Chapter 12
Ice Reservoir

Markus Weber, Monika Prasch, Michael Kuhn, Astrid Lambrecht, and Wilfried Hagg

Abstract In the alpine regions of the Danube drainage basin, glaciers play a key role in the water balance of the headwater regions. They not only contain an important reservoir of freshwater, but they also have a regulating effect on run-off in alpine rivers. To calculate ice melt in a numerical model, information about surface topography and ice thickness must be provided at the highest possible resolution. Ninety-two percent of the glaciers within the Upper Danube have surface areas that are smaller than the 1×1 km^2-grid (proxel) used for DANUBIA, and these glacial areas' basin can be subdivided into 556 subareas, which are distributed over 1,196 proxels within the limits of the DANUBIA model.

For each proxel, an area-altitude distribution was prepared using the available digital glacial boundaries and a high-resolution digital elevation model from the glacial inventory of Austria, the Swiss glacier inventory and the Bavarian Glacier project. Additional for each partial area value for the thickness of the ice in the year 2000 was determined either by measurements or by estimation.

In Map 12.1, the water equivalent of the entire ice mass is calculated for the area of a proxel and distributed evenly across the area. The values are thus directly comparable to other hydrological variables such as the total annual precipitation or discharge rate. The value for the potential meltwater contribution distributed across the entire drainage basin of 213 mm is approximately comparable to the precipitation in the basin for the two summer months.

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12.1 Introduction

In the alpine regions of the Danube drainage basin, glaciers play a key role in the water balance of the headwater regions. They not only contain an important reservoir of freshwater, but they also have a regulating effect on run-off in alpine rivers, since during warm, dry periods, the meltwater is almost instantly fed into the channels. This fact has particular significance in dry periods of summer, because extremely low water levels are prevented as a result of the glacial meltwater.

Melting in glaciers takes place primarily at the surface. The quantity of meltwater is therefore proportional to the area of the glacier. However, changes in size over time do not simply depend on snow accumulation in winter and melt in the summer; change is largely the result of thickness distribution of the ice mass and the rearrangement of ice through ice flow. This sort of information must be gathered at the highest possible resolution for a model and be available at model initialization.

When described in terms of the 1×1 km^2-grid size used for DANUBIA, 92 % of the glaciers have surface areas that are smaller than one proxel (see Fig. 12.1). Over one-third cover only 10 % of the area of a proxel. At the same time, the glaciers within a proxel extend to up to 1,000 m altitudes and are therefore exposed to very different climatic conditions across short distances. Glaciers experience the most obvious notable changes in their geometry as a result of climate change in the lowest elevations and at their edges, where the ice is thinnest and almost no ice movement is observed.

The detailed data for glaciers form the basis for the simulation of the contributions of meltwater and the future status of the glaciers. The location and extent of the glacial ice reservoir in the year 2000 within the Upper Danube basin are depicted on Map 12.1 at the scale of the computational grid used by DANUBIA; also illustrated is the varying hydrological significance of the ice for the respective Alpine portions of the basin.

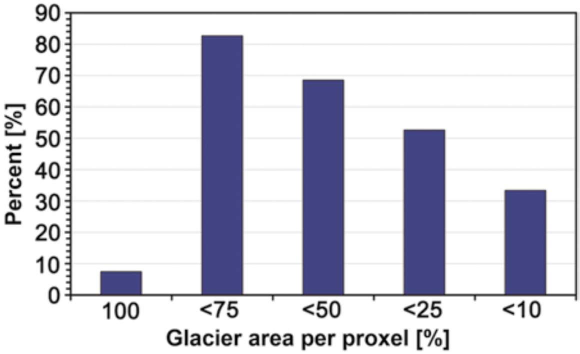
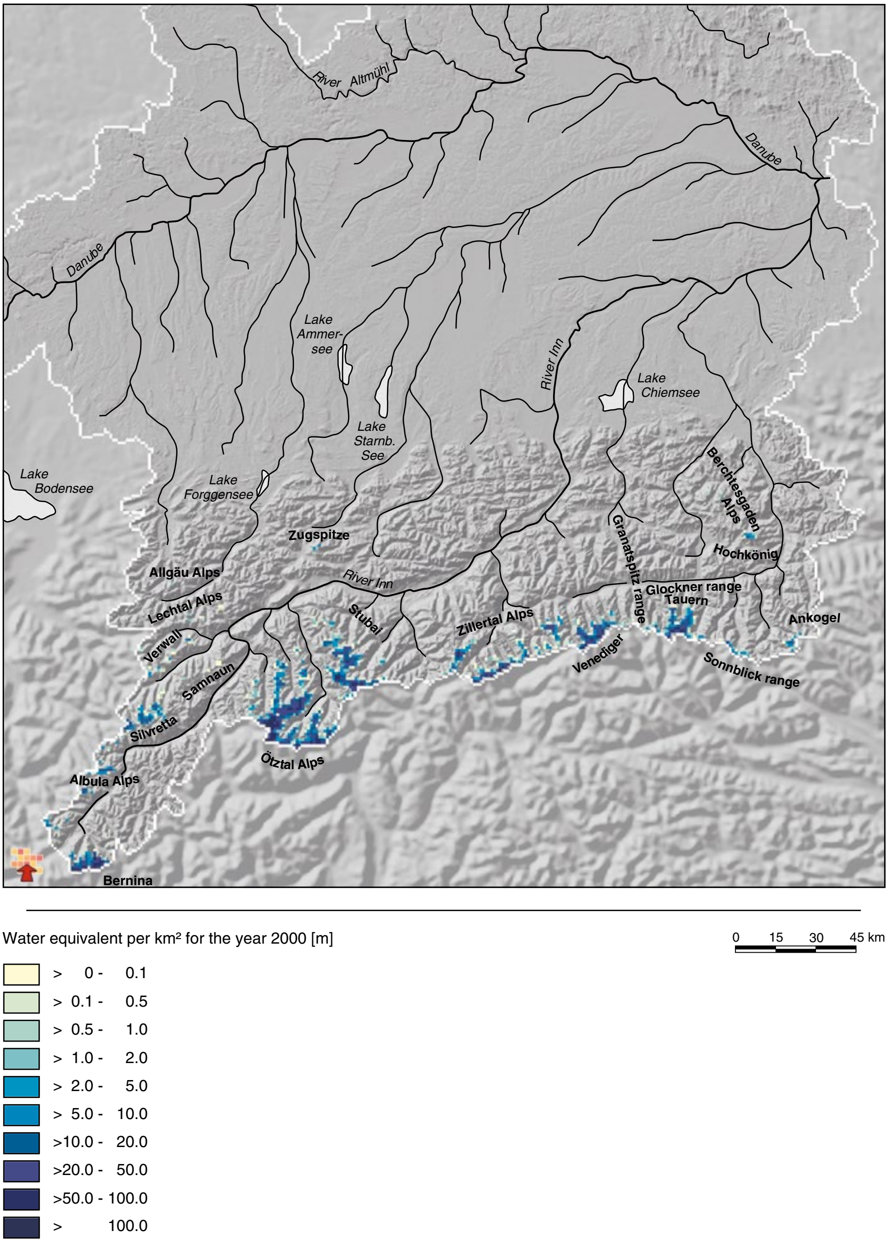


Fig. 12.1 Percentage of proxels where the percentage of glacier area is below the given threshold in %



Map 12.1 Ice reservoir (Data sources: Austrian Glacier Inventory 1998 of the Institute of Meteorology and Geophysics, University of Innsbruck, Hagg (2006), Swiss Glacier Inventory of the University of Zurich, Switzerland, Jarvis et al. 2008, DANUBIA river network)

12.2 Data Processing

Depending on nomenclature, the current glacial areas within the Upper Danube basin can be subdivided into 556 subareas, which can be assigned to the Eastern Alps according to Table 12.1. Within the limits of the DANUBIA model, these are distributed over 1,196 proxels. For each proxel, an area-altitude distribution into classes up to a maximum of 50 m elevation was prepared using the available digital glacial boundaries and a high-resolution digital elevation model (DEM). For the Austrian glacier that comprises approximately 90 % of the glaciated area in the basin, the data from the new glacial inventory of the Institute of Meteorology and Geophysics at the University of Innsbruck (Institut für Meteorologie und Geophysik Innsbruck, IMGI) (Lambrecht and Kuhn 2007) was used; this inventory uses elevation models with a grid width of 10 m and glacial masks prepared using aerial photographs that were taken in the period from 1996 to 2002.

The boundary line polygons for the areas of the glaciers in Switzerland could be generated using the remote sensing data kindly provided from Swiss glacier inventory from the year 2000 (Paul et al. 2002). With this information and the 90 m DEM from the SRT mission flown by NASA in February 2000 (Jarvis et al. 2008; Rabus et al. 2003), the Swiss glaciers were distributed into 50 m elevation levels.

Table 12.1 Distribution of glaciers in the drainage basin on different mountain ranges

Mountain range	NG	*A* [km²]	*V* [km³]	PS [mm]
Abula Alps	23	8.72	0.260	3.40
Allgäu Alps	1	0.09	0.002	0.02
Ankogel range	9	2.51	0.061	0.79
Berchtesgaden Alps	3	1.99	0.038	0.50
Bernina Alps	15	30.35	1.629	21.26
Glockner range	42	26.75	1.358	17.71
Goldberg range	17	5.07	0.135	1.76
Granatspitz range	6	2.24	0.115	1.50
Lechtal Alps	5	0.29	0.004	0.05
Ötztal Alps	152	129.39	6.581	85.85
Samnaun	3	0.08	0.001	0.01
Silvretta	36	17.65	0.584	7.63
Stubai Alps	101	52.20	2.234	29.14
Venediger range	32	31.97	1.507	19.65
Verwall	23	2.02	0.045	0.58
Wetterstein	3	0.73	0.012	0.15
Zillertal Alps	85	45.87	1.838	23.98
Total	556	357.92	16.402	213.98

NG number of glaciers, *A* glacier area, *V* stored water volume, *PS* potential meltwater discharge, scaled to the size of the drainage basin

For completeness, the five German glaciers in the Bavarian mountains were also included in the dataset. The terrain data required to determine the areas at 20 m intervals of elevation were taken from the Bavarian Glacier project of the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) (Hagg 2006).

Each partial area needed to be assigned a realistic value for the thickness of the ice in the year 2000. Although the surface of glaciers can all be measured very precisely, in general, the knowledge about the shape of the glacier is still rather incomplete but yet essential for a realistic model of the glacier. For this reason, many glaciology research groups have recently made an effort to eliminate these knowledge gaps using measuring techniques applicable in the area, such as radio-echo sounding. Measurements of ice thickness were already made for approximately 50 glaciers of varying size and location within the study area (Span et al. 2005; Fischer and Kuhn 2013), and the list is steadily growing. For example, in 2007, detailed distributions of ice thickness were determined for the Vernagtferner, a large glacier in the Ötztal Alps. But even smaller areas such as the Schneeferner on the Zugspitze or the Schwarzmilzferner in the Allgäu Alps now have precise measurements (Hagg et al. 2012). These allow ice thicknesses to be determined directly for the partial areas (see Fig. 12.2).

However, measurements of ice thickness are still lacking for the majority of glaciers. Estimated or historical empirical values were adopted for these glaciers; these values are further supported by (1) data from neighbouring glaciers with known ice volumes or known ice thickness patterns, (2) formulae for estimating the maximum possible ice thickness with a given gradient (Paterson 1981) and (3) a relationship between the volume of a glacier V [km^3] and its area A [km^2] according to Bahr et al. (1997) that uses an exponent determined for alpine regions:

$$V = 0.02\ \mathrm{A}^{1.36}$$

As a consequence, it is likely that data on ice masses for the glaciers with no thickness measurements are containing errors, which in some cases can amount to as much as 100 %, but in most cases, the 10–20 % tolerance range of the process

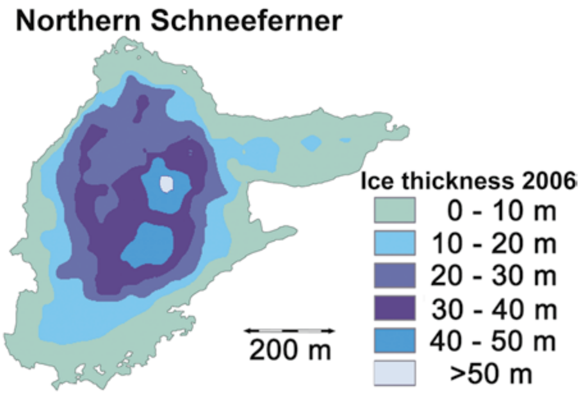


Fig. 12.2 Measured ice thicknesses at the Northern Schneeferner

model is not exceeded. The total integrated volume of water equivalent from all glaciers across the simulation area of 16.4 km^3 listed in Table 12.1 does not significantly deviate from previous integral estimates for the Eastern Alps; similarly, the value for the potential meltwater contribution distributed across the entire drainage basin of 213 mm is approximately comparable to the precipitation in the basin for the two summer months. Still, as a result of the scope and the quality of the base data in the existing inventory, this is assumed to be the most precise and detailed representation of the ice reservoir in the Eastern Alps.

12.3 Results

In Map 12.1, the water equivalent of the entire ice mass is calculated for the area of a proxel at 1×1 km^2 and distributed evenly across the area. The values are thus directly comparable to other hydrological variables such as the total annual precipitation or discharge rate.

The glacial annual storage of ice portrayed in the map can be considered as local sources for freshwater in hot dry periods. The extent of their usefulness as a source increases with the amount of area occupied by the ice mass. Higher values for water equivalent generally mean a thick ice cover and are thus associated with a larger area of the glacier, as described by the relationship given above between the volume and the area of glaciers. Hence, high values for water equivalent do not only represent a large reserve of glacial ice but also a productive source of meltwater.

Map 12.1 makes clear that the truly glaciated areas in the Danube basin are found in the main Alpine ridge of the region, in which the majority of peaks reach well over 3,000 m asl. More than half of the ice mass in the Upper Danube basin is situated within the Ötztal and Stubai Alps mountain ranges. In addition, the Zillertal Alps, Venedig and Glockner ranges as well as the Bernina range are all highly glaciated; the latter, at 4,049 m asl, is the highest point of the study area. Ice storage up to 50 times the annual precipitation is still stored in a few places there.

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