2003). The preservation of forests as suppliers of drinking water of good quality requires a more interdisciplinary approach to the forest–soil–aquifer system in studies of the water cycle in forested areas; at the same time it is essential that the quality of the groundwater is systematically observed over long periods of time (see figs. 7-12 and 7-42). This task is fulfilled by the national network for the observation of groundwater quality (NAQUA) (see Section 7.4).

Fig. 7-42: Lutry spring in Savigny (NISOT measuring network): observation of isotopes in the water cycle.

7.12 Hydrogeological maps

A hydrogeological map provides information about groundwater; this includes on the one hand aquifers and on the other the groundwater itself. The contents and scale of the map will basically depend on its purpose as well as on its potential users.

7.12.1 The presentation of hydrogeological data

A hydrogeological map provides information about the occurrence and type of circulation of groundwater (e.g. groundwater in pores, fissures or karst), the characteristics of aquifers (principally permeability) and the location of recharge and discharge areas (see Fig. 7-1) and of the larger springs. It is therefore a summary of the available hydrogeological data (IAH 1989). An essential basis is a geological map. Profiles can be added to a hydrogeological map to provide information about conditions in three dimensions; examples of large-scale and small-scale hydrogeological profiles can be found in BUTTET et al. (1992) and BOUZELBOUDJEN et al. (1997).

In the broader sense the presentation of selected hydrogeological data can also be termed a hydrogeological map. The following maps are examples: maps showing the location and form of the water table, maps of springs, observation and water supply wells, maps of tracer tests showing the direction of groundwater flow and maps that show the spread and concentration of a given soluble substance in the groundwater (e.g. hardness, nitrates and hydrocarbons).

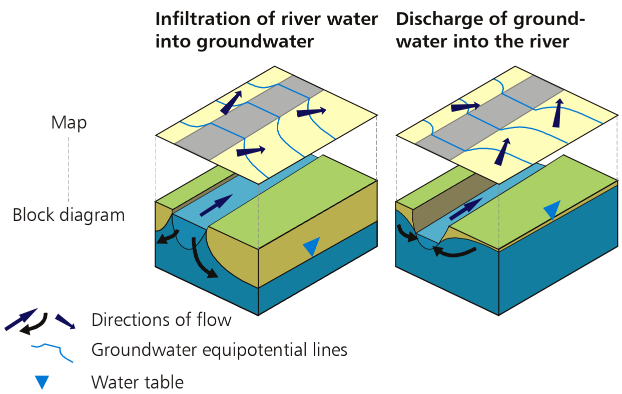


Fig. 7-43: Explanatory diagram of water table (after SCHÜRCH et al. 2004).

The water table can be estimated by interpolating and extrapolating measurements of the groundwater level, taking into account geological conditions (see Fig. 7-43). This is then translated onto a map using groundwater equipotential or isopiestic lines (lines joining points which exhibit at the same time an identical water table level in relation to a horizontal plane).

Directions of flow can be deduced from these equipotential lines; the direction of flow of groundwater is most often perpendicular to the equipotential lines. When an aquifer is linked to a river the stretches with groundwater discharge into the river or with river-water infiltration into the groundwater can be determined using groundwater equipotential lines and directions of flow.

7.12.2 Hydrogeological maps in Switzerland

An overview of hydrogeological maps published in Switzerland can be found in BUTTET et al. (1992). These maps are of different scales, depending on their purpose.

Small-scale maps (1:500,000 or less) provide an overview of the whole country and are aimed at specialists in planning, the authorities and universities, as well as interested lay users. They are drawn up by specialised federal agencies (see Section 7.12.3) or research institutions (JÄCKLI & KEMPF 1967). A reduced and simplified version of the 1:2,200,000 Hydrogeological Sketch of Switzerland published for example in DUPASQUIER & PARRIAUX (2002) is shown in Figure 7-6.

Medium-scale maps (1:100,000) provide an overview of a part of the country. At the same time they provide a general basis for cantonal planning. The target users are the same as for the small-scale maps. To date six sheets of the 1:100,000 Hydrogeological Map of Switzerland have been published (SGTK from 1972 on; see Fig. 7-45, HAERING et al. 1993); a further sheet is in preparation. A 1:100,000 hydrogeological map of the canton of Berne, comprising two sheets, has also been published (OEHE 1998, 1999).

Large-scale maps (1:25,000, in some cases 1:50,000) are tools used for planning and implementation. They are drawn up by the cantonal authorities and take into account local requirements. They are used for exploiting, managing and protecting groundwater. In various cantons only hydrogeological conditions of the unconsolidated porous aquifers are shown; these maps are often called groundwater maps. Among other things they show the extent and size of groundwater resources, the water table and the direction of flow of the groundwater (Fig. 7-44). The water protection maps, also drawn up by the cantonal authorities, are referred to in Section 7.10 "Protection of groundwater".

Detailed hydrogeological maps (with a scale larger than 1:25,000) are mainly drawn up specifically for concrete water supply or infrastructure projects and are not usually published.

7.12.3 Digital 1:500,000 hydrogeological map of Switzerland

In connection with the revision of the Geological and Tectonic Map of Switzerland (1:500,000) as part of a geographical information system (GIS) (OFEG in prep. a and b, HEITZMANN & PHILIPP 1999) it became necessary to further develop the existing hydrogeological map (JÄCKLI & KEMPF 1967). The new 1:500,000 Hydrogeological Map of Switzerland comprises a first sheet entitled "Groundwater resources", which shows the various groundwater resources in Switzerland and their yield, and a second sheet entitled "Vulnerability of groundwater resources", in which groundwater resources are characterised by their vulnerability (susceptibility to pollution). The groundwater resources plate (Fig. 7-46), which has been published in both the Hydrological Atlas of Switzerland (Table 8.6 in BITTERLI et al. 2004) and in the FOWG 1:500,000 map series (OFEG in prep. c), also includes the type of groundwater circulation in karstic, fissured or unconsolidated porous aquifers and the principal tapped springs and water supply wells, as well as giving hydrodynamic information about the recharge and discharge areas. A quantity of evaluation was carried out of natural criteria such as soil type, the top layers and the unsaturated zone, which are relevant for assessing vulnerability, in order to draw up the vulnerability sheet; the results have then been combined and presented in the form of a map. Both hydrogeological maps and the Geological and Tectonic Map of Switzerland have been developed from the same database and together constitute a geographical information system. It is planned to make these maps available to interested users as a printed product and in digital form.

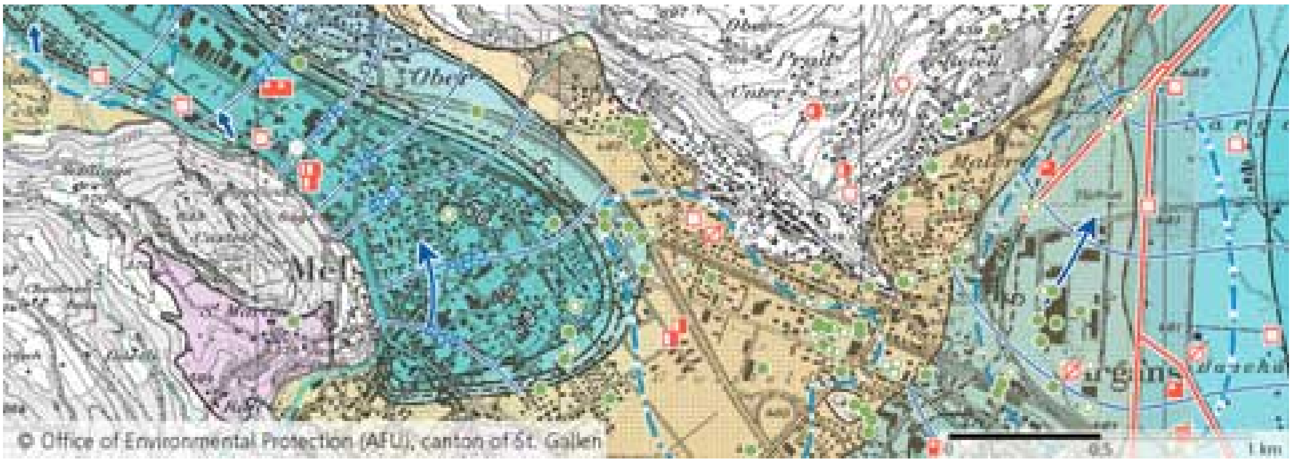


Fig. 7-44: Section of the groundwater map of the canton of St. Gallen (1:25,000).

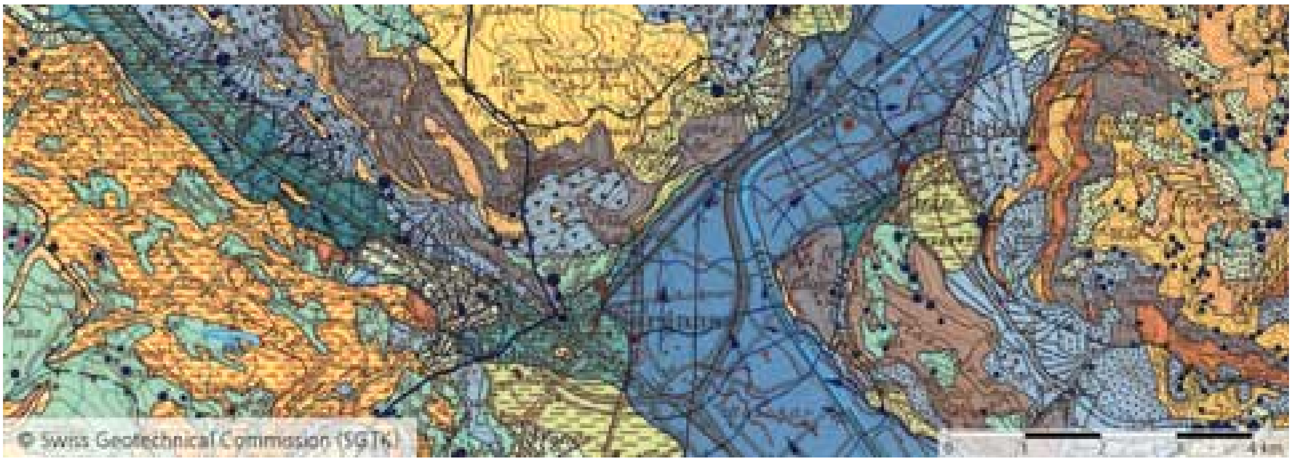


Fig. 7-45: Section of the Hydrogeological Map of Switzerland (1:100,000), Toggenburg sheet (HAERING et al. 1993).

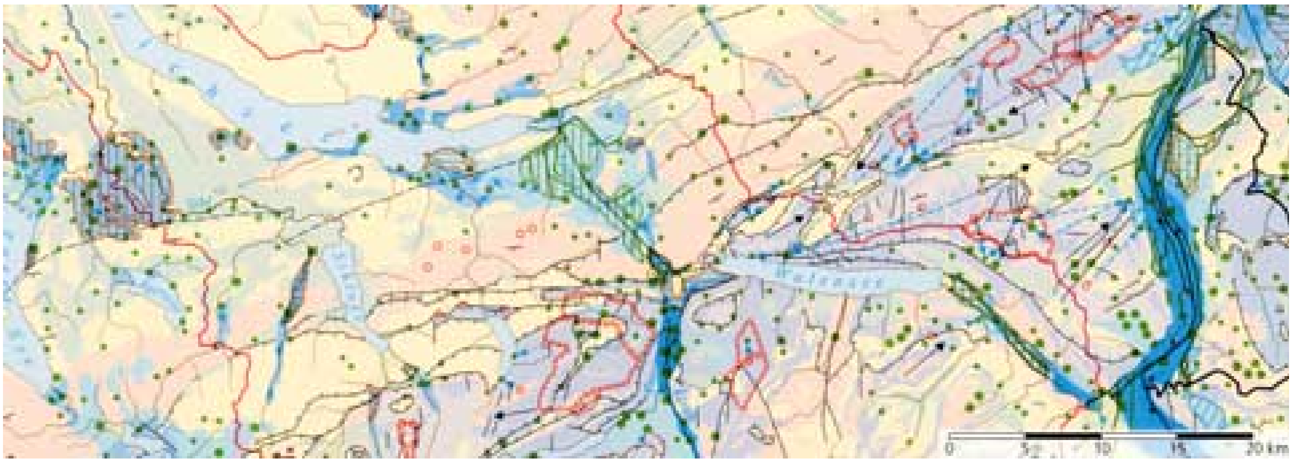


Fig. 7-46: Section of the Hydrogeological Map of Switzerland (1:500,000) (BITTERLI et al. 2004).

8 Monitoring sediments

Statistics						Source: FOWG
Mean annual sediment load	Rhine – Diepoldsau (1979–1999)	2,800,000	t/year	89	kg/s	
	Rhone – Porte du Scex (1979–1999)	1,900,000	t/year	60	kg/s	
	Ticino – Bellinzona (1983–1999)	240,000	t/year	8	kg/s	
Mean sedimentation rate	Lake Constance	0.04	mm/year			
	Lake Walen	0.10	mm/year			
	Lake Thun	0.30	mm/year			
	Lake Maggiore	0.36	mm/year			
	Lake Brienz	0.50	mm/year			
Specific sediment load	(areas observed)	10–40,000	m^3/km^2 per year			

8.1 Measuring sediments

The term sediment covers all the solid particles that are transported or deposited in water. Sediments therefore include bed load, suspended load, floating solids and ice. Suspended and bed loads are recorded through a special measuring network using appropriate instruments and installations.

8.1.1 Processes involving sediment

These processes include the generation, mobilisation, transport and depositing of all solids found in water. Solid rock is loosened and disintegrates under the effects of weathering. The resulting loose material is fed into water courses through surface runoff, rockfalls or landslides. These solids are then transported downstream by torrents and rivers, part of the material being deposited in channels and eroded all over again. Large amounts of sediments are deposited in lakes and reservoirs (GHO 1987).

8.1.2 Suspended load

The process of measuring suspended load focuses on the concentration of the particles, the total load and the variation in grain size.

The concentration of suspended sediments can be measured relatively easily. Using a manual sediment probe (see Fig. 8-1) the quasi momentary concentration of particles can be measured in a given point of the chosen cross-section. Integrated samples can be taken across the vertical profile using a sediment-measuring trailer (see Fig. 8-2).

The advantage of automatic sampling (see Fig. 8-3) over the manual method is that a sufficiently compact series of samples can be taken during short floods.

The total load (per day, per year) in rivers and streams can be determined from the sediment discharge and

Fig. 8-1: Use of a manual instrument with a cable and rod for measuring suspended load.

the corresponding discharge volume. In natural lakes, settling basins and reservoirs total load can also be estimated by measuring the depth of the body of water (bathymetric measurements). Such measurements should also be combined with an analysis of samples taken from the bed of the lake, however.

Fig. 8-2: SNHS trailer for measuring suspended load – measuring instrument featuring an impeller.

In many places it is not easy to determine the total load using random sampling of sediment concentration and continuous discharge measurement. On the one hand it is difficult to fix a representative measuring point in the cross-section of a river because the cross-section can change depending on discharge conditions and other factors (see Fig. 8-4). On the other hand, as Figure 8-5 shows, the continuous transport of sediments can only be estimated approximately from random samples. Furthermore, in many bodies of water there is a clear correlation between discharge and sediment concentration (see Fig. 8-6). For this reason, the measuring stations operated by the Swiss National Hydrological Survey (SNHS) try to use a combination of continual turbidity measurements and random samples of sediment concentrations.

The SNHS's standard measuring network covers various major rivers in the main catchments in Switzerland (see Fig. 8-7). The measuring network is such that the sediments carried into the largest lakes in Switzerland can be recorded and the sediments that are transported from Switzerland to its immediate neighbours can be roughly estimated (OFEG 2004).

Fig. 8-3: Example of an automatic measuring station at Ringgenberg on the R. Aare (canton of Berne). The station is not part of the standard measuring network (see Fig. 8-7).

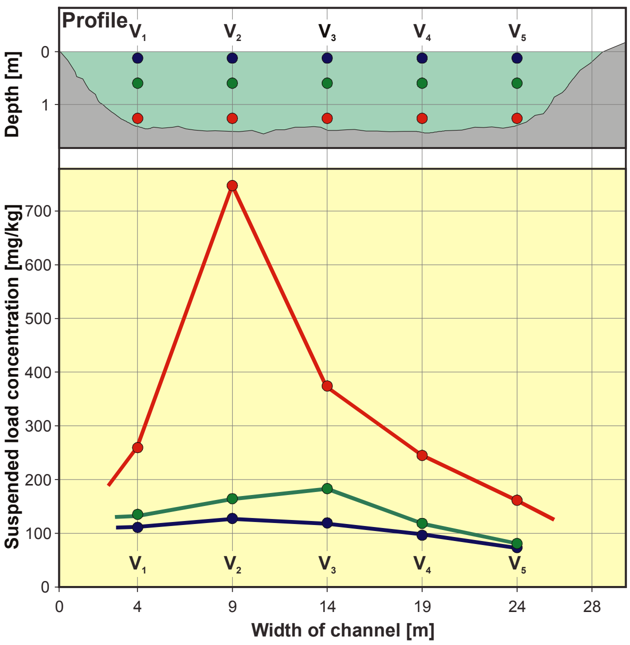


Fig. 8-4: Variation of suspended load concentration in a river profile: problem of determining a sampling site that is representative (data: FOWG).

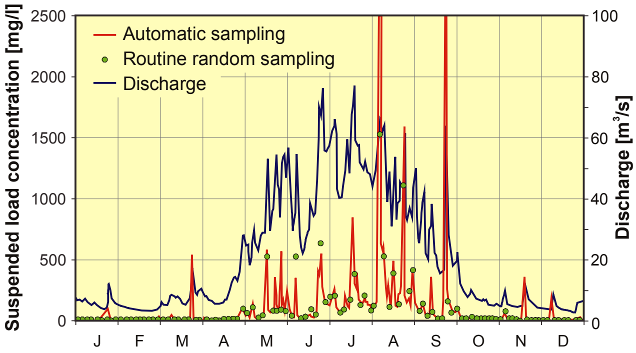


Fig. 8-5: Temporal variation in suspended load concentration at Gsteig on the R. Lütschine (1994): problem of random sampling (data: FOWG).

8.1.3 Bed load

Since 1987 the SNHS, the WSL (Swiss Federal Institute for Forest, Snow and Landscape Research) and interested cantonal authorities and research institutes have been measuring total load (bed and/or suspended loads) in sediment collectors (see Fig. 8-8) as part of a measuring programme run by the Group for Applied Hydrology. Data are collected in such a way that both load means and extreme values can be recorded. The measurements constitute a basis for improving existing approaches to estimating load volumes. It is planned to operate the measuring network (see Fig. 8-9) for at least 30 to 50 years in order to obtain a representative statistical estimation.

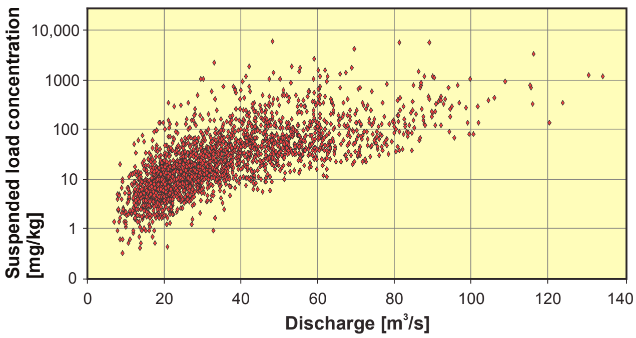


Fig. 8-6: Correlation between suspended load concentration and discharge at Mollis on the R. Linth (1976–1997) (data: FOWG).

Fig. 8-8: Site of bed load deposit in the Schipfenbach stream at Silenen (Uri).

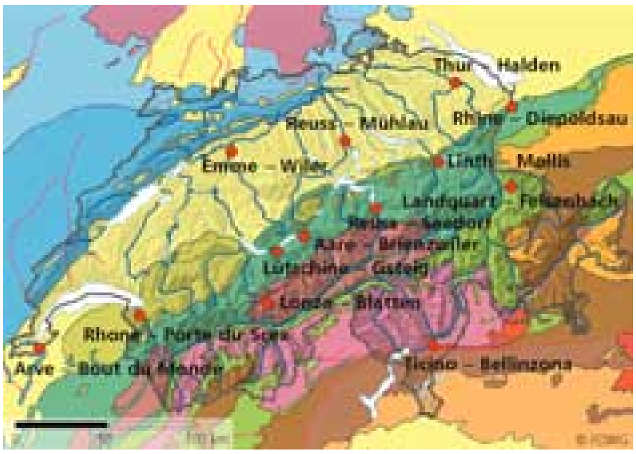


Fig. 8-7: Swiss National Hydrological Survey standard measuring network for recording suspended load in rivers and streams (see Fig. 8-9 for labelling of the geological overview map) (data: FOWG).

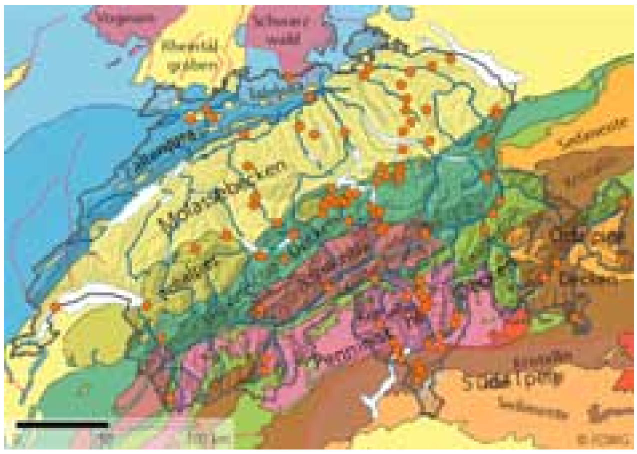


Fig. 8-9: Measuring stations in the bed load measuring network with location of stations according to the geological areas of Switzerland (data: FOWG).

Fig. 8-10: Bed load measuring station at Leissigen on the Spissibach stream (canton of Berne) operated by the Geographical Institute of the University of Berne.

Fig. 8-12: Debris flow weighing apparatus in the Illgraben (Valais).

Various institutes operate research stations and installations for measuring sediments. In the Leissigen test area in the canton of Berne, for example, the bed load currently transported by the Spissibach stream is being recorded using 18 hydrophones as well as bed load scales developed by J. Schenk of the Geographical Institute of the University of Berne (see Fig. 8-10) (KIPFER 2000).

8.1.4 Debris flows

In the Alps and other mountain ranges all over the world debris flows (also known as lahars) constitute a significant potential hazard. They occur principally in scree slopes and in the channels of mountain torrents. Debris flows are fast-moving masses of earth, stones and boulders mixed with a large volume of water. They often occur after extreme rainfall, as for example during the heavy storms of 1987, 1993 and 2000, or after intensive summer storms. If a mountain torrent cone is built over or an excessive amount of water flows into a receiving water body, debris flows can cause immense damage through the sudden arrival of large quantities of bed load.

Fig. 8-11: WSL debris flow observation stations.

Owing to the fact that they normally include only a rough estimation of the depth and velocity of the mud-flow, descriptions of such events in specialised literature are suitable only for testing models in certain cases or corroborating existing laboratory results. There is therefore a worldwide need for precise data on the characteristics and flow pattern of debris flows obtained from measurements in the field.

The first automatic monitoring of debris flows in Switzerland was carried out in 1993 in the torrent that flows through the village of Randa in the Matter valley (Valais). The WSL has been operating this station since 1995. Three further stations have been built since then at Schipfenbach (1997), Illgraben (2000) and Riale Valegión (2002) (see Fig. 8-11).

In these catchments rain gauges are used to record the precipitation that leads to a mud-flow, geophones measure flow velocity for certain sections, radar or echo sounders are used to determine the depth of the flow and all stations are equipped with video cameras to record the event visually.

In 1993 an additional debris flow weighing apparatus was installed in the Illgraben station, where several debris flows occur every year. This machine consists of a horizontal 4 x 2 m slab screwed onto a steel frame (see Fig. 8-12). Four vertically and two horizontally attached measuring cells record the forces of the

Fig. 8-13: First recording of debris flow on the weighing apparatus in the Illgraben (Valais).

Fig. 8-15: Maggia delta in L. Maggiore.

debris flow, from which the mass on the scales can be determined. The density and water content of a debris flow, together with the depth of the flow and the velocity, can thus be continuously determined. Figure 8-13 shows the first debris flows recorded in summer 2004 using the weighing apparatus.

All these measurements help scientists to gain a better understanding of the debris flow process and are used to develop numerical simulation models for use in the field. The WSL is one of the institutions that have devised such models.

8.1.5 Sedimentation in lakes

By far the largest proportion of sediment is transported into lakes by tributaries (see Fig. 8-15). The volume of sediment is determined by periodic measurements of the bed of the lake (delta measuring). Delta monitoring provides information about the influence of hydro-engineering measures (river modifications and rerouting), changes in gradient, silting up, and ecological and ecomorphological changes in the erosion behaviour of the river. The first measurements were made at the end of the 19th century and involved a wire-weight gauge. From around 1940 on measurements were taken from boats using ultrasound.

The rate of sedimentation (depth of the layers of sediment per unit of time) can be determined using sediment traps and sediment profiles.

8.1.6 Variation in grain size

The variation in grain size within the material deposited on the bed of the lake and in the suspended load (see figs. 8-14 and 8-16) is important in many

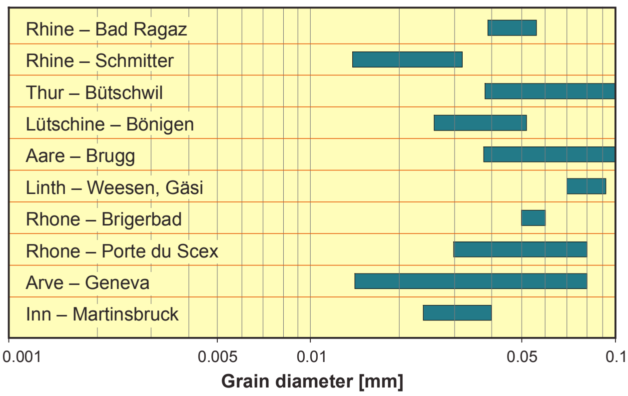


Fig. 8-14: Range of variation in means (median) at selected stations (data: FOWG).

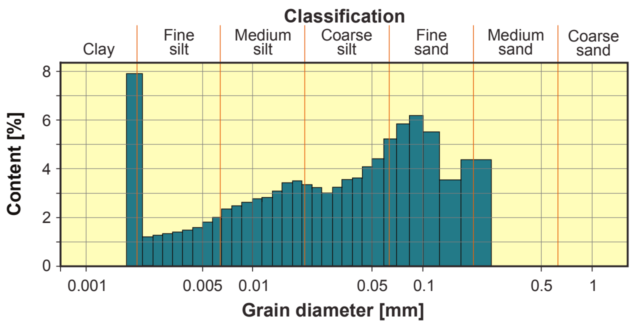


Fig. 8-16: Frequency distribution of suspended load in the R. Rhone at the Porte du Scex station (data: FOWG).

respects, in particular for calculating the transport capacity of a stretch of river. Line and surface samples are taken to determine the larger components (uppermost layer). Volume samples are mainly used to examine the material in the lower layers. The variation in grain size in the suspended load is determined using manual (Attenberg limits method, pipettes) and electronic measuring instruments (sedigraphs, Coulter counters, laser).

8.2 Results

8.2.1 Sediment concentration and total load

It is necessary to determine the concentration and total sediment load in rivers in order to foresee how rivers may dam up. Since, from the point of view of volume, suspended load is more important than bed load they are also of significance as a measure of the extent to which the surrounding land is being eroded into the catchment.

Figure 8-17 shows sediment concentrations and absolute total load measured at Brienzwiler on the R. Aare (see Fig. 8-18). The highest sediment loads can be observed from May to September, when discharge is also high. Figure 8-19 also shows that the concentration of sediments increases when discharge is high. There is only a moderate correlation between sediment concentration and mean daily discharge, however, namely 0.45 (for the period 1993–1997). This correlation coefficient varies in Swiss rivers from 0.2 (R. Reuss at Mühlau) to 0.9 (R. Areuse at Boudry).

The sediment load measured at the Brienzwiler station above L. Brienz is around 125,000 t/year (for the period 1994–2003), which is low by national comparison (see Fig. 8-20). It is the sections of the Alpine rivers above the Alpine foothill lakes that transport the largest loads of sediment (R. Rhine at Diepoldsau: 3 million t/year; R. Rhone at Porte du Scex: 2.7 million t/year; period: 1994–2003).

8.2.2 Bed and suspended loads

It can be seen from Figure 8-21 that the smallest loads can generally be observed in the Central Lowlands (geology: molasse). Apart from the influence of geological factors, this phenomenon is obviously linked to the topography of the area. During rare major events some rivers will transport several times their normal annual load. The specific annual total load decreases the larger the catchment (see Fig. 8-22).

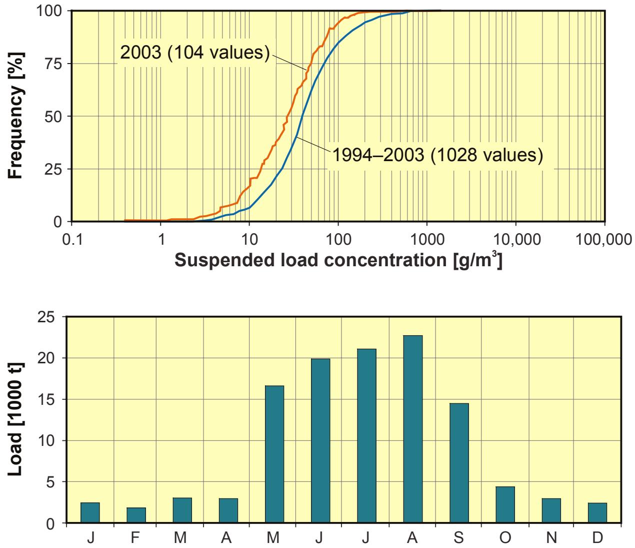


Fig. 8-17: Percentage frequency of below-average annual suspended load concentration (top) and mean monthly suspended load for the period 1994 to 2003 (bottom) measured on the R. Aare at Brienzwiler (OFEG 2004).

Fig. 8-18: Brienzwiler measuring station on the R. Aare (canton of Berne).

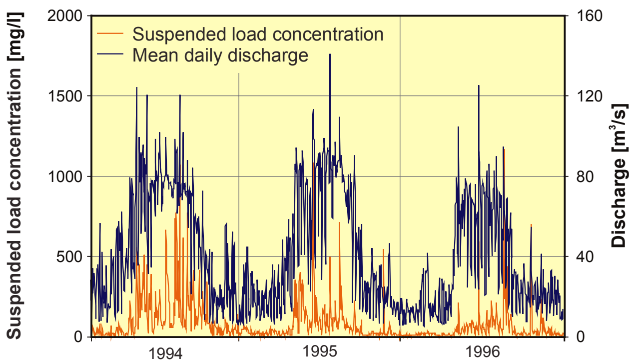


Fig. 8-19: Comparison of discharge and suspended load concentration measured at the Brienzwiler station on the R. Aare (data: FOWG).

Fig. 8-20: Mean annual suspended load for selected Swiss rivers [in tonnes] (after OFEG 2004, Jakob & Spreafico 1997, Spreafico 1988).

8.2.3 Delta studies: The Linth delta

The first bathymetric study of the Linth delta in Lake Walen (see Fig. 8-23) was carried out in 1860. The total volume of sediment transported into the lake each year from the catchment of the River Linth (621.7 km^2) was estimated at between 60,000 and 80,000 m^3. This corresponds to a transport volume of 96.5–128.5 m^3/km^2 per year.

A new map of the delta was drawn in 1911. A total of 9640 measurements were made over an area of the delta of 2.83 km^2. Between 1860 and 1911 the River Linth deposited 3,738,000 m^3 of sediment in L. Walen,

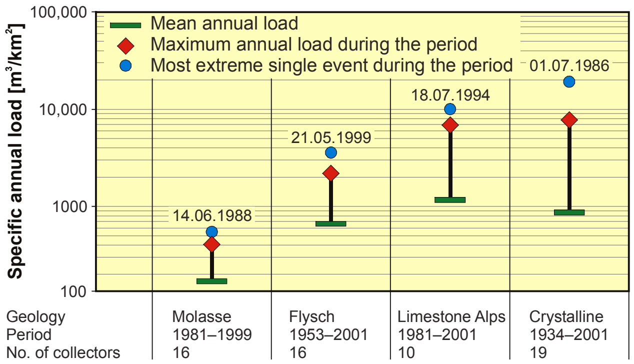


Fig. 8-21: Sediment load transported by selected bed load collectors of different geological ages (data: FOWG).

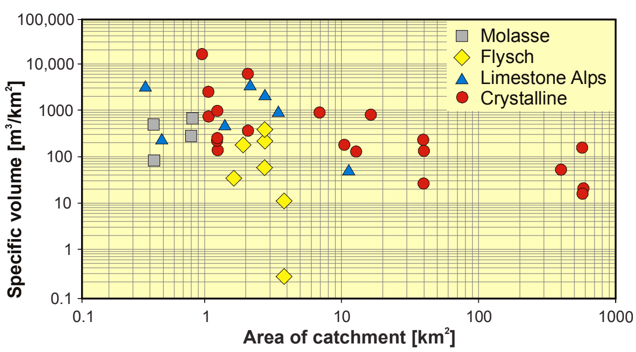


Fig. 8-22: Specific annual load in the areas studied (data: FOWG).

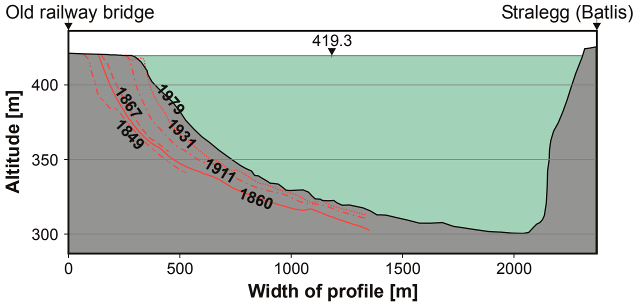


Fig. 8-23: Changes in the delta of the R. Linth between 1849 and 1979 (LAMBERT 1980).

in other words an annual mean of 74,000 m^3. The specific volume per year and per km^2 was 119 m^3 (COLLET et al. 1916).

The delta study was repeated in 1931. The volume of sediment deposited between 1911 and 1931 was estimated at 2,400,000 m^3, corresponding to an annual amount of 114,300 m^3. This was compensated for by an estimated volume of 11,400 m^3 of sediment that was dredged. The balance is therefore around 202 m^3/km^2 per year (EAWW 1939).

In June 1979 the western part of the bed of the lake was measured again. It was estimated that a volume of 6,500,000 m^3 of sediment had been deposited between 1931 and 1979, corresponding to a mean annual erosion rate of 0.23 mm for the catchment.

Compared with earlier studies (0.17 mm/year for the period 1911–1931; JÄCKLI 1958) this would imply that the volume of sediment deposited has risen (LAMBERT 1978, 1980).

8.2.4 Silting up in reservoirs

It can be assumed that within a few decades 50% of the worldwide storage capacity of reservoirs will disappear. In Switzerland silting up is not so dramatic a process (see Table 8-1, Fig. 8-24) for various reasons including the fact that reservoirs are regularly flushed out by opening the sluices at the bottom of the dam.

Reservoir	**Area of catchment** [km^2]	**Specific annual sedimentation rate** [m^3/km$^2\cdot$year]	**Retention volume** [million m^3]	**Annual loss of capacity** [%]	**Source**
Gebidem (Valais)	200	430,000	8.7	5.0	BOILLAT et al. 1996, RECHSTEINER 1996
Palagnedra (Tessin)	139	93,000	2.1	2.0	MÜLLER 1996, VISCHER 1981
Grimsel (Berne)	74	68,000	94	2.8	VISCHER 1981
Dixence (Valais)	47	28,000	400	0.0	BEZINGE & AESCHLIMANN 1981
Luzzone (Tessin)	36.5	35,000	87	0.0	EPFL 1997
L. Sihl (Schwyz)	31.9	68,000	91.8	0.1	AMMANN 1987

Table 8-1: Selected examples of loss of capacity through silting up of reservoirs in Switzerland.

Fig. 8-24: Storage reservoir in Luzzone (Tessin).

Nevertheless, in Switzerland it is extremely important to gain a better understanding of erosion and sedimentation processes, to identify density currents, to know more about the effects of measures taken to reduce the inflow of sediment and to develop strategies for optimal flushing out.

8.3 Estimation of total sediment load in mountain torrents

Floods and debris flows that transport sediment regularly cause a good deal of damage in settlements in the Alps. The WSL draws up an annual summary of such damage in Switzerland (e.g. HEGG 2003). High priority is given to planning and implementing protective measures. Unfortunately, the basic information collected in this respect is still imprecise and incomplete. For this reason the SNHS has been working with the Geographical Institute of the University of Berne to develop a method that can be used to estimate the transport capacity, the load volume, the potential load and the sedimentation rate (see Fig. 8-25). A theory book, a manual and a computer programme are available to help in the application of this method.

After preliminary work in the office, including an initial assessment of the torrent, a field study is carried out. The channel is inspected from top to bottom, the potential load is estimated, and the sedimentation sites are identified and assessed. After this field study the torrent is allotted to a category indicating its transport behaviour. Although this procedure has resulted in an improved estimation of transported load in steep channels, satisfactory solutions have not yet been found to all the problems that are involved.

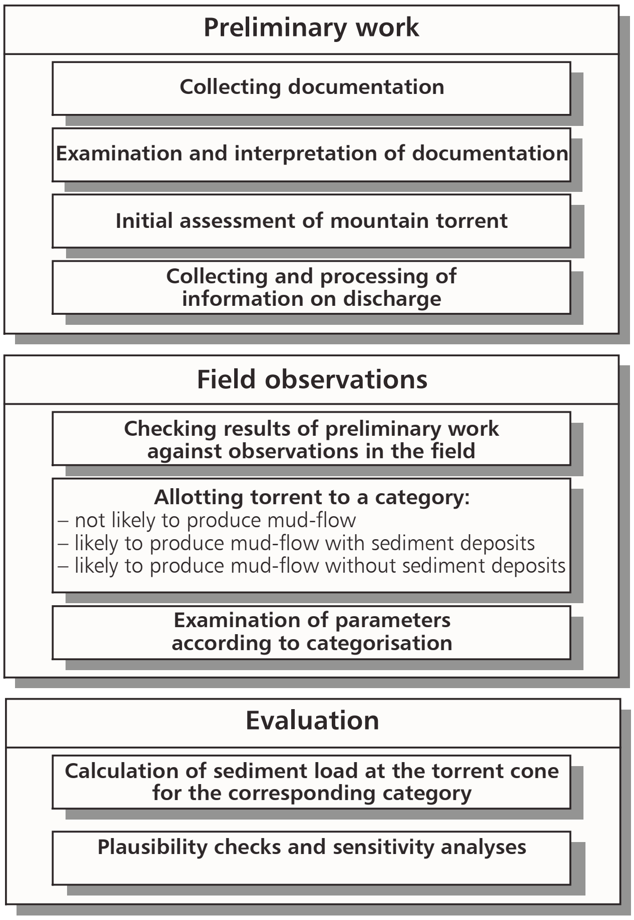


Fig. 8-25: Overview of the process of estimating sediment load (after GHO 1996).

As an example, Figure 8-26 shows a result obtained from calculations concerning the Guppenruns (Glarus). The channel of the torrent is shown in diagram form from cross-profile no. 21 (gorge) down to the confluence with the R. Linth (no. 1). The more important natural sedimentation sites (which can be seen at cross-profiles 19, 18, 13, 8 and 7) are not sufficient to reduce the load carried into the R. Linth to such an extent that the river could not be blocked.

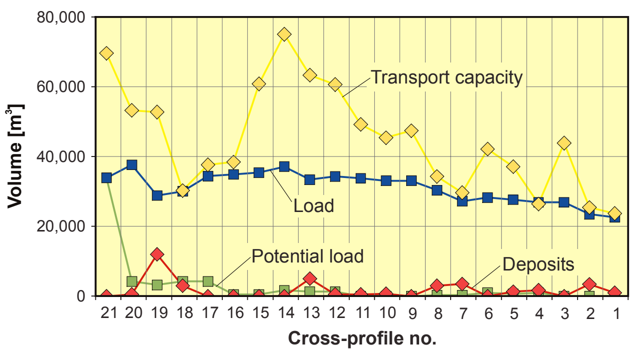


Fig. 8-26: Sedimentation during a storm in the Guppenruns (Glarus) (data: FOWG).

It was shown, however, that the load transported during a major event could be reduced through the planned sedimentation site around cross-profiles 8 and 7 together with additional retaining measures further upstream (around cross-profiles 14 to 12) to such an extent that the R. Linth would practically never be blocked.

8.4 Assessing load after storms

Appropriate measures can be devised more easily if data are collected concerning the processes in the river channel after a flood, the main bulk of the load, the volume of material eroded, sedimentation and the key sites. Moreover, this information also helps to provide an understanding of the process, which is essential for drawing up longer term protective measures. Documentation about sedimentation processes and the volume of material transported as a result of storms is therefore an important part of the comprehensive information about the event. Figure 8-27 provides an overview of the process.

Aerial survey of area in question

- **Mapping of:**
  - – break-away points/cause of event
  - – processes
  - – damage
  - – key sites
- **Initial rough assessment of risk**
- **Planning of inspectation route**

Data collection in area of deposits

- **Assessment of volume of sediment deposit**
  - – measurement of area and gradient of sediment
  - – determination and mapping of sediment deposited
  - – estimation of composition of deposits
- **Assessment of the break-away point**
- **Determination of transport process**

Collection of data in catchment

- **Verification of transport process**
- **Estimation of discharge**
- **Analysis of the channel and the bulk of the load**
- **Drawing up of load balance**
  - – assessment of changes in the channel
  - – estimation of volume of material eroded
  - – estimation of volume of material deposited
  - – calculation of balance
  - – collecting data on composition of material
- **Recording damage caused**
- **Release and pattern of the event**
- **Additional important observations**

Fig. 8-27: Overview of the process of recording sediment deposited after storms (after GHO 1996).

9 Water quality

Statistics						Source: OFEG 2004
Mean concentration at selected NADUF stations in 2003 (weight of load)						
Station	**Nitrates**	**Total N**	**Orthophosphates (filt.)**	**Total P**	**Organic carbons DOC (diss.)**	**Organic carbons TOC (total)**
	N [mg/l]	**N [mg/l]**	**P [mg/l]**	**P [mg/l]**	**C [mg/l]**	**C [mg/l]**
Catchments mainly in Alps or Alpine foothills						
Rhine – Diepoldsau	0.52	0.64	0.003	0.099	1.0	2.8
Kleine Emme – Littau	1.06	1.90	0.013	0.211	3.3	8.3
Rhone – Porte du Scex	0.46	0.50	0.005	0.184	0.9	2.6
Inn – S-chanf	0.27	0.30	0.003	0.091	1.0	1.8
Major rivers in Central Lowlands with lakes in catchments						
Rhine – Rekingen	1.18	1.23	0.010	0.031	2.2	2.7
Rhine – Weil	1.36	1.44	0.014	0.038	2.3	2.9
Aare – Hagneck	0.92	1.02	0.003	0.029	1.6	2.1
Aare – Brugg	1.64	1.68	0.012	0.038	2.7	3.4
Reuss – Mellingen	0.75	0.92	0.006	0.044	2.7	3.3
Rhone – Chancy	0.62	0.76	0.020	0.085	1.7	2.5

This chapter deals principally with issues of the quality of the water in rivers and streams. Questions pertaining specifically to the quality of lakes and groundwater are dealt with in chapters 6 and 7.

9.1 Measuring water quality

The condition of a body of water can be described using many different parameters. As part of its project entitled the national long-term surveillance of Swiss rivers (NADUF), which was started in 1972, the FOWG examined selected principal chemical and physical parameters for rivers and streams.

The focus of interest is those chemical components that can be used for estimating human pollution of bodies of water. The table of statistics above shows the mean concentration of nitrogen (see Section 9.2.3), phosphorus (see Section 9.2.2) and organic carbons (DOC = dissolved organic carbons; TOC = total organic carbons) for 2003; the values are weighted according to load. The measuring stations have been divided into two groups according to geographical characteristics. In contrast to other stations in the same group, the Littau station on the Kleine Emme recorded a higher rate of nitrogen and phosphorus pollution, which can be explained by the more intensive agricultural use of the land in the catchment. The phosphorus concentration in the remaining rivers, whose catchments are in the Alps or the Alpine foothills, follows a seasonal pattern: thanks to erosion (e.g. apatite), the total phosphorus concentration is higher in summer, when rivers are fuller, than in winter. This contrasts with the orthophosphate concentration, which is lower in summer than in winter owing to the dilution effect of higher discharge, the varying origin of the water and reduction in summer due to biomass production.

Other important parameters such as dissolved oxygen content (see Section 9.2.4) and water temperature (see Section 9.2.1) are not direct indicators of pollution although they determine the habitat of aquatic organisms.

9.1.1 Measuring networks and sampling practices

NADUF, a joint project involving the FOWG, the Swiss Agency for the Environment, Forests and Landscape (SAEFL), the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) and the Swiss Federal Insti-

Fig. 9-1: Selected NADUF measuring stations in Switzerland.

tute for Forest, Snow and Landscape Research (WSL), provides information for assessing the present condition of rivers and streams as well as forecasting medium and long-term changes (Jakob et al. 1994). Normally, every 2 weeks sample series are taken in proportion to discharge and examined for several chemical components. In addition, the pH, electrical conductivity, temperature and concentration of dissolved oxygen are recorded at most measuring points. Figure 9-1 shows the location of selected NADUF stations.

The majority of chemical analyses of bodies of water are carried out by the cantonal water protection offices. The type and number of samples collected by individual cantonal offices vary considerably, even from the point of view of location and intervals. Either 4, 12 or more random samples or between 12 and 365 twenty-four-hour sample series are taken from rivers and streams every year. In the case of lakes between 2 and 12 samples are taken, with random sampling at various depths. In some cases high-resolution depth profiles are drawn up using measuring probes to analyse the water for dissolved oxygen, temperature, electrical conductivity and turbidity.

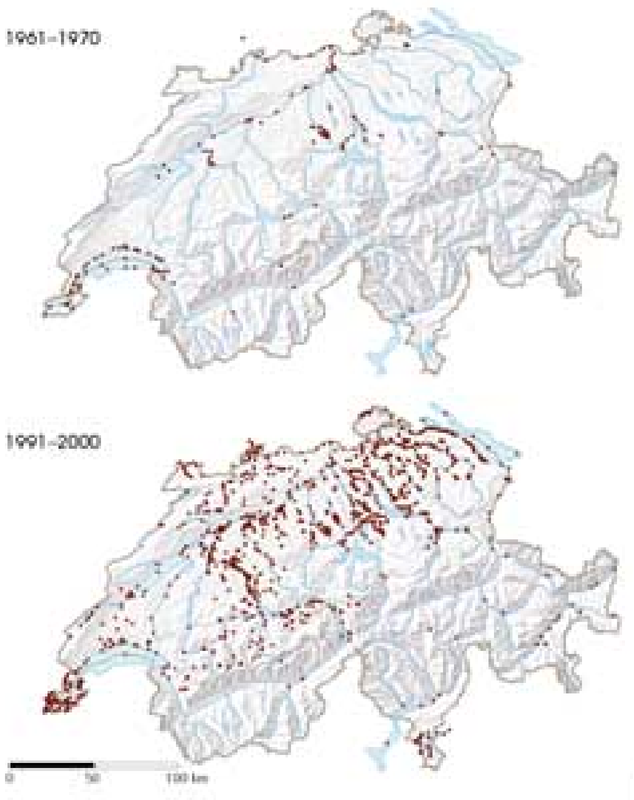


Fig. 9-2: Development of the measuring network (after Jakob & Geissel 2004).

The results of analyses carried out by federal and cantonal offices to assess the chemico-physical properties of Swiss rivers and lakes are stored in the Water Condition Database (WCD), which is managed by the FOWG. This database, whose application can be accessed by several users simultaneously, includes user-friendly management and evaluation functions (Jakob & Guntersweiler 1996).

Figure 9-2 shows the development of the measuring networks for determining chemical and physical parameters in rivers and lakes and is based on the measurement results stored in the WCD. Apart from the chemical parameters, it also includes data on sediment content and individual measurements of temperature and electrical conductivity. The measuring points with available data on rivers and lakes recorded for the various years are indicated, regardless of the number and type of samples that are taken. This overview shows clearly that in many places comprehensive water analyses were only started after 1970, when the second Water Protection Act came into force. This means that in many places the start of the measurement series coincides with the point when pollution was at its worst. In most places there are no long measurement series with data that have been collected regularly.

Owing to the trend in temperature change in rivers and lakes that has been observed since the end of the 1980s, new measuring points located on smaller bodies of water that are subject to as little influence as possible have been added to the FOWG temperature-measuring network since 2001.

9.1.2 Sampling and NADUF measuring apparatus

At the FOWG stations, a submerged pump is used to provide automatic samples of river water for continuous measurement (see Fig. 9-3). The photograph shows the container fitted with measuring electrodes into which the water flows. Electrical conductivity, oxygen concentration and pH are determined continually. At the beginning of 1990 the FOWG started to install digital recorders, and since 1999 ten-minute means for temperature, pH, oxygen concentration and electrical conductivity have been transmitted by telephone, thus permitting more frequent data control.

The measuring electrodes are cleaned and recalibrated every month. Any discrepancies between the recorded and the real values are taken into account when the data are analysed. The tubes through which the water flows in and out of the apparatus, as well as the sampler, are thoroughly cleaned at the same time when the probes are serviced.

At fixed intervals, the sampling apparatus takes two consecutive individual samples from a depth of one and two millimetres. Wherever possible, the sampling apparatus operates in proportion to the discharge. If it is not possible to take samples in proportion to discharge they are taken in proportion to time. The automatic samples are fed into containers through a distribution system (acidified for heavy metal analysis, not acidified for analysing other parameters) that are kept refrigerated (see Fig. 9-3). Up until 1980 these so-called sample series were taken weekly and subsequently analysed. Since 1981 the weekly sample series have been combined to form 14-day mixed samples before they are analysed. In the case of measuring stations downstream from lakes, sample series have been taken and analysed every two weeks since 1993 because peak flood levels there are attenuated in contrast to stations upstream from lakes, which means that the risk of the sample jars overflowing is lower and 14-day sample series are therefore sufficient. The sample jars are cooled and sent as quickly as possible to the EAWAG for analysis.

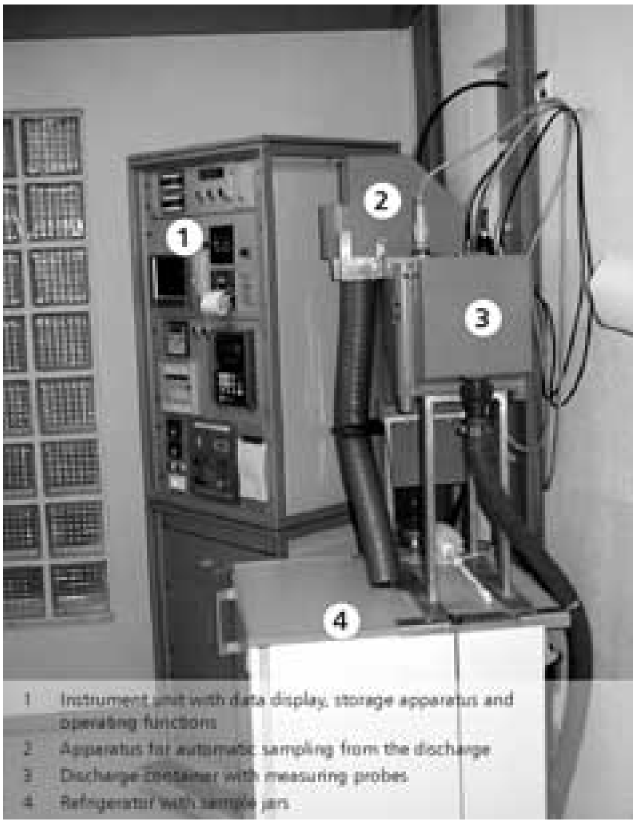


Fig. 9-3: NADUF measuring station.

9.2 Selected parameters

Questions concerning water quality can be answered by analysing water temperature as well as phosphorus, nitrogen and oxygen content.

9.2.1 Water temperature

The temperature of the water is one of the principal regulators of life in rivers and lakes. All metabolic processes, the duration, pattern and speed of growth, and the composition of biocoenoses are influenced by temperature.

The viability and activity of aquatic organisms depend on certain extreme and optimal temperatures. The temperature pattern is therefore one of the factors that account for the differences in fish populations in Central European rivers. The frequency of quite a number of fish species in certain stretches of river can be explained solely by their preference for and tolerance of specific ranges of temperature. In the upper reaches of the rivers fish that prefer colder water are more frequent, for example, while species which live in larger populations in the lower reaches are better adapted to higher water temperatures and are largely insensitive to greater temperature fluctuation.

Gases are dissolved less readily as the water temperature rises and the ability of water to absorb oxygen also decreases. At the same time the activity of animal organisms rises, as does their oxygen requirement. If the demand for oxygen is high and at the same time supply is low, fish show symptoms of stress. One of the consequences of this stress is reduced feeding. If the temperature exceeds the limit for a given species it will not survive unless it can escape from the warmer water. Moreover, temperatures of 15°C and above promote outbreaks of proliferative kidney disease, which can kill off many fish.

Each species has its own optimum temperature. *Salmonidae* such as trout, whitefish or grayling may show symptoms of stress if the water rises above 18–20°C;

they may die if it exceeds 25°C. Other species such as carp, perch or pike endure high temperatures better.

In the case of flora and fauna in rivers and streams it is not the mean temperature over a given time that is crucial but the duration of the stress situation caused by the temperature of the water. The longer an organism is subjected to unfavourable temperatures the more likely it is to display the corresponding symptoms.

Apart from their biological effect, higher temperatures also change the chemical composition of the water. For example, ammonium (NH_4^+) is converted to ammonia (NH_3), or algae spread and cause what is known as "biogenic decalcification".

The temperature balance of bodies of water depends on many environmental factors. In this respect, the temperature of the spring water and tributaries, solar energy absorbed and lost, precipitation, evaporation, condensation and snow melt all play a decisive role, as well as heat exchange with the subsoil and the air. For example, the heat exchange process between the water and the environment is more marked in rivers owing to the movement of the water. Finally, environmental factors such as shade from vegetation along the bank or shore or the infiltration of colder groundwater can also have a major influence on the temperature of the water. In the case of the Alpine rivers, the proportion of melt water from snow and ice is an additional factor influencing temperature.

All these factors are subject to both short and long-term fluctuation, which in turn affects the dynamics of the temperature balance of water. The temperature of water at a given point therefore depends on the sum of many individual factors as well as the duration of their influence in higher reaches and in the catchment.

The initial temperature of a body of water is determined by the temperature of the groundwater in the vicinity of the spring, which in turn depends on altitude. Apart from thermal springs, the temperature of spring water normally corresponds to the mean annual temperature of the air at the place in question and fluctuates very little. The temperature of rivers and streams at lower altitudes rises more and shows a greater annual variation.

Lakes in catchments tend in particular to attenuate short-term temperature fluctuations in the rivers that flow out of them. On the other hand, a lake comprises

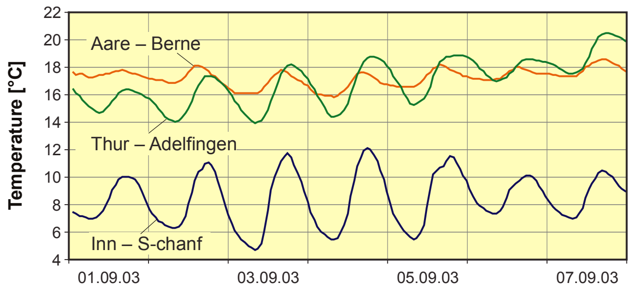


Fig. 9-4: Daily variation in water temperature (R. Aare in Berne: attenuated through the influence of lakes) (data: OFEG 2004).

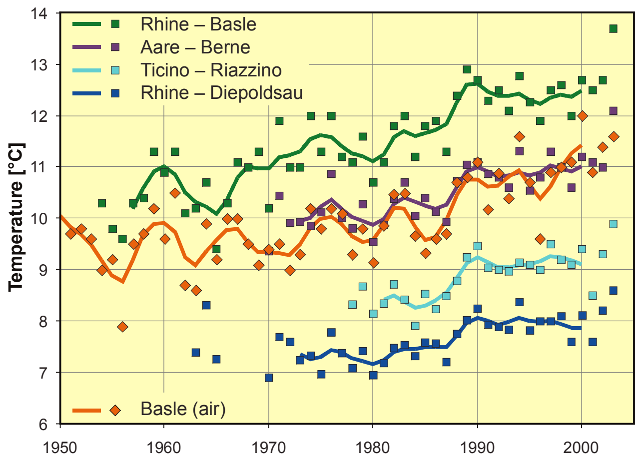


Fig. 9-5: Change in water temperature at selected FOWG measuring stations since 1950: annual means (squares) and moving average over seven years (lines). For the sake of comparison the change in air temperature in Basle is also given (after BUWAL/BWG/MeteoSchweiz 2004).

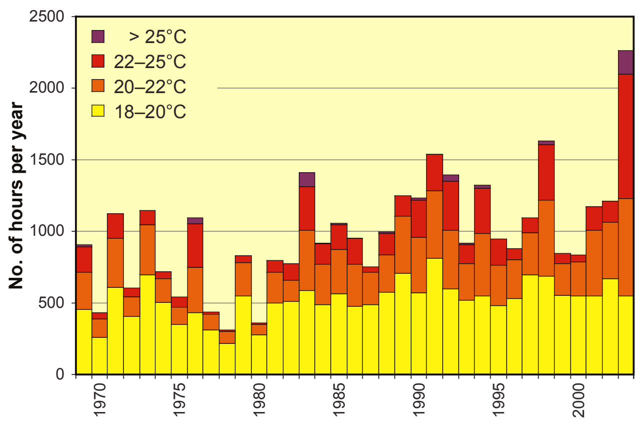


Fig. 9-6: Duration of water temperature over 18°C in the R. Thur at Andelfingen (no. of hours per year). The chosen temperature limits correspond to the sensitivity zones of certain fish species (after BUWAL/BWG/MeteoSchweiz 2004).

a large surface of water that can be warmed by the sun. Since in summer it is generally the top layer of warm water that flows out of a lake, rivers flowing out of lakes are generally warmer than those that flow into them.

When the water level in rivers and streams is low they heat up more quickly than when they are full, since the water in a low river is distributed over the whole width of the profile and thus presents a larger surface for heat exchange.

In sunny weather, the daily fluctuation in water temperatures shows a marked and mostly sinusoidal periodicity, the difference between day and night temperatures often being in the order of a few degrees (see Fig. 9-4). The lowest temperatures can be observed in the early morning and the highest during the afternoon.

There is also a clear sinusoidal pattern in the seasonal temperature variation, which is more marked in the Central Lowlands than in the Alps. This variation is the result of the pattern of solar radiation over the year. The effect of short-term meteorological influences such as cold and warm fronts or the occurrence of north or south winds can also be clearly seen on the temperature curve as a deviation from the sinusoidal seasonal pattern.

Since 1954, longer water temperature measurement series produced by selected FOWG stations have shown a rise in temperature (see Fig. 9-5). This increase is over 2°C at the R. Rhine in Basle, for example. Measurements taken there between 1988 and 2003 gave an annual mean of over 12°C, regardless of channel flow, which is considerably higher than in previous years. In 2003 the mean annual temperature was well above 13°C for the first time. A similar trend has been observed in bodies of water in the Central Lowlands. It is due to several factors including climate change, warmed water being fed in and changes in discharge pattern (for example through damming and drainage).

A clear increase in periods when the temperature is high has also been observed in the case of the R. Thur at Andelfingen, whose catchment is in the Central Lowlands and which is not subject to additional influences of lakes or glaciers upstream (see Fig. 9-6). It is noticeable that the period in 2003 when the water temperature was over 20°C is two to four times longer than those in the drought years of 1976 and 1983.

On average, the temperature of the water rises in April or May, which is earlier than in the 1970s, thus lengthening the summer period during which water temperatures are high.

9.2.2 Phosphorus

Phosphorus is the most important factor that limits growth. It occurs naturally in solution or in solid form and can be either organic or anorganic in origin. Orthophosphates are phosphorus components which have a direct physiological effect on plants. Concentrations should be as low as possible in lake tributaries in particular, in order to avoid the lake becoming increasingly enriched with nutrients (eutrophication) (see Section 6.4.1). Phosphates enter the water by being leached out of the soil in agricultural areas and occasionally from waste water pipes and rain overflow basins.

Over the past few years the concentration of phosphates in Swiss bodies of water has decreased (see Section 6.4.2). This is the result on the one hand of sewage treatment plants being improved in particular through the installation of phosphate extractors, and on the other of phosphates being banned in washing powders in 1986. Today the larger part of all phosphorus that enters the water comes from agriculture,

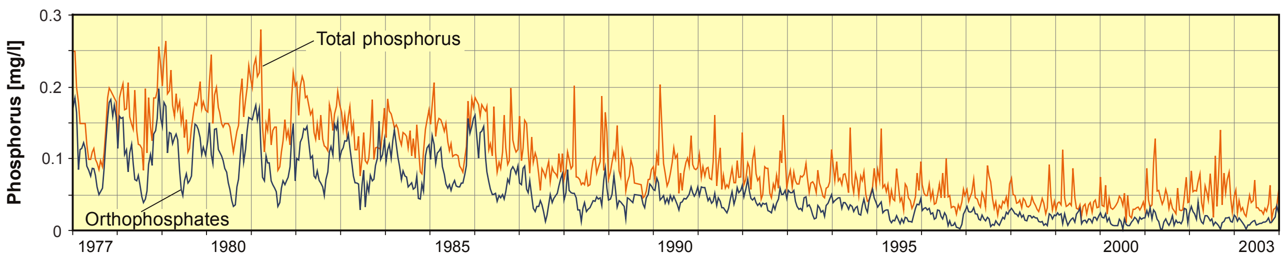


Fig. 9-7: Hydrograph of phosphorus concentration in the R. Rhine at Village-Neuf/Weil (after JAKOB et al. 2004).

although this sector has also become more environmentally aware in recent years. A particular problem is the accumulation of phosphorus in the soil in many parts of the Central Lowlands. Since phosphorus is not always permanently bound in the soil (regardless of the type of soil and the soil hydrology) more phosphorus will accumulate in the medium to long term and may lead to eutrophication, even after further measures have been imposed with respect to agriculture.

In Figure 9-7 it can be seen that both the concentrations and fluctuations of phosphorus have decreased in rivers and streams downstream from lakes. This reduction in phosphorus content has led to a shrinking of the algae biomass and thus less turnover of material.

9.2.3 Nitrates

Nitrates are a good indicator of pollution from agriculture and treated sewage. After a period of increase which lasted until the end of the 1980s, in most places the nitrate content in bodies of water has fallen again over the past ten years (see Fig. 9-8). This is the result of encouraging farmers to adopt more environmentally friendly practices as well as a drop in emissions of NO_x due to the introduction of catalytic converters in petrol engines.

Figure 9-9 shows the changes in selected chemical parameters between 1976 and 2000. The map is taken from the Hydrological Atlas of Switzerland (HADES) and shows categories of mean concentrations of three chemical compounds for various periods.

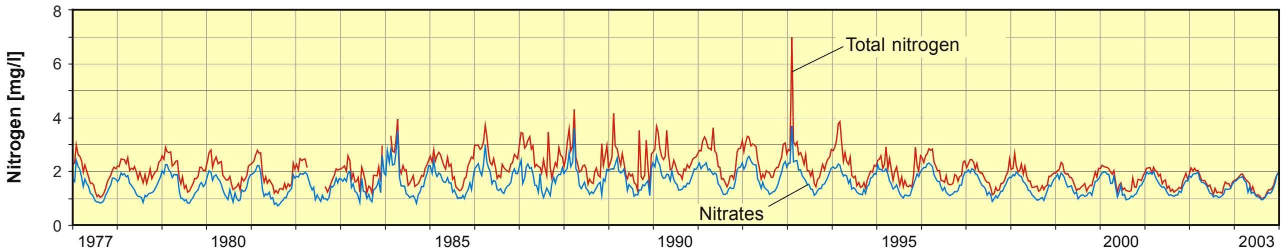


Fig. 9-8: Hydrograph of nitrogen concentration in the R. Rhine at Village-Neuf/Weil (after JAKOB et al. 2004).

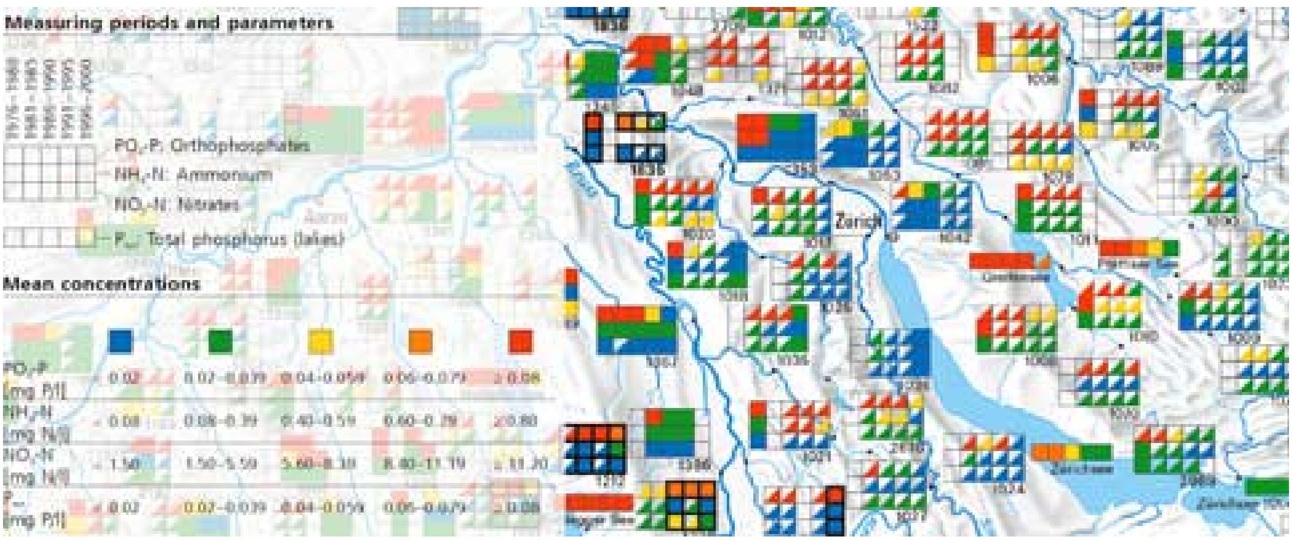


Fig. 9-9: Part of the HADES map entitled “Changes in selected chemical parameters in rivers and lakes between 1976 and 2000” (JAKOB et al. 2004).

9.2.4 Oxygen

For organisms that live in rivers and lakes, a high water temperature causes stress, in particular if at the same time the amount of oxygen in the water is low. Measurements made at the Andelfingen station on the R. Thur show differences between the periods 1986 to 1990 and 1996 to 2000 that indicate a clear rise in oxygen concentration, especially in the winter months (see Fig. 9-10).

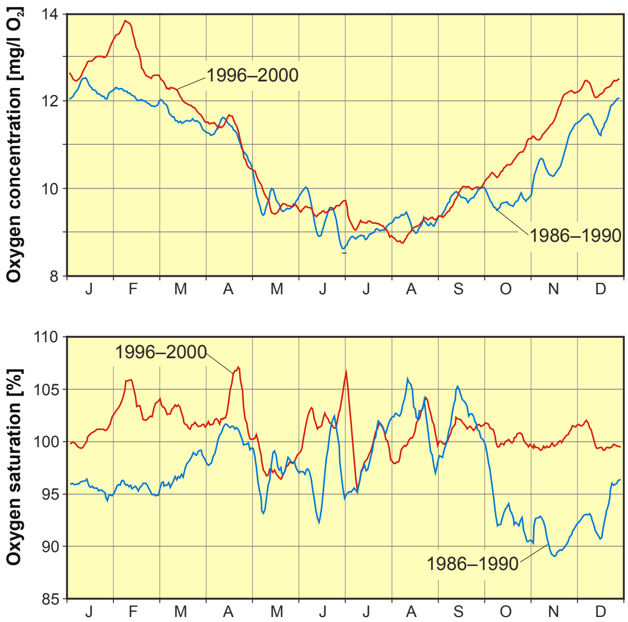


Fig. 9-10: Mean measured oxygen concentration and calculated oxygen saturation in the R. Thur at Andelfingen. Daily means over moving periods of 7 days (after JAKOB et al. 2002).

By calculating oxygen saturation the portion of oxygen content over the year that is dependent on temperature can be eliminated. On average oxygen saturation rose from 97% in 1986–1990 to 101% in 1996–2000. During the first period the saturation level was well under 100% for longer periods of time. By the end of the 1990s the situation was considerably better, especially during the winter. This can be explained to a large extent by measures taken concerning the disposal of sewage. On average the level of orthophosphates decreased between the two periods from 5.3 g P/s (1986–1990) to 2.8 g P/s (1996–2000), for example. In the bodies of water in the Central Lowlands investigated as part of the NADUF where temperatures had risen during these periods no clear lack of oxygen was observed. In contrast, over-saturation of up to 200% is possible in the short term, in stagnant water in particular, if oxygen is produced in a body of water through photosynthesis. In rivers and streams the excess oxygen is released more quickly, depending on the amount of movement in the water.

The extraordinary intensity of solar radiation and record temperatures experienced in August 2003 were reflected in the oxygen content in rivers and lakes. During the heat wave the variation in oxygen saturation observed at NADUF stations downstream from lakes reached a level that had never been seen since measurement series were started, even in the drought year of 1976 (see Fig. 9-11). This effect is emphasised by slow-flowing river water, which does not help to establish a balanced exchange with atmospheric oxygen. In this respect, the length and morphology of the stretch of river from where it leaves the lake to the measuring station are of importance. On the stretch of water from Lake Biel to the measuring station on the R. Aare at Brugg, for example, there are nine large weirs in which the Aare flows slowly. The R. Reuss is also affected by four weirs down to the measuring station at Mellingen, but these four stretches are insignificant in comparison with the whole river. In the hot summer of 2003, exceptionally low oxygen values during the night (< 80%) were observed at the Brugg measuring station, while the Mellingen station recorded especially high values during the day (> 170%).

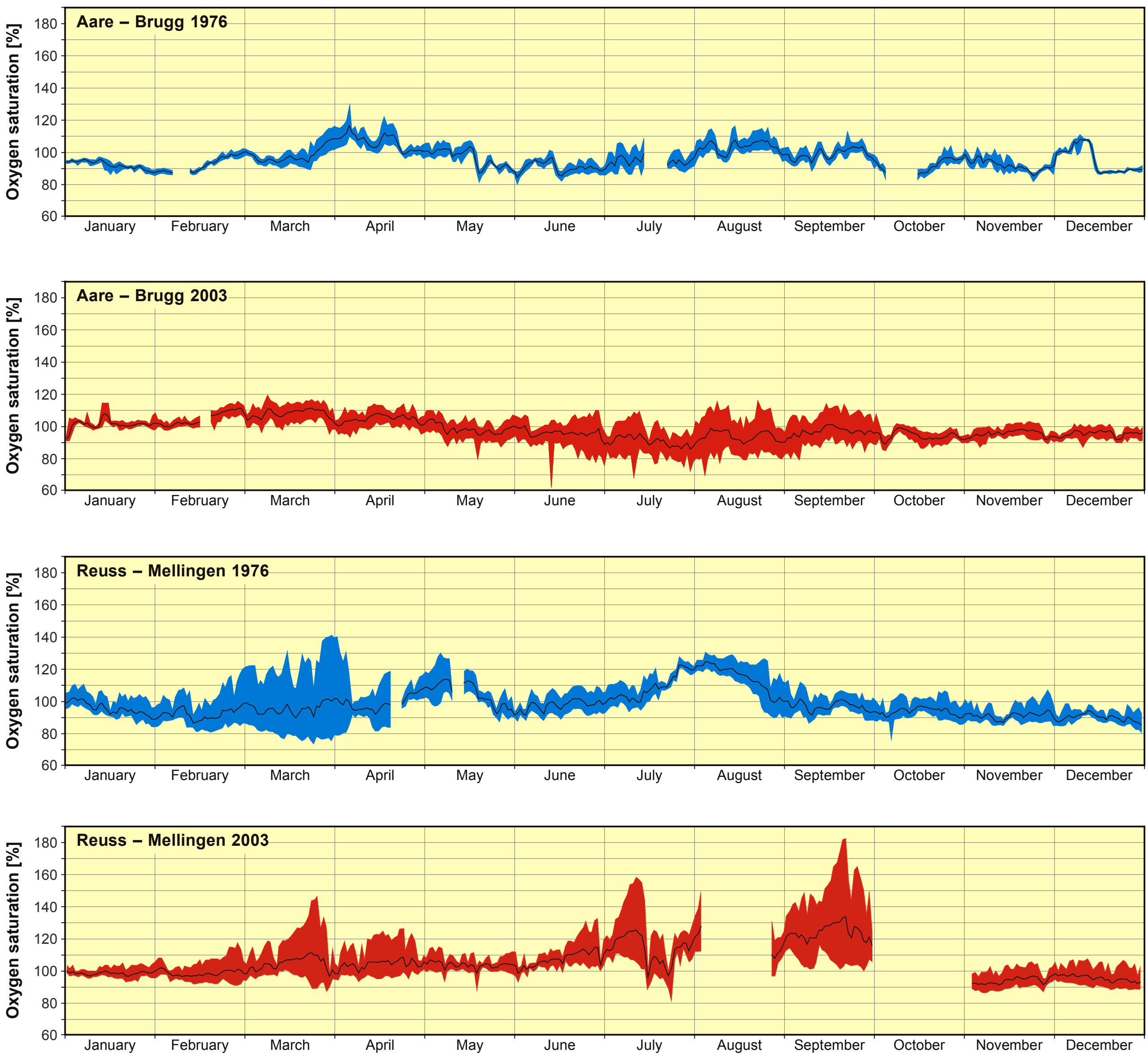


Fig. 9-11: Oxygen saturation of the R. Aare at Brugg and the R. Reuss at Mellingen during the droughts of 1976 and 2003. Daily mean and variation between minimum and maximum values (after BUWAL/BWG/MeteoSchweiz 2004).

10 Water balance

Statistics

Water balance in Switzerland (period: 1961–1990) — Source: SCHÄDLER & WEINGARTNER 2002a

Canton	**Precipitation P [mm/a]**	**Runoff R [mm/a]**	**Evaporation E [mm/a]**	**Storage δS [mm/a]**	**Subterranean inflow/discharge I [mm/a]**	***Percentage of total runoff (CH) [%]***
Aargau	1086	521	565	–	–	*1.8*
Appenzell I	1891	1229	480	0	–182	*0.5*
Appenzell A	1596	1059	537	–	–	*0.6*
Berne	1484	1028	465	–2	7	*15.0*
Basle-Land	988	455	533	–	–	*0.6*
Basle-Stadt	942	393	549	–	–	*< 0.1*
Fribourg	1242	720	522	–	–	*2.9*
Geneva	981	363	618	–	–	*0.3*
Glarus	1971	1617	417	–6	57	*2.7*
Grisons	1443	1099	346	–2	–	*19.1*
Jura	1181	680	501	–	–	*1.4*
Lucerne	1318	748	547	–	–23	*2.7*
Neuchâtel	1339	818	521	–	–	*1.6*
Nidwalden	1785	1290	495	0	–	*0.9*
Obwalden	1781	1316	453	–1	–13	*1.6*
St. Gallen	1658	1156	498	0	–4	*5.7*
Schaffhausen	916	364	552	–	–	*0.3*
Solothurn	1106	570	536	–	–	*1.1*
Schwyz	1997	1499	498	0	–	*3.3*
Thurgau	1027	421	606	–	–	*1.0*
Tessin	1971	1474	497	0	–	*10.1*
Uri	2088	1711	382	–5	–	*4.5*
Vaud	1250	678	572	0	–	*5.3*
Valais	1457	1062	401	–6	–	*13.6*
Zug	1447	872	575	–	–	*0.5*
Zurich	1221	662	559	–	–	*2.8*
Switzerland	1458	991	469	–2	0	*100.0*

10.1 The hydrological cycle

The global hydrological cycle, i.e. the movement of water from the oceans via the atmosphere to the continents and back, is intrinsically linked to regional hydrological cycles over given areas of land. It is composed of precipitation (P), runoff (R), evaporation (E), changes in the quantity of water stored (δS) and subterranean inflow and discharge (I).

Evaporation is often chosen as the starting point of the hydrological cycle (see Chapter 4). Water may evaporate direct from bodies of water or areas of land or be given off into the atmosphere from the soil and groundwater through the transpiration of plants. Clouds and fog form through the condensation and resublimation of water vapour (see Fig. 10-1). On average a water molecule remains in the atmosphere for about 9 days (BAUMGARTNER & LIEBSCHER 1990) before it returns to the ground in the form of rain, hail, snow, hoarfrost or drizzle (see Chapters 2 and 3). Once it reaches the ground it appears in rivers and streams (see Chapter 5), in lakes (see Chapter 6) or in the form of snow in glaciers (see Chapter 3) and in the groundwater (see Chapter 7).

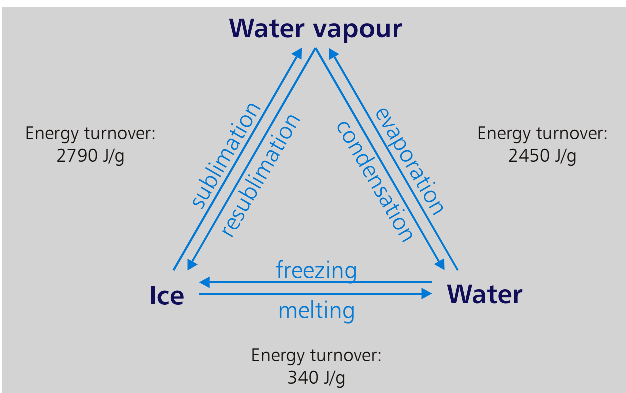


Fig. 10-1: Aggregates in water.

On its route water takes up solid and soluble material. The erosive effect of water leaves its mark on the surface of the earth, e.g. through the transport and accumulation of solid material (see Chapter 8), and makes it necessary to regularly service all hydro-engineering installations (see Chapter 5). For many of its uses, the quality of the water is of the essence (see Chapters 6, 7 and 9). At the latest when it evaporates again the water leaves all the material it has carried behind ... and the hydrological cycle begins all over again (see Fig. 10-2).

Fig. 10-2: Hydrological cycle and water balance.

The isotopes of a water molecule (oxygen-18, deuterium and tritium) are ideal natural tracers for examining hydrological processes, for example for determining the origin or the age of groundwater (see Section 10.5).

10.2 The water balance

The water balance encompasses all flowing water in a given area. As part of the hydrological cycle, evaporation is the most difficult process to measure and is often calculated as the remaining water not accounted for in other ways. Thanks to a hydrological "new interpretation" of the water balance it is now possible to determine area precipitation in mountain areas in Switzerland with greater accuracy than before (SCHÄDLER & WEINGARTNER 2002b).

The water balance describes the circulation of water in a given area and over a given period of time. It provides an overview of the water resources that will be available in the long term. By dividing Switzerland into 287 balance zones (catchments with an area of between 100 and 150 km^2) it is possible to gather detailed information about the water balance for any given geographical area. The balance zones are aggregated to determine the water balance of river valleys, cantons (see statistics at the beginning of this chapter) and finally the whole of Switzerland (see SCHÄDLER & WEINGARTNER 2002a).

10.2.1 The classical water balance

The water balance equation ($P = R + E + \delta S - I$) can be solved according to the evaporation:

$$E = P - R - \delta S + I$$

where:
- E is area evaporation [mm/a]
- P is area precipitation [mm/a]
- R is area runoff [mm/a]
- δS is change in water stored in glaciers [mm/a]
- I is natural subterranean inflow and discharge [mm/a]

If evaporation is calculated using this formula the values obtained are often unrealistic owing principally to incomplete precipitation measurements, errors in measuring precipitation in the mountains and finally the subsequent interpolation (see Chapter 2). Figure 10-3 shows area evaporation in the Rhine catchment at Felsberg calculated using the water balance equation. The results obtained are not plausible since they are extremely varied and are higher at greater altitudes. For purposes of comparison, the figure also shows the expected evaporation for the same area,

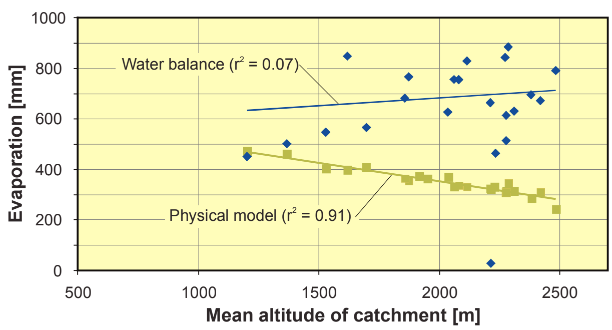


Fig. 10-3: Comparison of evaporation calculated from the water balance for the balance zones in the Rhine catchment at Felsberg, based on measured and regionalised precipitation (data: KIRCHHOFER & SEVRUK 1992) with values obtained using a physical model (data: MENZEL 1997) (after SCHÄDLER & WEINGARTNER 2002b).

which decreases at greater altitudes, calculated using a physical model (MENZEL 1997).

10.2.2 The hydro*logical* water balance

On the basis of the problem described in Section 10.2.1 SCHÄDLER & WEINGARTNER (2002b) took up the suggestion made by LANG (1985) for determining precipitation in the Alps. In their hydro*logical* "new interpretation" of the water balance they assume that it is not evaporation but precipitation measured in the mountains and the area precipitation deduced from it that are the main source of error, particularly since today reliable figures for evaporation are available for all areas (see Section 4.4) and the change in the volume of water stored in individual typical glaciers has been researched (see Section 3.7).

"Hydro*logical*" means that both the water balance components within one balance zone and the water balances of several balance zones match (see Fig. 10-4). In this respect it is essential that the runoff data are accurate. The water balance can be determined directly in areas for which reliable runoff data are available. The runoff from areas with less reliable data has to be estimated by balancing one region against another. SCHÄDLER & WEINGARTNER (2002a) were the first to present data on all water balance components for the whole of Switzerland.

10.2.3 The water balance of Switzerland

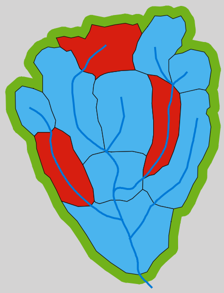
With the hydrological approach described in Section 10.2.2 individual components of the water balance can be determined for the whole of Switzerland (see Fig. 10-5) and for each of the 287 balance zones. Figure 5-32 shows for example the area runoff of the balance zones calculated by SCHÄDLER & WEINGARTNER (2002a).

The proportion of precipitation that evaporates is 50% in the Central Lowlands and the Jura (see Fig. 10-6); in some cases, however, it can reach as much as 70% of area precipitation. Absolute values for area evaporation are around 500 to 650 mm/a with a maximum of 720 mm per year. In the Alps the proportion of precipitation which evaporates is very small; in the balance zones of the high Alps up to 90% of the precipitation will be transformed into runoff (SCHÄDLER & WEINGARTNER 2002b).

Balance zones with plausible runoff data → all components of the water balance (incl. area precipitation) can be determined directly

Balance zones with less plausible runoff data → area precipitation must be estimated

Primary catchment with plausible runoff data → reliable determination of area precipitation (P) is possible



Procedure for regional adjustment

1) Calculate area precipitation, weighted according to area, from the area precipitation of the balance zones ($\hat{P}$)

2) Adjust any difference between $\hat{P}$ and P in area precipitation for the areas marked in red

3) Calculate runoff from areas marked in red

Fig. 10-4: Calculation of the water balance for balance zones with regional adjustment (after SCHÄDLER & WEINGARTNER 2002b).

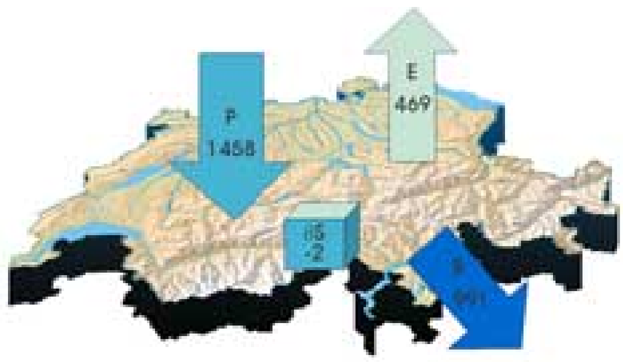


Fig. 10-5: Water balance for Switzerland: annual water depth in mm (period 1961–1990) (data: SCHÄDLER & WEINGARTNER 2002a).

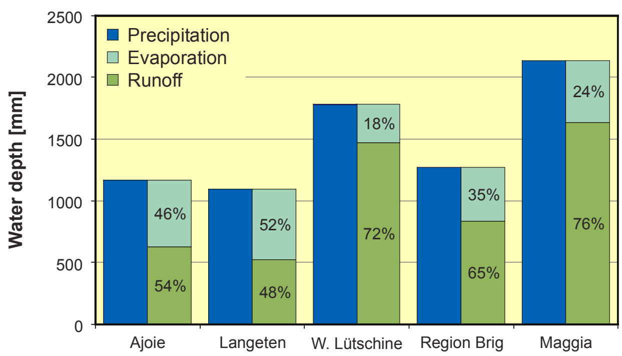
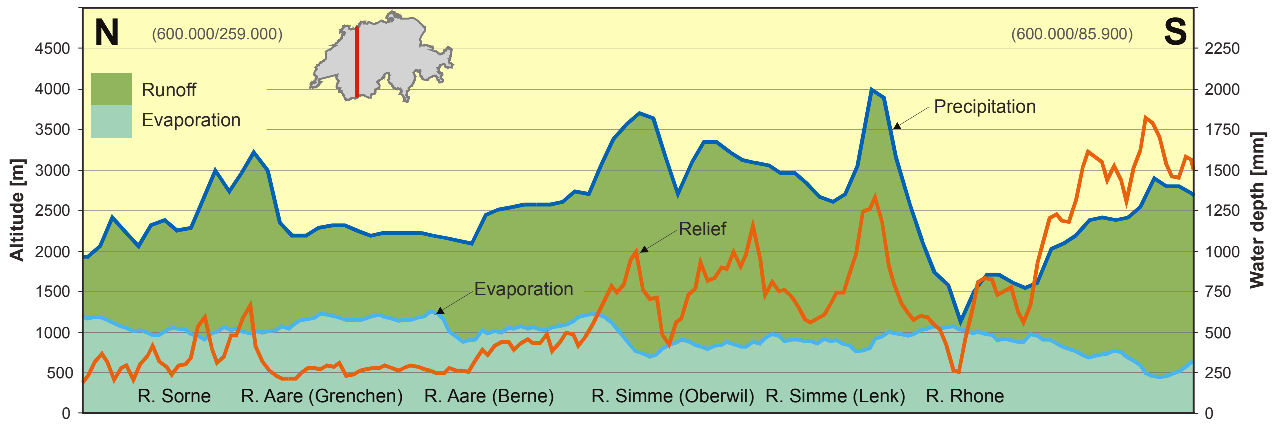


Fig. 10-6: Characteristic mean water balance of balance zones along a profile Jura – Valais – Tessin (period 1961–1990) (after SCHÄDLER & WEINGARTNER 2002b).

Figure 10-7 shows fluctuations in two water balance components, namely precipitation and evaporation, along two north–south profiles. Runoff is the difference between the two components, discounting subterranean inflow and discharge and changes in the volume of stored water.

The water balance of larger catchments or cantons can be calculated for other purposes. The proportion per canton of total runoff in Switzerland varies from less than 0.1% (Basle-Stadt) to 19.1% (Grisons) (see statistics at the start of this chapter). These figures naturally reflect the difference in size of the cantons. In order to compensate for this, an efficiency factor has been calculated for each canton based on the ratio of the runoff percentage of a given canton to its area. Using this approach, the canton of Uri (4.5% of total runoff) has an efficiency factor of 1.7, followed by Glarus with a factor of 1.6 and Schwyz and Tessin with 1.5. This means that, owing to a high rate of precipitation, the canton of Uri provides 1.7 times more runoff than could be expected from the fact that its area represents 2.6% of the surface of the country. In comparison, the "runoff efficiency" of the cantons of Thurgau, Schaffhausen and Geneva is only 0.4, thanks to their lower precipitation and higher evaporation rates. By indicating the various components in mm/a (see statistics at the start of this chapter) a direct comparison can be made of the different water balances regardless of the area of each canton.

Figure 10-8 shows the variation in water balances between different cantons. As can be seen in the case of Appenzell Innerrhoden, the proportion of subterranean inflow or discharge in karst areas can be considerable and should not be disregarded. By contrast, the importance of changes in the volume of water stored in relation to the mean annual balance is negligible on a regional scale, although not necessarily on a local scale (maximum –6 mm, cantons of Glarus and Valais).



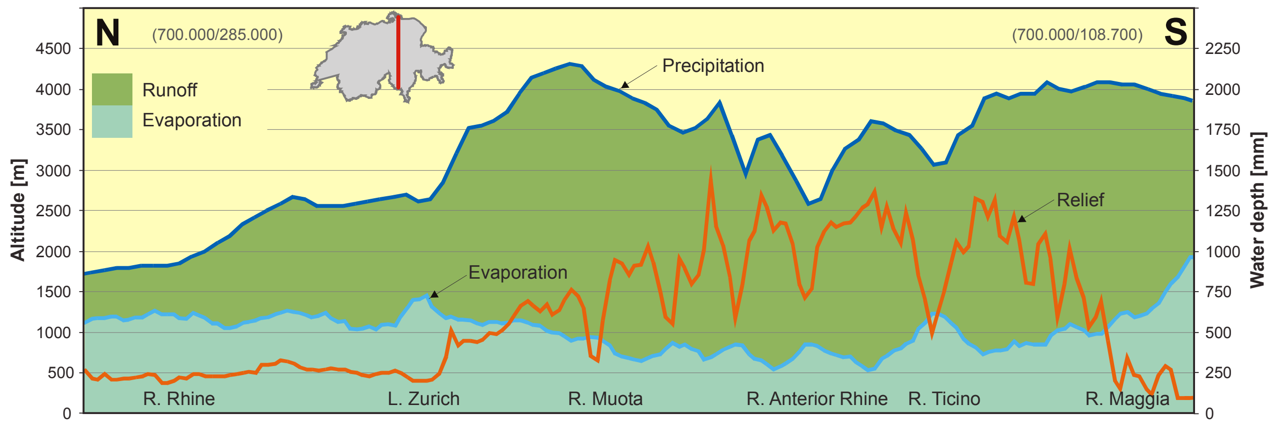


Fig. 10-7: Variation in precipitation and evaporation along two north–south profiles (total annual precipitation for the period 1971 to 1990 from Figure 2-14 and real annual evaporation for the period 1973 to 1992 from Figure 4-9 (data: SCHWARB et al. 2001a; MENZEL et al. 1999).

Nevertheless, the quantities of water stored in lakes, in groundwater and in glaciers are considerable (see Table 10-1). Glaciers alone contain the equivalent of some 67 km^3 of water, which corresponds to a layer of 1600 mm of water spread across the whole country and equals approximately the amount of precipitation in Switzerland in one year. Moreover, the fact that water is temporarily stored in snow has a definite influence on the discharge patterns of rivers (see Section 5.3.2) and helps Switzerland fulfil its role as the "water tower" of Europe.

Type of storage	**Quantity** [km^3]	**Depth** [mm]	**Proportion** [%]
Artificial reservoirs	4	97	1.1
Groundwater	50	1210	14.1
Glaciers	67	1610	18.7
Natural lakes (incl. those on Switzerland's borders)	235	5690	66.1
Total	356	8607	100.0

Table 10-1: Water reserves in Switzerland (source: MAISCH et al. 1999).

10.3 The Alps as the "water tower" of Europe

Thanks to the high rate of precipitation, the low rate of evaporation and the temporary storage of water in the form of snow and ice, mountains can be considered as water towers for the surrounding countries. The remote hydrological influence of the Alps has been quantified by VIVIROLI & WEINGARTNER (2004).

The Alps owe their nickname of the "water tower" of Europe to the fact that they experience high precipitation and low evaporation. The result is that the Alps produce considerably more runoff than the surrounding areas (see Table 10-2).

	Earth	**Land area**	**Europe**	**Alps**
Precipitation	973	746	780	1460
Evaporation	973	480	510	480
Runoff	–	266	270	980

Table 10-2: Mean water balance in mm (sources: BAUMGARTNER & LIEBSCHER 1990, MOUNTAIN AGENDA 1998).

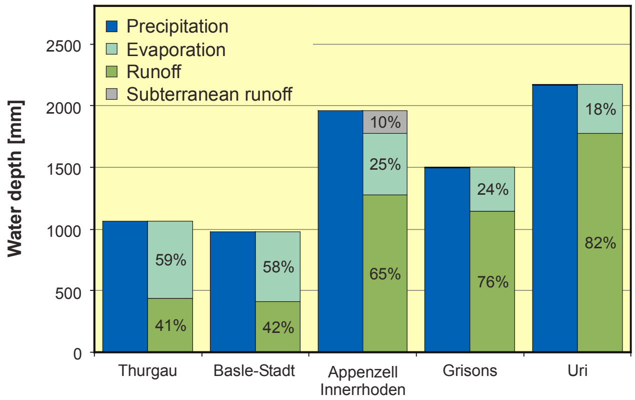


Fig. 10-8: Water balance for selected cantons (period 1961–1990) (data: SCHÄDLER & WEINGARTNER 2002a).

An additional decisive factor with regard to the role of a water tower is seasonal variation in runoff in mountainous areas. Winter precipitation is stored in the form of snow and ice. This water is only discharged in spring and summer, which is precisely when there is less water in the surrounding lowlands and the demand for water from agriculture is high. In this way the lower valleys of the Alpine rivers, namely the Rhine, the Rhone, the Po and the Danube, take advantage of runoff from the Alps, particularly in the summer months.

The proportion of runoff originating in the Alps has been determined on a monthly basis in order to quantify the remote hydrological influence of the Alps. When the rivers that have their sources in the Alps leave the mountains they have 100% influence. This proportion is then reduced by tributaries flowing into

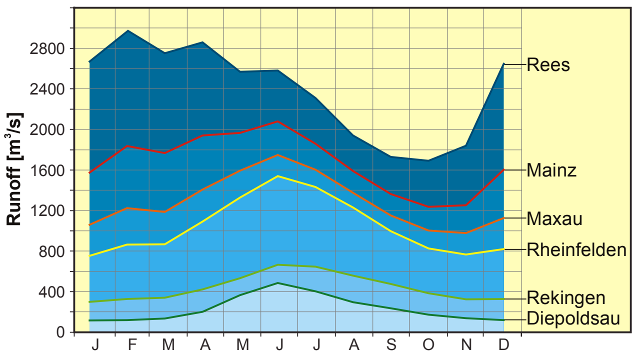


Fig. 10-9: Mean monthly runoff of the R. Rhine between Diepoldsau (Switzerland) and Rees (Germany) (after VIVIROLI 2001). Rees lies at the German–Dutch border and is typical of the Rhine catchment as a whole.

them in the lower reaches; if the tributaries also rise in the Alps, however, this can raise the proportion. Figure 10-9 shows the composition of the mean monthly runoff of the R. Rhine. The upper sections of the Rhine (Diepoldsau measuring station) and the Aare (which flows into the Rhine above the Rheinfelden measuring station) drain the Alpine part of the Rhine catchment. The area of this Alpine part represents only 15% of the entire Rhine catchment, but contributes on average 34% of total runoff in Rees (see tables 10-3 and 10-4). In summer this proportion rises to as much as 52% (mean contribution from the Alps in June) (VIVIROLI & WEINGARTNER 2004).

Runoff measuring station	Distance from spring [km]	Mean annual runoff [m³/s]	Mean proportion of Alpine runoff to total runoff [%]
Diepoldsau (CH)	150	223	100
Rekingen (CH)	298	443	49
Rheinfelden (CH)	356	1043	74
Maxau (D)	568	1288	60
Mainz (D)	704	1672	47
Rees (D)	1043	2385	34

Table 10-3: Annual runoff for the R. Rhine and proportion of total runoff represented by the Alpine catchment (source: VIVIROLI & WEINGARTNER 2004).

As Table 10-4 shows, the Alpine parts of the Rhine valley contribute 2.3 times more water than would be expected from their relative area. This table also provides an overview of the Alpine contribution to runoff of other major rivers that rise in the Alps. In all rivers, the contributions from the upper reaches are considerably higher in July and August, ranging from 36% (R. Danube) to 80% (R. Po).

River	Mean proportion of Alpine runoff to total runoff [%]	Proportion of area of Alps [%]	Overproportionality factor of Alpine area
Rhine	34	15	2.3
Rhone	41	23	1.8
Po	53	35	1.5
Danube	26	10	2.6

Table 10-4: Proportion of Alpine runoff to total runoff for the R. Rhine, the R. Rhone, the R. Po and the R. Danube (source: VIVIROLI & WEINGARTNER 2004).

10.4 Changes in water balance components

The period from 1961 to 1990 saw higher rates of precipitation and evaporation than most of the overlapping periodic means for the 20th century, the only exception being the upper Inn valley with a mean altitude of 1800 m.

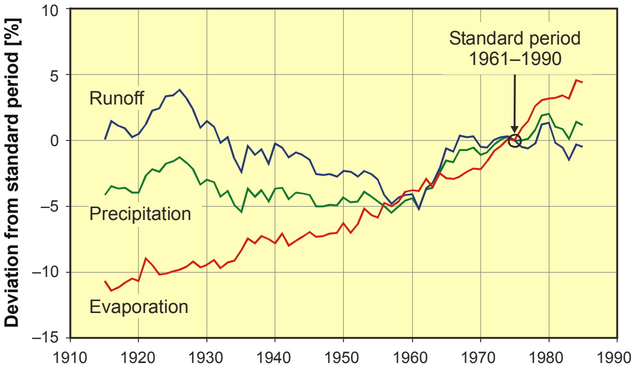


Fig. 10-10: Comparison of means for overlapping 30-year periods (1901–1930, 1902–1931, ..., 1971–2000) of water balance components for the Rhine catchment in Switzerland with values for the standard period 1961–1990 (after SCHÄDLER & WEINGARTNER 2002b).

Using the R. Rhine catchment as an example, Figure 10-10 shows a comparison between the mean values for water balance components for the period from 1961 to 1990 (standard WMO period) and the mean values of the overlapping 30-year periods 1901 to 1930, 1902 to 1931, 1903 to 1932, etc. up until 1971 to 2000. Interesting trends can be noted:

- The periodic mean rate of evaporation steadily rose during the 20th century, principally as a result of a rise in temperature; periods before the standard WMO period of 1961 to 1990 therefore all show lower values and periods after 1961–1990 higher values than the standard period.
- At the beginning of the last century, mean area precipitation was relatively constant with values around 96% of the periodic mean for 1961–1990. It is interesting to note that from the 1946–1975 period on there is a marked rise in area precipitation. Since the 1961–1990 period, precipitation seems to have settled at a higher level.
- The effects of temporal fluctuations in precipitation can be seen primarily in area runoff. Runoff conse-

quently dropped in the first half of the 20th century, then increased and finally levelled off in a similar way to precipitation.

Similar temporal patterns can be seen for the other river valleys in Switzerland, with the exception of the R. Inn. It should be mentioned that there was a marked rise in mean area evaporation in the Ticino valley with values of 360 mm/a at the beginning of the century and 485 mm/a for the 1961–1990 period.

As far as concerns the R. Inn, mean area evaporation at the beginning and the end of the 20th century was systematically higher than during the standard period of 1961–1990; in a graph this would give a U-shaped curve. Mean area precipitation shows less marked temporal fluctuation than can be seen for other river valleys; the documented rise in precipitation in the Rhine valley in the second half of the 20th century cannot be seen here.

10.5 Isotopes in the hydrological cycle

The isotopes of water molecules are used as natural tracers, in particular in hydrological, hydrogeological and climatological studies. The national network for the observation of isotopes in the water cycle (NISOT) provides the necessary comparative data and long-term measurement series without which such information could not be interpreted.

10.5.1 Measuring isotopes in the hydrological cycle

The stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H) and the radioactive hydrogen isotope tritium (^{3}H) are components of a molecule of water. In Switzerland they are measured in water samples by various organisations. An inventory has been drawn up which includes some 135 stations that measure isotopes in rainwater, rivers, lakes, glaciers, snow and groundwater (Parriaux et al. 2001 and www.bwg.admin.ch). These measurements do not constitute the long-term data series covering the whole country that are necessary for a reference, however. For this reason the national network for the observation of isotopes in the water cycle (NISOT) was set up in 1992.

At present, NISOT comprises 21 measuring points that are as representative as possible and are spread throughout the country (see Fig. 10-11): 11 stations for precipitation, 7 for surface water and 3 for groundwater. The samples they take are analysed to determine the proportion of oxygen-18, deuterium and tritium in the water (Schürch et al. 2003b, Parriaux et al. 2001, Schotterer et al. 1995).

The precipitation stations are located near meteorological stations run by MeteoSwiss where among other parameters temperature and vapour pressure are measured. Global monthly samples taken from a precipitation gauge that is emptied once a day are used for measuring the isotopes. Stations belonging to the Federal Office for Water and Geology (FOWG) where discharge and water temperature are measured have been chosen for the river stations. Depending on the local infrastructure, either 28-day global samples are taken automatically in proportion to discharge or two random samples are taken manually every month. At the groundwater stations (one spring and two water supply wells) random samples are taken monthly and water temperature, electrical conductivity and spring discharge or groundwater level are determined. Once they have been validated, the data are stored and made accessible to the general public (see www.bwg.admin.ch as well as the Hydrological Yearbook of Switzerland, e.g. OFEG 2004).

Fig. 10-11: NISOT observation stations as at 2003 (after Schürch et al. 2003b).

10.5.2 Measured parameters

The isotope ratios of deuterium ($^2H/^1H$) and oxygen-18 ($^{18}O/^{16}O$) are expressed as delta values (δ^2H or $\delta^{18}O$), which describe the relative deviation of a water sample from the international standard based on ocean water (Vienna Standard Mean Ocean Water or VSMOW) per thousand parts (PARRIAUX et al. 2001, ETCHEVERRY 2002).

$$\delta^2H = \frac{(^2H/^1H)_{sample} - (^2H/^1H)_{VSMOW}}{(^2H/^1H)_{VSMOW}} \cdot 1000 \qquad [‰]$$

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{VSMOW}}{(^{18}O/^{16}O)_{VSMOW}} \cdot 1000 \qquad [‰]$$

$(^2H/^1H)_{VSMOW} = (155.76 \pm 0.05) \cdot 10^{-6}$
$(^{18}O/^{16}O)_{VSMOW} = (2005.2 \pm 0.45) \cdot 10^{-6}$

A negative deviation indicates a reduction in heavy isotopes (^2H or ^{18}O).

Tritium concentration is given in tritium units (TU). A tritium unit is defined as the ratio of an atom of tritium to 10^{18} atoms of normal hydrogen; this corresponds to an activity of 0.119 Bq/l (1 Bq = the activity of a quantity of radioactive material in which 1 nucleus decays per second).

10.5.3 Presentation of selected measurement series

The reason why the isotopes of oxygen and hydrogen leave a “fingerprint” on the various components of the hydrological cycle lies principally in the isotope fractionation during the formation of precipitation.

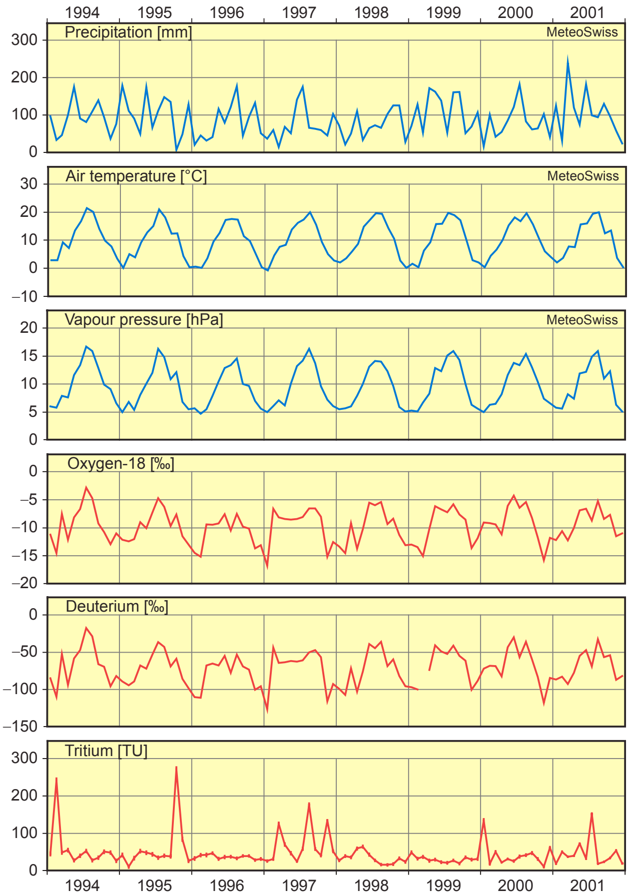


Fig. 10-13: Meteorological data and isotope ratios in precipitation at the Berne measuring station (after OFEG 2002).

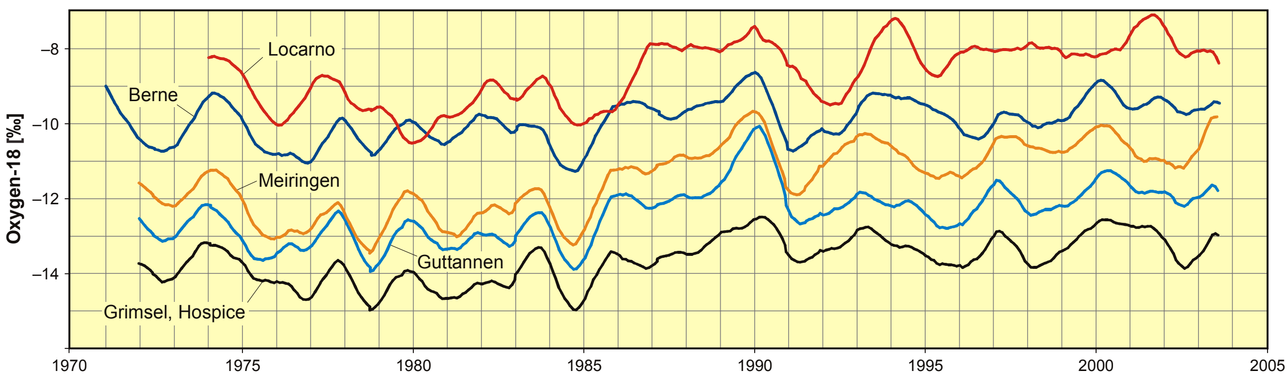


Fig. 10-12: Oxygen-18 in precipitation: sliding monthly mean for selected stations (modified from SCHOTTERER et al. 2000, PARRIAUX et al. 2001).

Through the physical processes (evaporation and condensation) that take place in the atmosphere lighter and heavier (containing either oxygen-18, deuterium or tritium) water molecules are split (fractioned). In this process the light isotopes are generally more easily mobilised. Isotope fractionation is very much dependent on temperature. As a consequence the isotope ratios in the precipitation change with the seasons (see Fig. 10-13). Otherwise the annual distribution of isotope ratios shows a general trend towards an increase in heavy isotopes (see increase of $\delta^{18}O$ in Fig. 10-12). This could be connected to either global warming or a gradual change in the origin of rainwater.

Despite the large number of influencing factors, stable isotopes show a more or less linear correlation with altitude (see Fig. 10-14). A characteristic isotope signal can be recognised for a specific precipitation zone and for a given season. For this reason these isotopes are useful for determining the mean altitude of the groundwater recharge area, although seasonal and regional differences as well as climatically controlled changes also have to be taken into account.

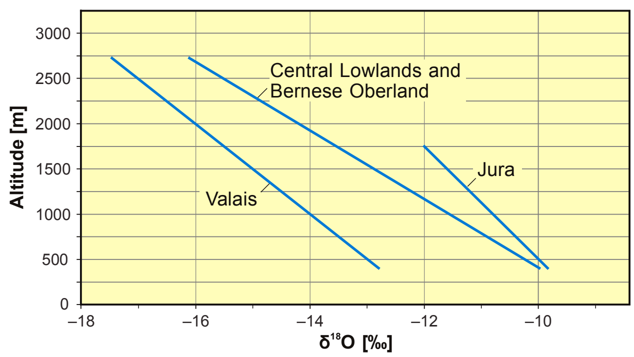


Fig. 10-14: Spatial variation in altitude dependency (period 1974–1983) (after SCHOTTERER et al. 1995, PARRIAUX et al. 2001).

The tritium "fingerprint" still corresponds to a large extent to the pattern left by nuclear weapons testing in the 1950s and 1960s. Since 1963, when the treaty banning the atmospheric testing of nuclear weapons was signed, tritium concentrations have steadily decreased. This trend can be seen in the tritium hydrograph for the Lutry spring (see Fig. 10-15). Despite this decrease, tritium concentration is a good tool for dating groundwater which is only a few decades old at the most.

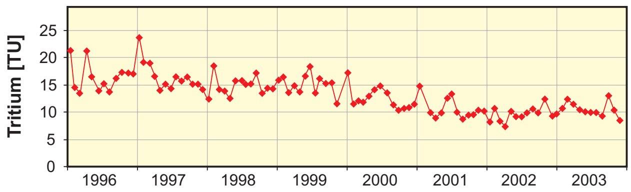


Fig. 10-15: Concentration of tritium in the Lutry spring (Savigny measuring point) (after OFEG 2004).

An example of how isotopes of water molecules are used in practice is given in Section 7.6. Some further examples of practical applications (including tritium-dating) can be found in PARRIAUX et al. (2001) and ETCHEVERRY (2002).

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