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A Comparison of the Hydrology of the Swiss Alps and the Southern Alps of New Zealand

The hydrology of the Alps in Switzerland and New Zealand is compared. Similarities and differences in topographical features, climate and weather characteristics, precipitation, and streamflow are identified. Precipitation and runoff are much higher in the Southern Alps of New Zealand, whereas the proportion and influence of snow to rainfall is greater in the Swiss Alps. Despite differences related to continental versus island characteristics and different altitudinal ranges, both Alps are important for producing water resources for downstream regions. Swiss evaporation data were used to improve knowledge of evaporation in the Southern Alps. Comparison of water volumes involved in the hydrological cycle highlighted the fact that the Southern Alps are one of the highest water-yielding regions of the world's temperate zones.

Keywords: *Mountain hydrology; precipitation; runoff; evaporation; water balance.*

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Introduction

In this article, we discuss hydrological similarities and differences between the Swiss Alps and the Southern Alps for a range of spatial and temporal scales. The two alpine regions, one in the Northern and the other in the Southern Hemisphere, occur at approximately the same latitude. An essential difference is that the Swiss Alps (latitude range 46°–48°N) are part of a greater continent, whereas the Southern Alps (41°–46°S) are in a maritime-island environment. We give a general comparative overview of the hydrology of the 2 mountain regions and support this with detailed information for selected representative catchments that highlight hydrological processes at a subregional scale and help understand the spatial variability of mean and extreme values. Our approach looks first at hydrologically significant landscape features such as topography and then examines in turn hydrological components (precipitation, evaporation, streamflow) and their interactions.

General landscape features of the Swiss and Southern Alps

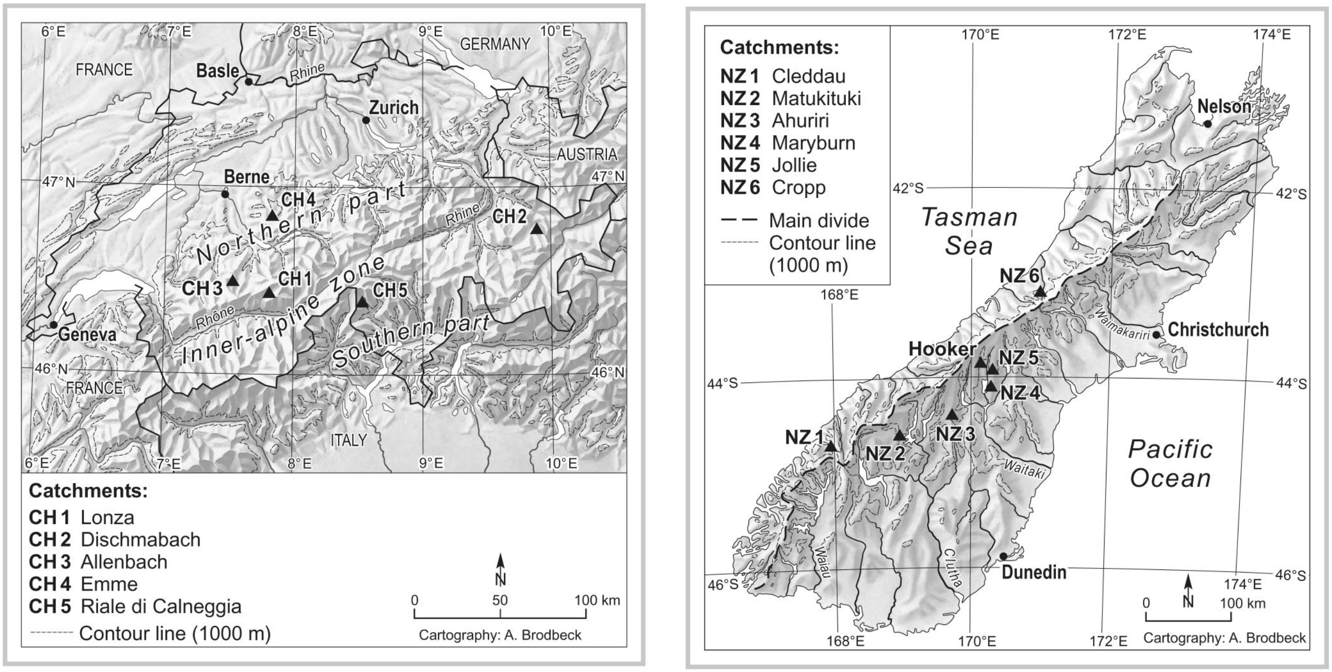
Mountain regions are defined by areas of high topographic elevation (eg, greater than 1000 m; Messerli and Ives 1997), and can be characterized hydrologically by rugged terrain, high slopes, high precipitation, and temporal storage of precipitation as snow and ice, resulting in high and dynamic runoff and strong seasonal variations. Mountain regions are an important source of freshwater and energy for people living in coastal and lowland zones (Liniger et al 1998).

By defining the spatial extent of mountain regions using contours above 1000 m elevation, we can select precipitation stations above this level for use in a hydrological study. However, for catchment hydrology, the elevation at the streamflow monitoring station is not appropriate as an indicator of an alpine basin since flows for many alpine catchments are measured at lower elevations. We use catchment mean elevation of 1000 m to define alpine regions for both the Swiss and Southern Alps since their latitudes are similar. Weingartner and Aschwanden (1992) show that a definition of 1000 m for alpine regions includes a prealpine hydrological range (1000–1500 m) for Switzerland. In this study, we focus on the Swiss Alps (Figure 1a) and not on the European Alps because of accessibility and consistency of data and information. With their location between Austria and France, they adequately represent the main hydrological features of the European Alps (Baumgartner et al 1983). For the Southern Alps, we focus on the 500-km-long southwest to northeast Main Divide mountain ranges of New Zealand's South Island (Figure 1b). The Main Divide itself is the most important landscape feature because it is a borderline between 2 distinct hydrological regions. The Alpine Fault, 2 km northwest of the 1000-m contour, west of the Main Divide, defines the northwestern edge of the Southern Alps. This tectonic line (over 400 km in length) helps explain the sudden steep relief of the Alps.

Figure 2 shows the hypsographic curves of Switzerland and the South Island. The mean elevation of the South Island (512 m) is half the mean elevation of Switzerland (1060 m). Switzerland has 21,570 km^2 (52% of its area) above 1000 m, whereas the South Island has 33,995 km^2 (23%) above 1000 m. Swiss topography extends to higher elevations than that of the South Island. High elevation is significant for the existence of snow and glaciers and therefore for all hydrological processes.

Due to the rugged topography of mountainous regions, a dense network of hydrological stations is desirable but not often present (Rodda 1994). Ease of access to mountainous areas can be a problem, particularly in the Southern Alps. Figure 2 shows that only 4% of South Island precipitation stations are at elevations greater than 1000 m, compared with 36% in Switzerland. Therefore, it is often quite difficult to obtain sufficient hydrological information for alpine regions, particularly given the sparse precipitation network of the Southern Alps. In general, the hydrological monitoring networks in Switzerland are denser and cover longer periods. The World Meteorological Organization (WMO 1981) recommends a precipitation density of 100–250 km^2 per station, which is the case for Switzerland. For the Southern Alps, the density is 500 km^2 per

FIGURES 1A AND B Location of the (a) Swiss and (b) Southern Alps and representative catchments used in this study. The Alpine Fault runs parallel to the west coast 1000 m contour; the Fault lies approximately 2 km northwest of this contour.



station, or 5000 km^2 per station for stations with records of more than 30 years' duration. Long-term stations provide vital information on water resources and extremes, particularly streamflow stations.

For example, in Switzerland there were 100 streamflow stations operating during the entire 1961–1990 period (standard WMO period) and over 40 stations for the South Island—many more stations were deployed in New Zealand as well as in Switzerland in the 1960s (Schädler and Bigler 1992a; Pearson 1998). In Switzerland overall, the hydrological network is one of the most dense in mountain areas, but even that is not enough for a comprehensive understanding of hydrological processes in alpine regions (Schädler and Weingartner 2001). In New Zealand deficiencies still exist. Some of the precipitation monitoring deficiencies have been addressed by specific scientific studies (Griffiths and McSaveney 1983; Sinclair et al 1997; Henderson and Thompson 1999).

For a hydrological comparison, we can compare each alpine region as a whole, which provides general information, and also make comparisons at the catchment scale for more specific insights. For the latter purpose, we selected a number of meso-scale catchments with reliable hydrological data (Table 1). Criteria for selection included geographic location within the alpine region, elevation, and glacial area. For Switzerland, the 5 basins represent the variety of alpine river regimes (Weingartner and Aschwanden 1992) and include examples from the main areas of the Swiss Alps—the northern, southern, and inner-alpine zones. For the Southern Alps, the 6 basins represent various locations to the east and west of the Main Divide with different altitudes and proximities to the Divide. Two New Zealand basins have mean elevations slightly less than 1000 m: The Cleddau Basin has its flow recording station at sea level, typical of the steep west coast rivers with altitudinal ranges of 0–3000 m within 20–40 km. The Maryburn Basin is an example of a low-lying basin within an alpine, rain-shadow environment.

Some important catchment characteristics relevant to hydrological processes are presented in Figure 3. The main focus of this figure is the comparison; therefore, the parameters used have been standardized,

FIGURE 2 Hypsographic curves of Switzerland and the South Island of New Zealand and altitudinal distribution of precipitation stations.

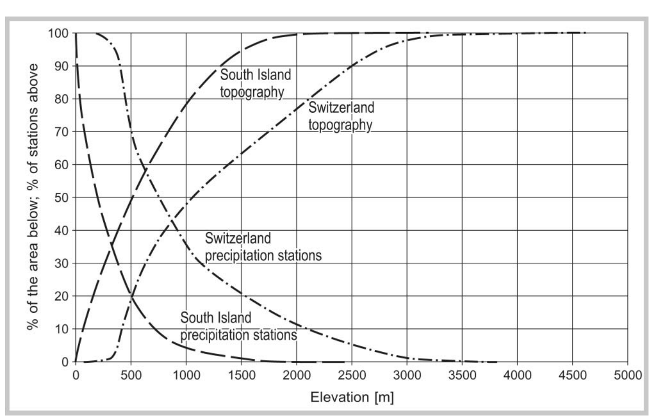


TABLE 1 Topographic and landscape features of the representative catchments used in this study (NZ, Southern Alps; CH, Swiss Alps).

	Number	Area (km^2)	Elevation (m asl) Mean	Max	Min	Range	Slope (degrees)	Area (%) Glaciers	Urban	Soil	Forest	Comment
Cleddau	NZ 1	155	973	2750	0	2750	33	10	0	92	31	W of MD, high rain
Matukituki	NZ 2	799	1130	2700	280	2420	29	5	0	89	21	E of MD, medium to high rain
Ahuriri	NZ 3	557	1251	2500	610	1890	27	1	0	74	4	E of MD, medium elevation
Maryburn	NZ 4	52.2	830	1220	640	580	9	0	0	90	0	E of MD, rain shadow
Jollie	NZ 5	139	1519	2630	580	2050	30	2	0	67	2	E of MD, high elevation
Cropp	NZ 6	12.2	1466	2140	860	1280	33	8	0	81	14	W of and near MD, high rain
Lonza	CH 1	77.8	2630	3895	1520	2375	25.3	36.5	0.2	26	4.3	Glacial regime, inner-alpine
Dischmabach	CH 2	43.3	2372	3131	1668	1463	22.9	2.1	0.1	65	5.9	Glacial to snow regime, N
Allenbach	CH 3	28.8	1856	2762	1297	1465	19.5	0	1	76	19	Snow regime, N
Emme	CH 4	126.2	1189	2221	745	1476	14.5	0	0.1	96	29	Snow to rain regime, N
Riale di Calneggia	CH 5	24	1996	2921	890	2031	27.8	0	0	45	5	Snow regime, S

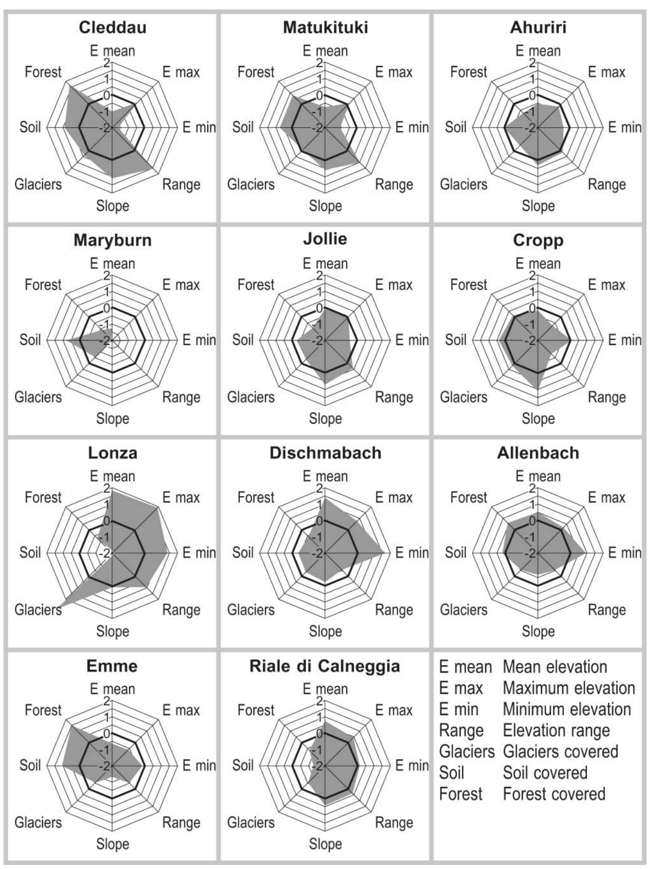


FIGURE 3 Relative landscape and topographic features of Swiss and Southern Alps representative catchments.

using mean and standard deviation of the combined sample of representative catchments in the Swiss and Southern Alps. The figure highlights the variability of the landscapes within the 2 regions. In general, the Swiss catchments show higher elevation, whereas the slopes of the representative basins of the Southern Alps are generally steeper. The extent and structure of basin soil, forest, and glacier coverage vary between and within both regions (eg, variability of soil types, forest species and densities).

In the Southern Alps, the west coast landscape contrasts markedly with that east of the Main Divide. Dense native rain forest predominates on the steep west coast, with its high energy relief. East of the Divide, tussock vegetation predominates on thin soils. The west coast rain forests do not impact significantly (through transpiration) on the water balance because of the very high rainfall amounts, perpetual saturation, steep slopes, and continuous runoff of the coast region (Chinn 1979). The density of channel networks and rivers draining the west coast is high. To the east, small streams are ephemeral in nature, and the large rivers are wide and braided—in contrast with the more or less artificial and straightened channels of Swiss rivers. In New Zealand, lakes east of the Main Divide, formed

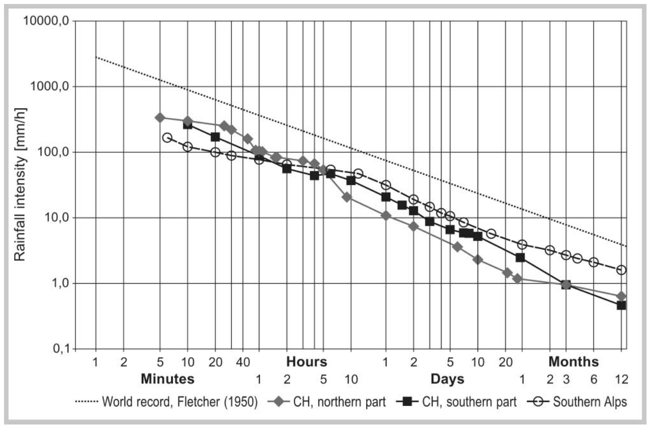


FIGURE 4 Maximum rainfall intensities for different durations. Southern Alps data are from Henderson and Thompson (1999) and Swiss (CH) data are from Zeller et al (1976–1992).

during the last Ice Age, are similar to lakes in the Swiss Alps, and the surrounding landscapes are similar to the inner dry valleys of the Swiss Alps. In Switzerland, the contrast between the main regions—northern, inner, and southern alpine—is less marked than in the Southern Alps. Elevation is the most important factor influencing the main elements of the landscape.

A number of catchment classification studies for hydrological purposes (using catchment characteristics) have been made for both countries (eg, Toebes and Palmer 1969; Mosley 1981; Breinlinger 1995). As the databases for these studies were different, only a cursory general comparison can be made. The general approach of these studies has been to find homogeneous hydrological clusters, not necessarily contiguous. Breinlinger (1995) found 11 alpine Swiss clusters based on analysis of over 10 basin characteristics relevant to hydrology. Toebes and Palmer (1969) identified 42 South Island regions, 9 of which are alpine.

Precipitation

There are many ways in which mountains influence atmospheric processes that lead to important spatial variations in patterns of precipitation (Sturman and Wanner 2001). These variations are complex and, in contrast with temperature variations, cannot be explained by elevation alone.

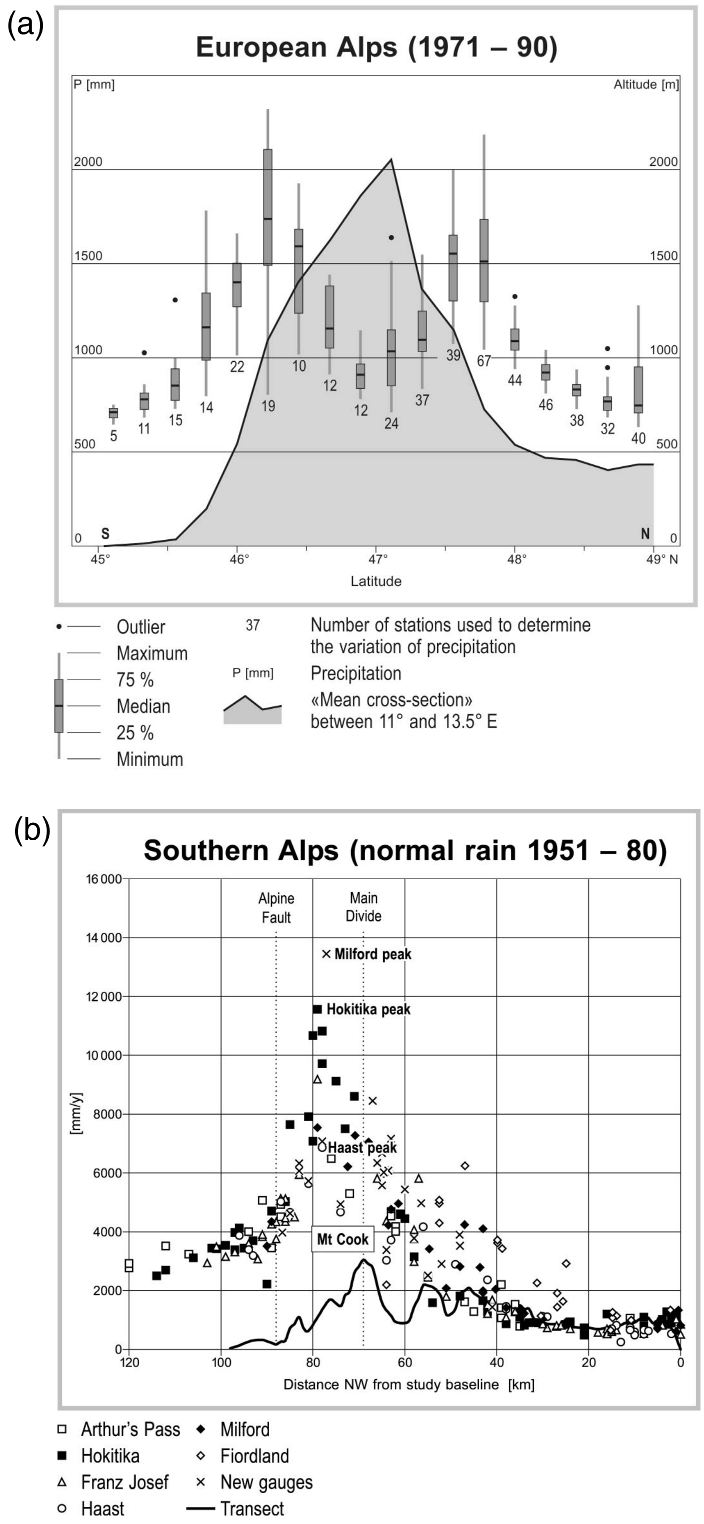
On a broad scale, the pattern of precipitation across the European Alps is characterized by 2 pronounced bands along the northern and southern edges of the area. These bands represent regions of high precipitation that converge in the central Swiss Alps. They are separated by internal drier zones (Tirol in Austria and Valais in the Swiss Alps), which are sheltered north and south by high mountain ranges (Schwarb et al 2001). Because of the lower precipitation in these drier zones (less than 600 mm per year), traditional farming, especially on sloping land, depends on glacier-fed irrigation channels.

The pattern of precipitation for the Southern Alps is characterized by a strong gradient from northwest to southeast, in line with the prevailing wind direction. The orthogonal barrier presented by the Southern Alps to these moist winds coming off the Tasman Sea causes orographic uplift and high annual and storm rainfalls along the Main Divide. The maximum annual precipitation is greater than 12 m, 2–3 times greater than the maximum Swiss values, as shown in Figure 4. Maximum Southern Alps rainfall intensities greater than 6 hours in duration exceed Swiss values. However, for shorter periods, Swiss maximum rainfall intensities are greater due to more frequent convective storm events.

The values presented above and in Table 2 are strongly influenced by the systematic error in precipitation measurement (Sevruk 1985a). Especially for the Southern Alps, it can be assumed that the values are even higher than indicated. Besides these problems and the problems of rain-gauge densities, there are also problems with the unreliability of rain gauges in repre-

	Number	P (mm/y)	P-su/P-wi	Snow-P (%)	I(1, 2.33) (mm/h)	I(1, 100) (mm/h)	I(24, 2.33) (mm/h)	I(24, 100) (mm/h)
Cleddau	NZ 1	6500	1.267	10	59	136	11	23
Matukituki	NZ 2	2460	0.98	10	18	41	5	12
Ahuriri	NZ 3	1780	1.064	10	21	49	5	11
Maryburn	NZ 4	920	0.841	5	14	32	3	6
Jollie	NZ 5	2290	0.945	20	32	76	9	20
Cropp	NZ 6	12,000	1.195	20	57	131	19	41
Lonza	CH 1	2181	0.69	79	20	59	2	5
Dischmabach	CH 2	1465	1.56	72	18	36	2	4
Allenbach	CH 3	1668	1.33	53	19	50	2	5
Emme	CH 4	1891	1.71	30	23	46	3	5
Riale di Calneggia	CH 5	2167	1.25	60	37	93	5	11

TABLE 2 Precipitation features of the representative catchments (P, precipitation; P-su/P-wi, ratio between mean summer and winter precipitation; I(1, 2.33), rainfall intensity of 1-hour duration and 2.33 years return period; I(24, 100), rainfall intensity of 24-hour duration and 100 years return period).



FIGURES 5A AND B Annual precipitation profiles and gradients of (a) the Eastern European Alps between the Gulf of Venezia and the Bavarian Forest (Schwarb et al 2001) and (b) the Southern Alps of New Zealand: NW–SE line through Mount Cook, between the West Coast and Burkes Pass (Henderson and Thompson 1999).

senting the complexities of alpine topography and rainfall processes. Furthermore, areal rainfall is often underestimated because stations tend to be located in valleys where people live. Despite these difficulties, intensive studies have shown that there are relationships between precipitation and altitude. There are considerable differences in gradient, however: Gradients of 200 mm per 100 m can be found at the northern foot of the European Alps and partly at the southern foot as well as in the peripheral ranges. In the inner alpine region and on the southern slopes, gradients vary between 0 and 60 mm per 100 m; small negative gradients may even occur (Schwarb et al 2001). Baumgartner et al (1983) describe a mean precipitation gradient of 57 mm per 100 m for the European Alps. Detailed investigation of gradients can be found in Sevruk (1997). In the Southern Alps, gradients average 1000 mm of rainfall per 100 m of elevation on the western slopes of the Southern Alps. East of the Main Divide, a negative gradient leads to a rain shadow effect (eg, annual rainfall of 400 mm at Alexandra, 100 km east of the Main Divide).

Figure 5a,b shows precipitation profiles through the eastern European Alps (south–north) and Southern Alps (west–east). The 2 highest bands of precipitation in the European Alps are centered around the 1000 m contour and decrease toward the main ridge of the Alps, forming a bimodal profile. The high values in the southern part of the European profile are related to specific spring and autumn weather patterns, which lead to greater precipitation depths than in the other seasons. In particular, high evaporation in autumn from the warm surface of the Mediterranean Sea and frequent low-pressure areas in the western part of the Mediterranean cause large amounts of humidity to be transported from the Mediterranean northward to the southern parts of the Alps (Schwarb et al 2001). This situation—warm humid air transported over the sea—is even more typical of weather patterns related to Southern Alps storm rainfalls (Mosley and Pearson 1997; Sinclair et al 1997), which most often occur in the austral spring (September–November). The high values in the northern region of the Swiss Alps are enhanced by summer convective activity, which is not experienced in the Southern Alps. The profile in the Southern Alps (Figure 5b) is unimodal, with the highest southwest–northeast band occurring 10 km northwest of the Main Divide, between the Alpine Fault and the Divide. During storm rainfall events in the Southern Alps, heavy rain falls west of and on the Main Divide and often spills over to the headwaters of the catchments east of the Main Divide. This spillover is used for hydropower and for irrigation in the rain shadow areas, which receive annual rainfalls below 1000 mm.

The total precipitation can vary from year to year in both the Swiss and Southern Alps, but the spatial patterns remain almost unchanged. Long-term positive trends in precipitation have been found in the northern and northwestern part of the Swiss Alps and negative trends in the eastern and southeastern parts of the

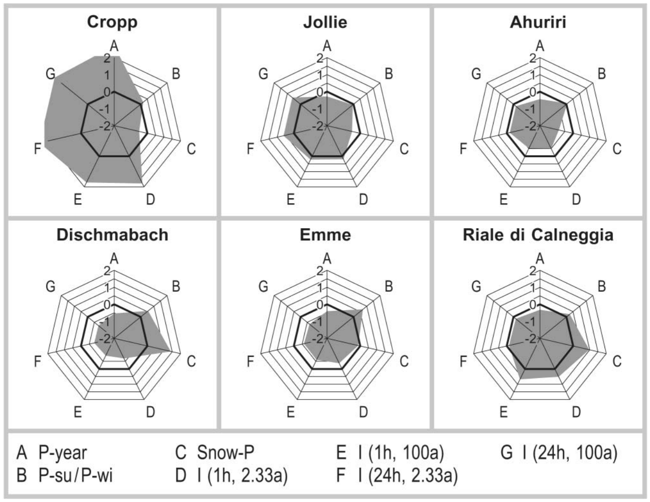


FIGURE 6 Relative precipitation features of representative catchments in the Swiss and Southern Alps (P, precipitation; P-su/P-wi, ratio between mean summer and winter precipitation; I (1, 2.33), rainfall intensities of 1-hour duration and 2.33 years return period).

Alps over the 20th century. These have been related to global warming (Schönwiese et al 1994; Widmann and Schär 1997; Schmutz 2000; Schwarb et al 2001). Similar significant trends in Southern Alps precipitation records have not been identified (McKerchar and Pearson 1997). However, summer precipitation is determined partly by the state of the El Niño Southern Oscillation phenomenon (McKerchar et al 1998). The increased frequency of high El Niño events since 1978 corresponds to an increase in precipitation since then.

The selected representative catchments reiterate the general patterns described above. Table 2 gives precipitation information for these basins, and the differences are summarized in Figure 6. The precipitation pattern is dominated by the extreme values of the Cropp (and Cleddau, which is not shown), which is mainly responsible for the largest recorded values in Figure 4. The rainfall values in the selected Swiss catchments were not necessarily those used to generate the Swiss curve in Figure 4. This explains why the Cropp dominates these Swiss catchments in Figure 6, even for periods of short duration. The Southern Alps catchments show a gradient from west to east (Cropp to Ahuriri). Most of the precipitation falls as rain, with between 5 and 25% falling as snow, depending on elevation above 1000 m (Barringer 1989; Fitzharris et al 1992). The precipitation in the catchments from the Swiss Alps has a greater component of snow (up to 80% at the highest elevations; Sevruk 1985b; Gurtz et al 2001) and higher proportions of summer precipitation than the Southern Alps. Generally, in Switzerland, summer semiannual precipitation (April–September) is significantly higher than semiannual precipitation in winter, except for the Valais. In the Southern Alps, there is no significant semiannual difference. Despite the lower proportion of snow precipitation in the Southern Alps, the amount of snowfall is still considerably high at high altitudes. The snow nourishes glaciers, which extend to low elevations. These, and especially the high amount of precipitation for a narrow, 500-km-long band of the Southern Alps, are responsible for the main differences in precipitation between the 2 regions. However, it is interesting to see that the overall precipitation patterns in Figure 6 are similar for the Emme and Ahuriri catchments.

Evaporation

Evaporation is a function of altitude—it decreases with increasing altitude. This is mainly due to longer periods of snow cover and generally lower temperatures, more than compensating for increases in short-wave radiation with altitude. Evaporation is also reduced in mountain regions because of thinner soils and sparser vegetation with short growth periods. However, examples given by Menzel et al (1999) show clearly that evaporation even from bare surfaces in the Alps can be high (200–250 mm per year). In the Alps, evaporation increases rapidly at the beginning of summer, when vegetation is growing at its fastest.

Table 3 gives annual Swiss evaporation rates by altitude. In the Swiss Alps, the mean annual evaporation is around 560 mm/y at altitudes up to 700 m. Up to an altitude of 3000 m, it decreases steadily to a value of approximately 230 mm/y. The gradient is –14 mm per 100 m, slightly lower than the figure given by Baumgartner et al (1983) for the European Alps (–18 mm per 100 m). Above 3000 m, there are insufficient data to suggest a significant correlation between altitude and evaporation.

In the Southern Alps, little is known about evaporation. Freestone (1981) estimated evaporation nationally using differences between runoff and precipitation for over 50 catchments. Given errors in estimating catchment precipitation and ignoring other components of the water balance, these estimates were very approximate for catchments in the Southern Alps and appear low in comparison with Swiss values (Table 3). However, it is interesting to see that the values from both regions

TABLE 3 Annual evaporation rates by elevation. Swiss Alps rates are from Menzel et al (1999).

Elevation (m)	Swiss Alps (mm/y)	Southern Alps (mm/y)	Combined[a] (mm/y)
500	590	540	591
1000	520	380	503
1500	445	220	416
2000	370	—	328
2500	300	—	241
3000	230	—	154
Gradient (mm/100 m)	–14	–32	–17

[a]Combined: rates derived from a combined sample of Swiss and Southern Alps representative catchments.

FIGURE 7 Evaporation (E) with elevation (Elev) using data from the representative catchments of both the Swiss and Southern Alps. The Cropp values were not used because precipitation was best estimated using runoff and Matukituki was not used because runoff exceeded precipitation.

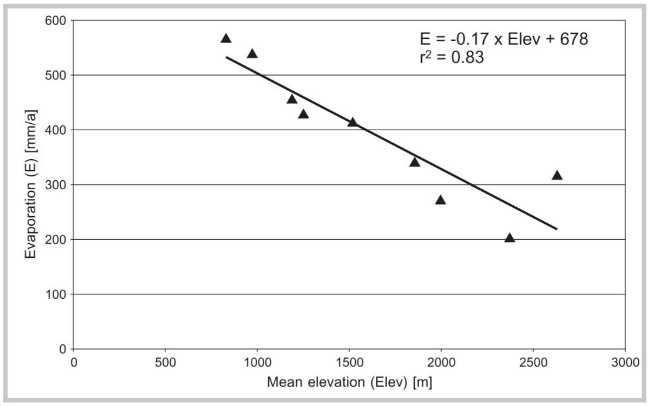
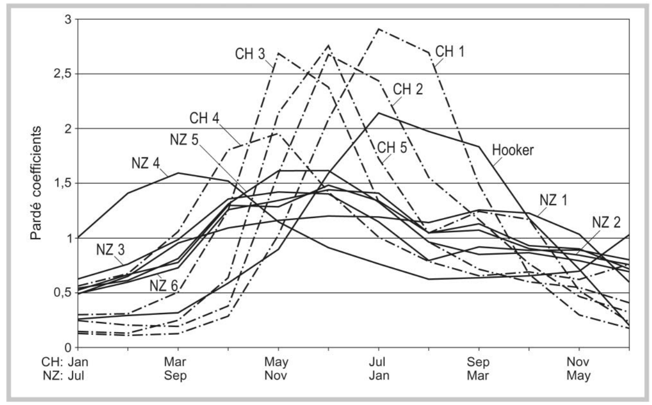


FIGURE 8 River regimes based on Pardé coefficients (monthly mean flows over annual mean flow) for representative catchments of the Swiss (CH) and Southern Alps (NZ), including the Hooker River catchment of the Southern Alps.



at 500 m asl are nearly the same, implying similar conditions at this "starting" altitude (latitude, radiation, temperatures, land cover). Above this altitude, the (erroneous) data imply a much higher negative gradient in the Southern Alps. To improve this situation, New Zealand data were augmented by Swiss data; using the representative catchments of both regions, a new gradient was estimated (Figure 7). The new gradient from Figure 7 appears in Table 3. With −17 mm/100 m, it is between the gradients of the European Alps mentioned above. The combined Swiss and Southern Alps values enhance knowledge of the New Zealand gradient and could replace the common practice of using an arbitrary evaporation value of 700 mm per year (McKerchar et al 1998).

Streamflow

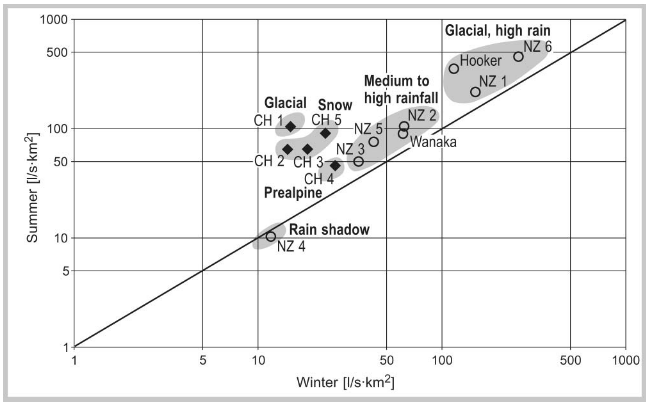
Runoff is a primary component of hydrology, and its variability is of great ecological and economic significance. The wide interest in water as a natural resource as well as a hazard necessitates a full understanding of flow characteristics of catchments. River regimes and seasonal patterns of monthly mean flows give an initial, integrated view of a catchment's runoff behavior and are very important for comparative studies.

A number of studies have been carried out for the purposes of classification and regionalization of river regimes. In Switzerland, Weingartner and Aschwanden (1992) found 7 alpine regime types that are dominated to different degrees by snow and ice melt. For each type, threshold values of elevation and glacial areas were defined that can be used to estimate flow regimes for river locations without flow data. Pardé (1960) found 3 main groups of South Island river regimes—glacial, snow, and rainfall. He compared them with Swiss and European regimes. One interesting aspect of Pardé's paper was that "world record average annual discharges are found in catchments in the South Island." Duncan (1992) and Grüter (1996) have provided further contributions to a better understanding of the river regimes of the South Island.

Based on the representative catchments, natural flow regimes of the Swiss and Southern Alps were compared using the Pardé coefficients—mean monthly flows divided by mean annual flow for each catchment (Figure 8). The pronounced Swiss Pardé curves are dominated by snow and ice, which means very low flows in winter and pronounced high mean flows in spring (snowmelt) and summer (icemelt) months. This overshadows the influence of rainfall and evaporation. In contrast, the Southern Alps catchments show a smoother seasonal pattern, caused by the dominance of rainfall over snow and ice. McKerchar et al (1998) show that snowmelt contribution from eastern draining rivers of the Main Divide is of the order of 20% of annual runoff. An exception is the high altitude Hooker River (average altitude 1720 m, glacial area of over 40% of the catchment's 103 km^2), which has the same behavior as the glacial Lonza River (CH 1) but with a higher influence of rainfall (smoother Pardé regime). The differences in the influence of snowmelt/icemelt and rainfall affect year-to-year variability of the river regimes, which is much lower in the case of snow- and ice-fed rivers in the Swiss Alps. Climate-change predictions of more rainfall as winter precipitation than snowfall in the lower Swiss Alps regions could lead to more Southern Alps-like, smoother river regimes in the Swiss Alps (Barben 1995).

Looking at the magnitudes of the seasonal variations (specific flows), we see the strong influence of rainfall on the Southern Alps regimes (Figure 9). The Swiss catchments, which in fact have explainable differences in their regimes, are closely clustered in comparison with the Southern Alps basins. The extremely high rainfalls and flows from catchments that drain from the Main Divide are in contrast with those that do not (eg, Maryburn, NZ 4). Pardé (1960) noted that almost the

FIGURE 9 Half-year summer (CH, April–September; NZ, October–March) versus winter-specific mean flows for the representative catchments of the Swiss and Southern Alps, including flows of the Hooker River and from Lake Wanaka for the Southern Alps.



entire range of flow regimes found in temperate zones of the world may be observed in New Zealand due to the effects of the Southern Alps (both high rainfalls and rain shadow regions).

Both regions have extensive hydropower developments that affect river regimes, but the developments are at different scales. In the Swiss Alps, there are many rivers where water is received in the headwaters, capitalizing on snow and ice melt, and transported to storage lakes. Especially during winter, the water is returned to lower parts of the river after being passed through power stations. Flows are therefore lower in the higher and midrange parts of the catchments (residual flows, down to 20% of the natural flows) and are affected by power production schedules in the lower parts (high diurnal variations). For example, in the Rhone basin to Lake Geneva (Figure 1a), the river flow in 38% of the river channels is affected by hydropower (Margot et al 1992; Weingartner 1999). In the Southern Alps, by contrast, the influence is not spread over many catchments but concentrated downstream on 3 major rivers (the Waitaki, Clutha, and Waiau rivers; Figure 1b). These rivers capitalize on the large amount of water coming from the Southern Alps upstream as well as the large glacial lakes in the headwaters of these rivers.

At finer time scales than monthly mean flows, flood flows are much higher. Although they last only for a matter of hours or days, they have devastating effects on alpine and downstream environments. Floods are of major concern to inhabitants of both the Swiss and Southern Alps regions. Even in earthquake-prone regions such as New Zealand, the costs of flood damage are higher on an annual basis than earthquake damage. Over 6.3 billion Swiss francs were spent on flood protection in Switzerland between 1877 and 1977 (Ulmi and Bertschmann 1977). Measures such as narrow river walls are common throughout the Swiss Alps, so natural river channel widths are rare. New Zealand has also spent significant (but lesser) amounts on providing downstream farm and town communities with protection from floods, usually using levees at a distance from the river's edge. In contrast with the Swiss Alps, the rivers from the Southern Alps are still naturally braided

TABLE 4 Streamflow features of the representative catchments.[a]

	Number	R (mm)	q ($L/s/km^2$)	mHq ($L/s/km^2$)	q100 ($L/s/km^2$)	qmax ($L/s/km^2$)	mHq/q (–)	q95 ($L/s/km^2$)	qmax/qmin (–)
Cleddau	NZ 1	5960	189	4385	16,130	11,930	23	33.4	817
Matukituki	NZ 2	2630	83	989	2503	1924	12	22.5	173
Ahuriri	NZ 3	1350	43	455	1395	1023	11	16.4	86
Maryburn	NZ 4	352	11	72	383	328	7	4.8	174
Jollie	NZ 5	1875	59	534	1914	1414	9	20.2	105
Cropp	NZ 6	11,650	369	14,240	35,250	28,850	39	77.7	609
Lonza	CH 1	1863	59	476	1066	1041	8	6	238
Dischmabach	CH 2	1261	40	270	473	441	7	6.7	239
Allenbach	CH 3	1326	42	722	2494	2604	17	8.7	682
Emme	CH 4	1434	45	944	2118	1976	21	2.3	1225
Riale di Calneggia	CH 5	1894	60	1666	5083	4375	28	4.6	1750

[a]R, mean annual runoff; q, mean annual specific flow; mHq, mean annual specific flood; q100, 100-year flood; qmax, highest observed flood; mHq/q, ratio of mean annual flood and mean flow (flow variability); q95, flow exceeded 95% of the time; qmax/qmin, ratio of highest observed flood peak and lowest observed mean daily flow (flow variability).

FIGURE 10 Maximum recorded flood peaks from catchments of different drainage area for New Zealand (Pearson 1992) and the world (Costa 1987) compared with the enveloping curve of Switzerland (Weingartner 1999).

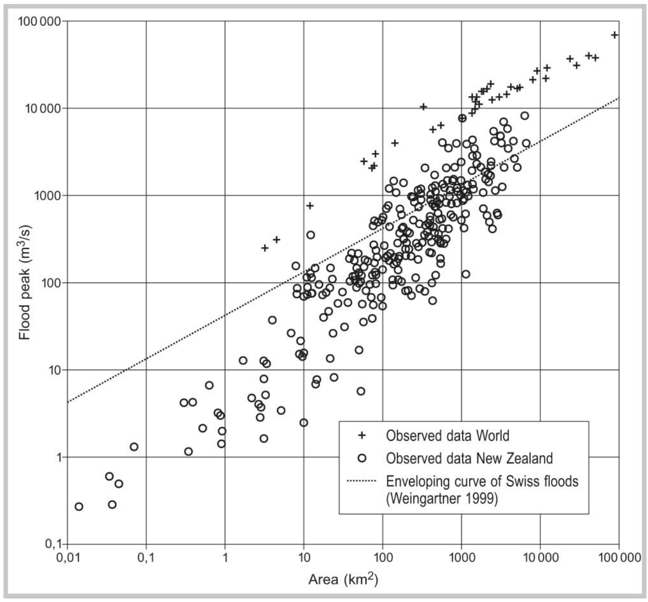
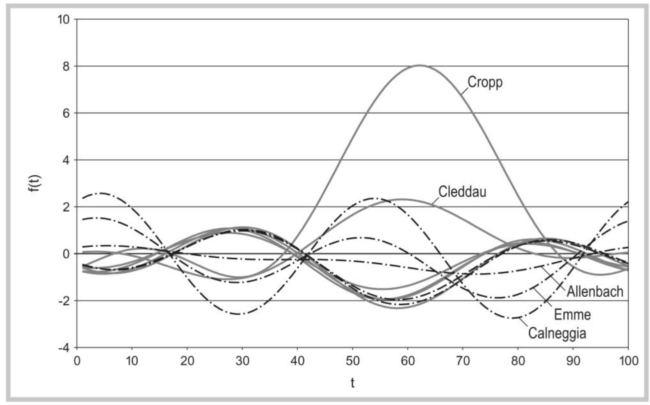


FIGURE 11 Andrews curves of streamflow characteristics of the representative catchments of the Swiss and Southern Alps used in this study.



rivers (see photo page 388 in this issue), such as the Waimakariri River, draining the Southern Alps and threatening Christchurch (population ca 330,000). Rivers within the Southern Alps region tend to have no flood protection works.

Figure 10 highlights the fact that the maximum recorded floods in the Southern Alps are much nearer world records than those in the Swiss Alps. As the analysis of precipitation has indicated, storm rainfall intensities from catchments near the Main Divide are extremely high and responsible for the extreme floods. The Swiss enveloping curve is based on the rivers in the southern area of the Swiss Alps, where the storm rainfall intensities are generally higher than in the northern regions (Figure 4) and the highest flood peaks occur after sustained storm weather situations over extended periods of up to 1 week (Grebner et al 2000). This is similar to flood-producing weather situations in the Southern Alps. Looking at the extremes, the landscape differences between the Southern and Swiss Alps do not cause major differences in flooding.

A more detailed perspective on floods is presented using the representative catchments and their flood characteristics (Table 4). Andrews curves (Andrews 1972) show the similarities and differences in these flood characteristics (Figure 11). As can be seen, the Cropp and Cleddau in the Southern Alps and the Calneggia in the Swiss Alps have their own distinctive flood behavior with outstanding specific flood flows for their respective Alps (Table 4). The Emme and the Allenbach are also different from the others, mainly because of their medium to high specific floods and large flow variability. Both have quick runoff response to storm rainfalls (Naef et al 1999). The remaining 6 catchments, from both alpine regions, are remarkably similar. Flood flows are of similar specific magnitude (mean annual specific flood mHq < 1000 L/s/km^2), while flow variability between flood and mean and flood and low flows are less than they are for the other catchments. For the Swiss catchments in this group, a dampening effect can be found: Precipitation at high elevations falling as snow is not immediately available for flood flows. The Southern Alps catchments in this group are located east of the Main Divide where rainfall is lower. The similarities in streamflow characteristics for catchments from both regions are extended to mean flows (Table 4). Specific mean annual discharges between 40 and 80 L/s/km^2 are common in both regions. In contrast, the natural low flows (q95) are lower in the Swiss Alps. There is greater frequency of rainfall events in the Southern Alps, which sustains low flows at higher levels, while in the Swiss Alps, longer low-flow spells occur during winter when precipitation falls as snow and is stored until spring (Figure 8).

Overall, the streamflow conditions in the Southern Alps are spatially much more variable than in the Swiss Alps and show exceptional extremes in close proximity to the Main Divide. On the other hand, catchments east of the Main Divide have streamflow similar to that of rivers in the Swiss Alps.

Water balance

Table 5 summarizes the findings of the previous sections regarding the main components of the water balance, focusing on the Alps regions as a whole and on the representative catchments. First, we compare water balances in Switzerland and the Southern Alps, which interestingly have almost the same mean elevation. Runoff from the Southern Alps is near world-record high levels (Pardé 1960) and is more than five times higher than in Switzerland. This is caused by frequent storm rainfall events from the Tasman Sea. Similar

TABLE 5 Water balances of the Swiss and Southern Alps: different regions as well as representative basins (mean elev, mean elevation; P, precipitation; R, runoff; ET, evapotranspiration; dS, changes in storage of glaciers; R/P, ratio between runoff and precipitation).

Region or catchment	Description	Area (km²)	Mean elev (m asl)	P (mm/y)	R (mm/y)	ET (mm/y)	dS (mm/y)	R/P	Period	Ref[a]
Swiss Alps										
Switzerland		41,285	1060	1481	961	513	7	0.65	1961–1990	A
Rhine, Felsberg	Northern part	3270	1996	1496	1118	371	7	0.75	1961–1990	A
Rhone to Lake Geneva	Inner Alpine	5458	2084	1600	1039	526	35	0.65	1961–1990	A
Ticino, Bellinzona	Southern part	1484	1690	1854	1357	492	5	0.73	1961–1990	A
European Alps		220,000	—	1450	910	540	—	0.63		B
Lonza (CH 1)	Inner Alpine glacial regime	77.8	2630	2181	1883	318	–20	0.85	1960–1990	C
Dischmabach (CH 2)	N., glacial to snow regime	43.3	2372	1465	1261	204	0	0.86	1961–1990	D
Allenbach (CH 3)	N, snow regime	28.8	1856	1668	1326	342	—	0.79	1961–1990	D
Emme (CH 4)	N, snow to rain regime	126.2	1189	1891	1434	457	—	0.76	1961–1990	C
Ri. Di Calneggia (CH 5)	S, snow regime	24	1996	2167	1894	273	—	0.87	1961–1990	D
Southern Alps										
Southern Alps		37,573	1070	4466	3975	491	—	0.89	1965–2000	E
W of Main Divide (MD)		14,088	918	7522	7004	518		0.93	1965–2000	E
E of Main Divide (MD)		23,485	1153	2672	2196	476	—	0.82	1965–2000	E
Cleddau (NZ 1)	W of MD, high rain	155	973	6500	5960	540	—	0.92	1964–1979	E
Matukituki (NZ 2)	E of MD, med-high rain	799	1130	2460	2630	—	—	—	1980–2000	E
Ahuriri (NZ 3)	E of MD	557	1251	1780	1350	430	—	0.76	1964–2000	E
Maryburn (NZ 4)	E of MD, rain shadow	52.2	830	920	352	568	—	0.38	1970–2000	E
Jollie (NZ 5)	E of MD, high elevation	139	1519	2290	1875	415	—	0.82	1965–2000	E
Cropp (NZ 6)	W of and near MD, high rain	12.2	1466	12,000	11,650	350	—	0.97	1980–2000	E

[a]A, Schädler and Bigler (1992b); B, Baumgartner et al (1983); C, Schädler and Weingartner (2001); D, runoff from *Swiss Hydrological Yearbook,* evaporation from Menzel et al (1999); E, rainfall normals 1951–1980 (New Zealand Meteorological Service, 1985), runoff data from National Hydrometric Database (Pearson 1998) of the Water Resources and Climate Archive.

storm situations occur less frequently in the southern part of the Swiss Alps with warm humid air coming from the Mediterranean Sea. However, rainfall amounts are comparatively low.

Table 5 shows differentiation in amounts of runoff from northern, inner, and southern alpine areas in Switzerland. The existing climate differences, with less precipitation in the inner alpine region, are dampened by the effects of high altitude, snow, and ice, so that the northern and inner alpine runoff values are similar (compare Rhine, Rhone, Ticino). In the Southern Alps, the water balance differences between catchments draining west and east of the Main Divide are much more marked, as catchment rainfall and runoff are at least 2–3 times higher in the west. Overall, the east-draining catchments have values quite similar to those in the catchments of the Swiss Alps (including the ratio of runoff to precipitation, R/P).

The results clearly demonstrate that the significance of snow accumulation (in winter) and snow melt (in spring) for runoff behavior increases with elevation. As the Swiss Alps are, in general, higher than the Southern Alps, the influence of these processes is greater there. In contrast, the greater influence of rainfall gives way to much higher temporal and—modified by the terrain—spatial variability of runoff in the Southern Alps. Furthermore, Gurtz et al (2001) show by adapting a hydrological model that the influence of glaciers is only minor in catchments where the portion of glaciers is below 5%, which is usually the case in Southern Alps catchments as well as in the catchments in the lower part of the Swiss Alps.

The water balance shows that there is around 4000 mm per year runoff from the Southern Alps. This corresponds to an annual volume of about 150 km^3, half of New Zealand's water production each year from just one seventh of its total area (270,000 km^2)! Less than 1% of New Zealand's water resources are used for domestic (46%), agricultural (44%), and industrial (10%) purposes (World Bank 1998). Hydropower is the major user of available water (100 km^3 annually for all of New Zealand; Waugh 1992), as nearly 80% of New Zealand's electricity is generated by hydropower.

Runoff production in Switzerland amounts to 40 km^3 but totals 53 km^3 including inflows from abroad (Schädler and Bigler 1992b). This results in a per capita volume of about 6000 m^3 each year. As in New Zealand, only a small amount (3%) is used, but in different proportions: domestic (23%), agricultural (4%), and industrial (73%) (World Bank 1998). The fact that hydropower generates about 60% of Swiss electricity highlights the importance of this resource, which is even more important for downstream countries, as the Swiss Alps are the water tower for Europe. The Swiss per capita volume, although small in relation to the New Zealand value (90,000 m^3 per person), is very high in comparison with the European lowlands. The contribution of Switzerland (21% of the catchment area) to the flow of the Rhine in the Netherlands is disproportionately large, varying seasonally from 30% in winter to 70% in summer.

Conclusions

The two most important hydrological features of the 2 alpine regions are:

- Large differences in precipitation amounts and gradients, caused by their continental versus oceanic settings.
- Differences in the proportions of precipitation due to rainfall and snow, caused by different altitudinal ranges.

These features are modified by the topography, especially in the Southern Alps, where the Main Divide separates 2 distinct regions. The hydrology of catchments west of the Main Divide is outstanding, not only as compared with Switzerland but also from a global perspective. However, similarities were identified between the catchments east of the Main Divide and those in the Swiss Alps (eg, flood behavior). Comparing the Swiss Alps and the Southern Alps as a whole, there are major differences in the water balance. If runoff from the Swiss Alps were as high as runoff from the Southern Alps, the effect on the Rhine River would be at least a doubling of the mean flow in the Netherlands! This highlights the richness of water resources in the Southern Alps.

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