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Source: Mountain Research and Development, 20(2) : 172-179

Published By: International Mountain Society

URL: https://doi.org/10.1659/0276-4741(2000)020[0172:GAOVAH]2.0.CO;2

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Mountain Research and Development Vol 20 No 2 May 2000: 172–179

Thomas Dirnböck and Georg Grabherr

GIS Assessment of Vegetation and Hydrological Change in a High Mountain Catchment of the Northern Limestone Alps

Large-scale vegetation mapping (1:10,000) was applied to obtain estimates of the hydrological properties and dynamics in catchment areas that supply water to the capital city of Austria (Vienna). Vegetation types as defined by standard relevé technique, such as alpine grassland, snow bed vegetation, and krummholz were related to habitat conditions. A GIS served as the focal exploration tool. The vegetation units show specific evapotranspiration rates, which were derived from literature on experimental research covering similar vegetation types in the Alps. Additionally, physical soil properties from field data were used to derive the specific soil water balance in relation to the mapped vegetation types. Finally, the hydrological balances for each landscape unit, as well as for the total catchment area, were presented by combining the estimates for evapotranspiration and soil water properties. The consequences of environmental change (forestry, pasturing, and climate warming) are a focus of attention for water management. Predicting general changes in vegetation patterns reveals contrasting scenarios about the consequences to be expected for the water supply of Vienna.

Keywords: *Alps; vegetation dynamics; water supply; evapotranspiration; soil water; Austria.*

Peer reviewed: *May 1999.* ***Accepted:*** *December 1999.*

Introduction

The headwaters of high mountain systems are important water resources in many parts of the world. Water resources totaling 40,600 km^3 are derived from mountainous areas, and 25% of the global population is supplied largely or entirely by karst water sources (Ford and Williams 1996). Direct and indirect effects of human activity include land-use change and climate change, which can be key issues for water resource planning and nature conservation (Becker and Bugmann 1997; Messerli and Ives 1997). Karst areas are far more susceptible to a large range of problems due to environmental impacts than other terrain because water transmission is accelerated by highly developed subterranean networks. The poor physical filtration capacity of shallow karst soils creates additional problems (Ford and Williams 1996).

The city of Vienna receives about 95% of its water from karst mountains of the northeasternmost Alps. The catchment areas for these water resources are exposed to dynamic land-use change, especially summer pasturing and forestry. Beyond that, vegetation patterns will probably be affected significantly by climate change (Grabherr et al 1995) so that hydrological consequences can be expected.

Within the framework of a long-term research initiative undertaken by the city of Vienna, a research project was established to guarantee the long-term availability of Vienna's water supply. In addition to geological, hydrological, and geohydrological information, vegetation mapping was undertaken to obtain spatial information about the soil–vegetation interface at the landscape scale. The highly variable topography of mountainous karst landscapes causes heterogenous biotic and abiotic patterns. Using modern tools such as Geographical Information Systems (GIS), large-scale vegetation mapping is practicable within a reasonable time, even for extensive areas. To estimate hydrological properties of homogenous landscape units, physical soil properties were measured and a survey of the literature on evapotranspiration data was carried out. Thus, landscape functioning was emphasized. It supported the purely qualitative structural information of vegetation mapping in order to derive a more comprehensive view of the main landscape characteristics, including structure, function, and change (eg, Forman and Godron 1986; Turner and Gardner 1990).

Site description

The catchment areas that supply drinking water to Vienna are mountainous karst areas with altitudes up to 2300 m, composed of limestone and dolomite. The regions are 100–200 km away from Vienna in the Northern Limestone Alps, from where the karst water is transported to the city via two conduit systems. The area under closer investigation focuses on Mount Schneeberg on the far eastern edge of the Northern Limestone Alps (Figure 1). Geologically, the mountain system is characterized by mighty Mesozoic limes and displaced plateau of different altitudes. The slate base layer represents a more or less impermeable layer forming a confining aquiclude, the so-called *Werfener Schichten*. For the most part, springs occur at this level. The catchment is defined mostly by this base layer and covers an area of 22 km^2. The soils throughout are typical calcareous, stony soils, while acid loamy soil can be found in depressions and flat slope positions. Historical and recent pasturing as well as intensive forest utilization have been and continue to be important factors that influence the present vegetation patterns.

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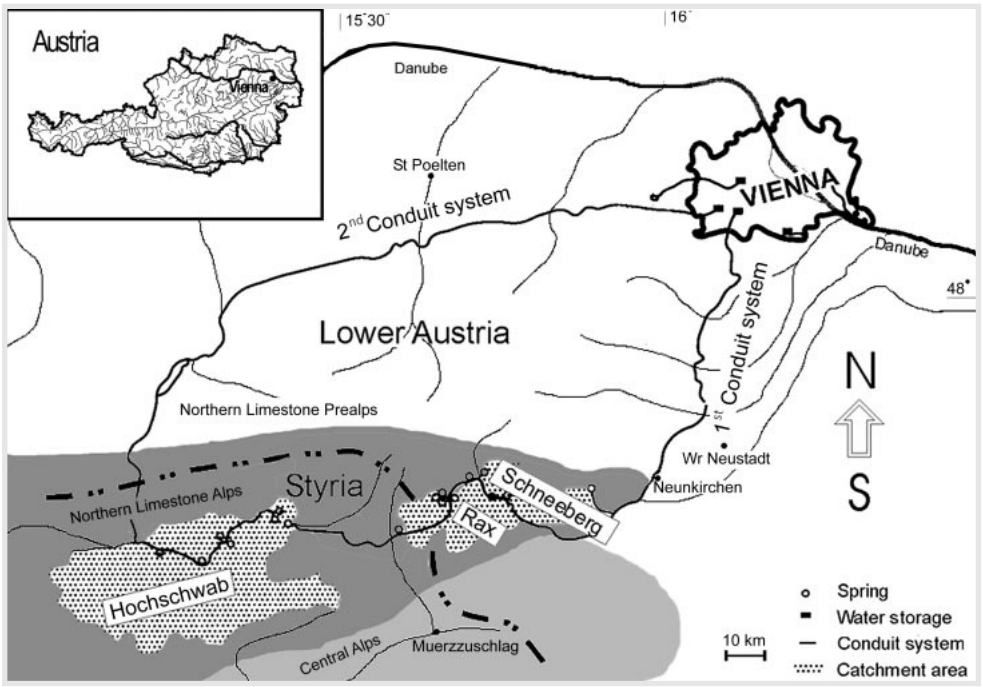


FIGURE 1 The catchment areas for Vienna's drinking water resources. Investigations were carried out on the easternmost mountain called Schneeberg.

Regional climate conditions

The geographical position of the study area on the eastern edge of the Alps and the proximity of the dry and warm pannonian continental climate have a strong influence on the regional climate. In comparison to the Northern Limestone Alps, precipitation is low. Furthermore, there is a significant decrease of precipitation from north to south and northwest to southeast. The altitudinal intensification of precipitation is 18 mm/100 m (during the summer). The altitudinal decrease in temperature is 0.6°C/100 m. Moreover, it is evident that micro- and mesoscale topographic conditions such as slopes versus plateau, large rocks, and the omnipresent dolines can produce considerable microscale contrasts, a common feature of mountain climate. Temperature inversion, with high summit temperatures and low valley temperatures, is important primarily in autumn and early winter.

Methodology

The methodological procedure was divided into the following:

1. Vegetation mapping.
2. Soil field survey, including calculation and estimation of physical soil properties.
3. A survey of the literature to examine evapotranspiration.
4. Spatial modeling of the water balance properties.

The large-scale vegetation map was produced in the classical way. The mapping units are based on phytosociologically defined plant communities according to Grabherr and Mucina (1993), Mucina et al (1993), and Zukrigl (1973). The position of the sample plots was chosen subjectively, with 92 altogether in the subalpine and alpine regions and another 81 in the forested area. The floristic description was done according to Braun-Blanquet (1964). Furthermore, canopy characteristics such as height and coverage of vegetation layers were recorded. Thirty-three mapping units were derived in the subalpine-alpine area. Data from the forest inventory and the forest site mapping were used and aggregated to derive 13 forest mapping units. In some regions where no data existed, they were interpreted from infrared aerial photographs (scale 1:6000). Overall management of the spatial data was supported by GIS.

The ecotope concept, very common in geoecology and landscape ecology (eg, Forman and Godron 1986), was employed to describe functional landscape aspects. According to this concept, an ecotope, better known as a hydrotope when hydrological properties are taken into account, can be identified by its range of lateral (eg, interflow) and vertical processes and the homogeneity of vertical processes (eg, soil moisture, infiltration, and evapotranspiration). The congruent development of soil and vegetation and their close correlation, especially in little-utilized landscapes such as the alpine zone, are well known and have often been verified (eg, Grabherr 1997). Consequently, soil properties of the

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upper subalpine and alpine zone were assumed to be homogenous for each vegetation unit. In contrast, soils in forested areas were mapped in the field in the course of the forest inventory.

Table 1 summarizes the parameters, procedures, and measuring units used to derive physical soil properties. While field capacity (FC) represents an equilibrium water capacity 2 to 3 days after rain, the maximum water capacity (WC_{max}) corresponds to the quantity of water that the soil, fully saturated, can absorb. Due to high precipitation, especially in the alpine and subalpine regions, soil moisture remains predominantly above field capacity (Körner et al 1989) except in extremely dry periods. Thus, the maximum water holding or retention capacity (RC_{max}) is defined as the difference between WC_{max} and FC and, accordingly, represents the quantity of water a soil can absorb after rainfall without substantial surface runoff.

In order to estimate the actual evapotranspiration (ET) of the hydrotopes, a comprehensive survey of the literature was carried out. A deductive data model was generated (see also Köppel and Pfadenhauer 1994). The literature survey showed that the data investigated were usually from small plot studies. Only data on identical and comparable vegetation types were examined. Papers on the ET of specific plant species were also analyzed. The data used showed climatically comparable overall conditions, a further limitation. Fifteen interception, 19 transpiration, and 90 ET measurements were evaluated for alpine and subalpine plant communities. Reviews of studies concerned with forests were consulted (eg, McNaughton and Jarvis 1983; Larcher 1984; Waring and Schlesinger 1985; Baumgartner and Liebscher 1996).

Three adjustment tools were applied to adapt the estimates of ET to the specific climatic situation of the examined area and to include the abiotic features of the evaporation process: (1) a potential ET model, (2) data from experimental sites with similar climatic conditions, and (3) total catchment ET to compare it with values from Baumgartner et al (1983). The potential ET was modeled according to Turc-Wendling (DVWK 1996) as

$$ET_{pot} = \frac{2.3\,(T + 22)}{(T + 123)(0.71R_G/L + 0.72)} \qquad \text{(Equation 1)}$$

where R_G = global radiation (J/cm^2), T = temperature (°C), and L = latent heat of vaporization (J/cm^2) (DVWK 1996). The temperature was calculated from monthly mean values applying linear regressions with the independent variable altitude (r^2 = 0.74–0.99). Precipitation distribution was calculated to transform relative ET values to absolute values. The precipitation pattern (for the vegetation period) follows a multiple linear regression (r^2 = 0.86) with the variables altitude, longitude, and latitude. In addition, a plausibility test of the hydrological model was made by comparing the catchment water budget with the pan-Alpine hydrological survey by Baumgartner et al (1983).

TABLE 1 Parameters, procedures and measuring units used to derive physical soil properties.

Parameter	Procedure	Measuring unit
Soil horizon depth	Field measurement	cm
Coarse earth fragment	Field estimation	% by volume
Textural class	Textural triangle (Schlichting et al 1995)	% by mass of fine earth fraction
Bulk density	Drying at 105°C (Schlichting et al 1995)	g/cm^3
Organic matter	Glowing at 430°C (Schlichting et al 1995)	% by mass of fine earth fraction
Field capacity (FC)	Estimation using texture, bulk density, coarse fragment, and organic matter according to AG Boden (1996)	% by volume
Maximum water absorption capacity (WC_{max})	Estimation using texture, bulk density, coarse fragment, and organic matter according to AG Boden (1996)	% by volume
Maximum retention capacity (RC_{max})	$RC_{max} = WC_{max} - FC$	% by volume

Results and discussion

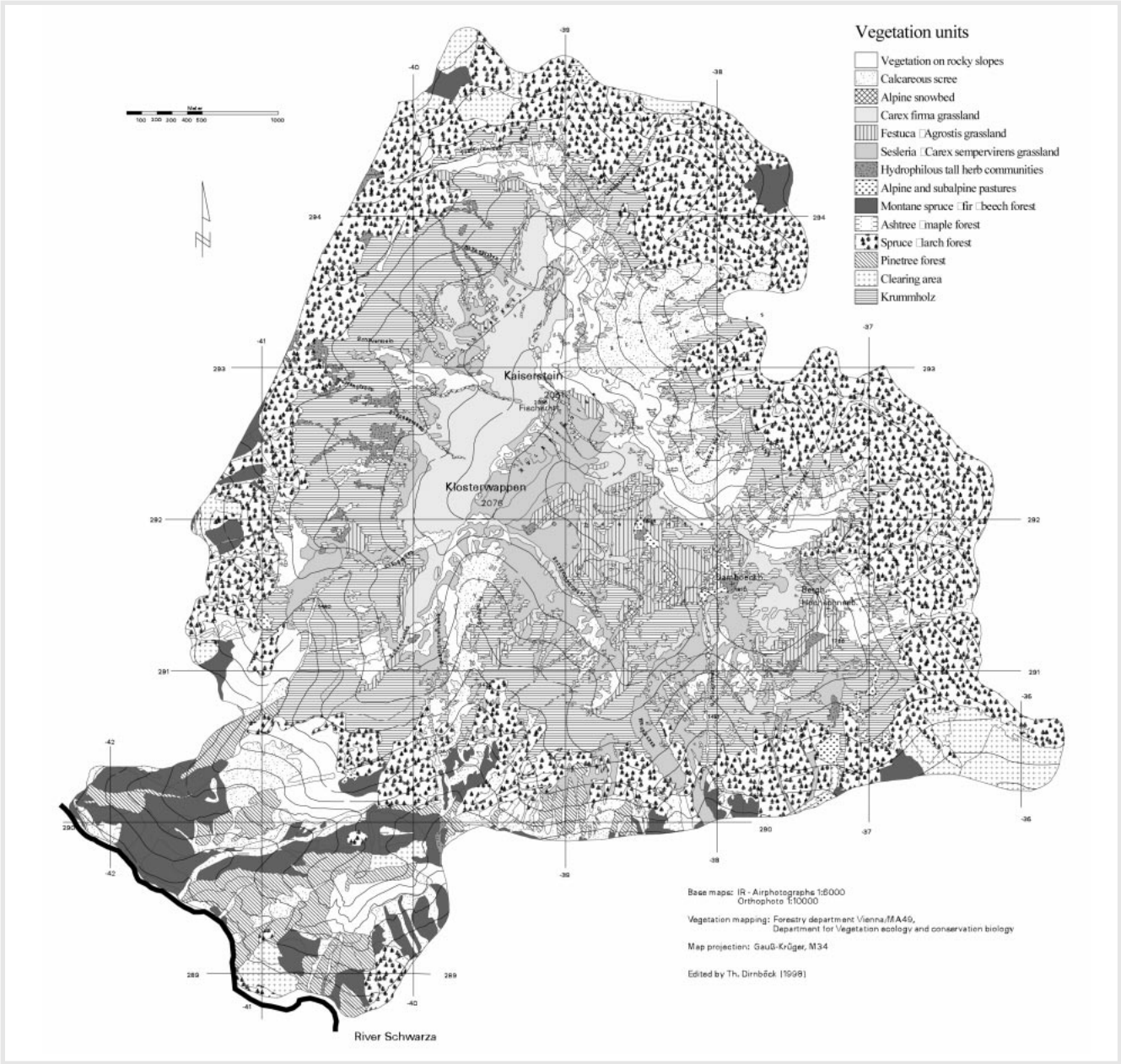
Vegetation and soil properties

The basin of Mount Schneeberg ranges from 500 to 2075 m above sea level. Forests grow up to 1600–1800 m, while a forest-like *Pinus mugo* belt (krummholz) reaches approximately 1900 m. Above this level, the landscape is characterized by alpine grassland. Beech forest and *Pinus nigra* forest are the two most common forest stand types from 500 to 1000 m. Spruce-beech-fir forests predominate in the upper montane zone from 1000 to 1500 m. On edaphically extreme sites on very steep slopes between 1200 and 1700 m, natural spruce forests are found. In addition, spruce forests, specifically spruce-larch forests, also occur naturally in the subalpine belt from 1400 m upward (Figure 2).

Calcareous soils are typical of almost all forest sites. Soil depth (subsoil as well as organic soil layer) can vary considerably. For example, the mollic A-Horizon of the krummholz can be as deep as 1 m, whereas *Pinus nigra*

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FIGURE 2 Vegetation map of the investigation area.



forest soils are very shallow. Dystric Cambisols were also found on some sites where acidic rock occurs.

The natural forests have been changed considerably by intense utilization over several centuries. The main impacts of this utilization are (1) a diminished proportion of deciduous trees, (2) unification of tree ages within the stands, and (3) clear cutting of the uppermost krummholz area in order to gain pasture (Figure 3).

In the alpine zone, grassland extends up to the summit area (2075 m). *Carex firma* grassland is the predominant plant community on wind-swept ridges as well as on slopes facing west. Their soils consist almost exclusively of organic material and a noticeable depth of 30–40 cm. In flat areas, the accumulation of clay and silt results in soils of the Humic Cambisol type. These sites are characterized by *Festuca pumila-Agrostis alpina* grassland and *Deschampsia cespitosa* grassland. Slopes facing south are dominated by *Carex sempervirens-Sesleria albicans* grassland on a shallow heterogeneous Rendzic Leptosol. Pasture grassland with soils similar to those in the above-mentioned *Festuca-Agrostis* grassland predominates on the plateau itself within the krummholz belt. Only initial soils and vegetation are found in depressions and ditches with long-lasting snow cover. Scree and rock vegetation cover huge areas.

Literature survey of evapotranspiration—facts and problems

The ET of a site is determined to a great degree by plants. Leaf diffusive conductance, leaf area index

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FIGURE 3 The plateau of Mount Schneeberg, showing a particularly disintegrated treeline. Due to summer pasturing, a pattern of krummholz, pasture grasslands on flat sites and natural vegetation in dolines (center and center left), is established. The summit in the background forms a ridge with grassland, scree, and snowbed vegetation as well as rocks on its slopes. (Photo by J. Greimler)



(LAI), and the aerodynamic conditions in and above the canopy, as well as soil water potential and saturation deficit, are important factors that control the transpiration process. A considerable number of catchment studies have been carried out in recent decades in Europe, but they have often produced conflicting results. Nevertheless, the following basic conclusions can be drawn:

1. Compared with forested areas, grasslands have reduced ET and greater discharge.
2. The transpiration rate from forests is comparable to that from grassland. It is therefore deduced that the difference is due to the aerodynamic roughness of the forest canopy and the significant evaporation of intercepted water.
3. There is a gradual maximization of annual stand ET with canopy closure.
4. Young forest will use water at an intermediate rate between that of the preceding vegetation and the developing forest (Bosch and Hewlett 1982; McNaughton and Jarvis 1983; Robinson and Blackie 1994).

With reference to published ET surveys, the dataset shows considerable qualitative and quantitative differences according to the various vegetation types. There are many detailed studies of single plants, but few deal with entire plant stands. Only forests and agricultural crops have been surveyed extensively. Summaries of the most important tree species of central Europe are given by McNaughton and Jarvis (1983), Larcher (1984), Waring and Schlesinger (1985), and Baumgartner and Liebscher (1996). Substantially fewer data exist for subalpine krummholz and alpine nonforested plant communities. Pisek and Cartellieri (1941) examined the transpiration of alpine species as well as plant stands, and Tranquillini (1964) also published a survey on the state of transpiration research on alpine vegetation. Later, Körner et al (1989) carried out substantial investigations in the Central and Northern Alps. Further research on the alpine karst plateau of Mount Dachstein was done by Gattermayr (1976) and Hauleitner (1970). Hydrological properties of alpine vegetation are also discussed in Körner (1999).

McNaughton and Jarvis (1983) and Kelliher et al (1993) describe the different processes of ET from forests and grassland. According to the results of these studies, forests have lower transpiration rates (summer values about 0.3 mm/hour) than grassland, while the hourly evaporation is very similar. Moreover, Jarvis (1981) indicated the similarity of transpiration rates due to the compensating effect of evaporated water from the understory (see also Roberts 1983; Kelliher et al 1993). Alpine grassland shows transpiration rates between 1.5 and 3 mm/day. Even the typically thin cover of scree vegetation still has a transpiration rate of 0.5–1 mm/day. Higher grassland and mesophyll tall herb communities reach extreme rates even in comparison with forests, for example, *Deschampsia cespitosa* grassland with a rate of 5.4 mm/day (Körner 1977). Little research has been carried out on transpiration of krummholz. Gattermayr (1976) reported 15–25% transpiration of the precipitation during the summer.

In contrast to transpiration, the evaporation from forests, specifically the evaporation of intercepted water, exceeds that of grassland and even differs considerably between tree species. Repeated rainfall can therefore lead to high evaporation rates, even on totally cloudy days. Frequency and duration of rainfall thus play an important role in ET (see McMillan and Burgy 1960; Jarvis and Stewart 1979; Robinson and Blackie 1994). Stand age and seasonal growth dynamics cause changed LAIs and can therefore induce substantial differences in intercepted water. The data collected by Blackie (1993) show an increasing catchment evaporation rate for growing trees on a postplanted stand. From the papers examined, a decisive trend in the interception rate of tree species can be deduced: krummholz (about 10%); beech (13–66%) intercepts less precipitation than conifers such as spruce (20–69%); larch (19–52%); and pine tree (20–69%). Interception in the understory can be as high as 10–15% of the precipitation (see Kelliher

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TABLE 2 Cornerstone hydrotopes in the study area and their hydrological properties.

Vegetation			Soil		
Label	**Key species**	**Mean ET[a]**	**Label**	**Field capacity[b]**	**Retention capacity[c]**
Vegetation on rocky slopes	*Draba stellata, Potentilla clusiana*	Very low	Bare	Very low	Very low
Initial alpine vegetation	*Dryas octopetala, Carex firma*	Low	Folic histosol	Very low	Very low
Carex firma grassland	*Carex firma, Loiseleuria procumbens*	Moderate	(Deep) Folic histosol	Moderate	Low
***Sesleria-Carex sempervirens* grassland**	*Sesleria albicans, Carex sempervirens*	Moderate	Rendzic leptosol	Low	Low
Alpine pastures	*Poa alpina, Leontodon hispidus, Crepis aurea*	Moderate	Humic cambisol	High	Moderate
Hydrophilous tall herb assemblage	*Deschampsia cespitosa, Poa supina, Aconitum napellus*	Moderate	Humic cambisol	Very high	High
Krummholz	*Pinus mugo, Rhododendron hirsutum, Vaccinium myrtillus*	Moderate	Rendzic leptosol	High	Moderate
Subalpine spruce forest on steep slope	*Picea abies, Adenostyles glabra*	Very high	Rendzic leptosol	Moderate	Moderate
Montane spruce/ fir tree/beech forest	*Picea abies, Abies alba, Fagus sylvatica, Galium odoratum, Sanicula europea, Carex sylvatica*	High	(Deep) Humic cambisol	High	High
Montane beech forest	*Fagus sylvatica, Corylus avellana, Lonicera xylosteum, Carex alba*	High	Rendzic leptosol	Moderate	Low
Pine tree forest	*Pinus nigra, Amelanchier ovalis, Cotoneaster tomentosa, Sesleria albicans, Erica herbacea*	High	Rendzic leptosol	Low	Low

[a]0–90 mm, very low; 90–180 mm, low; 180–270 mm, moderate; 270–360 mm, high; 360–450 mm, very high.
[b]0–30 L/m^2, very low; 30–80 L/m^2, low; 80–160 L/m^2, moderate; 160–250 L/m^2, high; 250–350 L/m^2, very high.
[c]0–10 L/m^2, very low; 10–25 L/m^2, low; 25–45 L/m^2, moderate; 45–70 L/m^2, high; 70–90 L/m^2, very high.

et al 1993). Interception losses in alpine grassland always remain below these rates and range between 5 and 10% of the precipitation.

Adjustment of evapotranspiration and validation

The various vegetation types show mean ET ratings from 50 to 409 mm. By comparison, the potential ET shows rates between 83 and 380 mm. For alpine sites, Körner et al (1989) reported a weekly precipitation surplus of about 10 mm. Hence, under such conditions, the actual and the potential ET can be more or less equal. Thus, especially rock, scree, and other open vegetation landscape types show great deviations from their potential ET and were therefore upgraded. ET of alpine grassland has, on the whole, been underestimated by 100–150 mm. The literature survey of comparable alpine plant communities also revealed higher absolute rates, that is, in the range of the potential ET.

Concerning forests, beech stands correspond best with potential ET, whereas subalpine forests, predominantly *Picea abies* forests, were overestimated. Köppel and Pfadenhauer (1994) have pointed to the problem that, if data from the literature are used for tree stands from low altitudes with low precipitation and are transferred to higher positioned subalpine forests, the results generally exceed realistic ET values. This fact seems to be verified here, too. Spruce forests were therefore downgraded by 5%.

After adjustment, the total catchment ET was calculated using the GIS. For the vegetation period, it resulted in precipitation of 615 mm and an ET of 246 mm, representing 40% of the precipitation. Baumgartner et al (1983) reported 310 mm ET at 1500 m from June to September. The special climate conditions in the investigation area mentioned above easily explain the slight excess value. Correspondence to the relative ET of 40% in Baumgartner et al (1983), however, is well demonstrated.

Functional landscape units—hydrotopes

Based on vegetation and soil data, 44 hydrotopes were defined (Table 2). Soil water properties are determined primarily by soil depth but also according to

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the portion of clay and silt, organic matter content, and coarse fragments. Due to low decomposition rates in the cold alpine climate, the proportion of organic matter is high. Folic histosols (so-called Pechrendzina) are extreme examples, with 50% by volume of soil. Seventy percent field capacity by volume and 80% maximum water storage by volume can be deduced. In krummholz, too, humus accumulation plays an important role in soil water storage. Generally, deep mollic A-horizons are typical under natural conditions. Poorly developed soils under krummholz are found on former pastures.

Past and future land use changes

Until the 19th century, huge areas of forest were cut and pastures were used much more intensively than they are nowadays. Up to now, clear-cut areas have been reforested, mainly with spruce. Hence, natural forests are rare throughout the region. The contribution of deciduous trees has decreased significantly. Moreover, the uppermost limit of montane mixed forests has been lowered due to human activity. The pressure of water management demands has brought about drastic changes in the use of forests and pastures. Natural forest management and recreation of natural forests are now generally accepted. Besides forest management, pasture abandonment also caused dramatic vegetation changes. The subalpine species *Pinus mugo* quickly establishes itself on these areas and totally transforms the vegetation cover from a pasture grassland into a two-meter high "forest" (Figure 3). In summary, the hydrological effects are as follows:

1. Pronounced accumulation of organic matter in krummholz increases the water absorption capacity and water retention capacity of the soils but also increases ET.
2. Pasture soils are often closely packed by trampling; hence, the strong root system of *Pinus mugo* increases soil pores and consequently increases water drainage.
3. Soil moisture changes due to transformation of intermediate krummholz stages into spruce forests on old abandoned pastures are small; only ET increases by approximately 100 mm during the vegetation period.
4. Development of natural montane mixed forests will result in higher humus decomposition rates and little decrease in ET, in contrast to the preceding artificial montane spruce forests (see Table 2).

Potential effects of climate change

Direct impacts of a changed climate on catchment hydrology have been discussed exhaustively in recent years (eg, Barry 1992; Becker and Bugmann 1997). The background climate conditions, especially the duration and ablation process of snow cover, dominate potential climate change impacts on high mountain hydrology. It is evident that vegetation also responds to climate change and has a scarcely known feedback effect on hydrology (eg, Loaiciga et al 1996). Upward migration of vegetation and changes in the community structure due to temperature elevation have been reported for high mountain ecosystems (eg, Grabherr et al 1995). Ecotones such as the timberline (Kräuchli 1994) or the alpine-nival ecotone (Gottfried et al 1998) are especially sensitive to climate change and may be most influenced. This is of importance with respect to the Mount Schneeberg basin. The krummholz, representing the transition zone from forests to alpine plant communities, determines the water balance of the whole catchment. Twenty percent of the entire basin is covered by krummholz, where a third of the catchment's soil water storage is also localized. Thus, hydrological priority coincides with high expected sensitivity to climate warming.

Conclusions

The basin of Mount Schneeberg exhibits vegetation patterns typical of the Northern Limestone Alps. Due to prior intensive land use (forestry and summer pasture), deviations from the potential natural vegetation are (1) displaced krummholz on the plateau, (2) depressed treeline and uppermost limit of montane mixed forest, and (3) a smaller portion of deciduous trees below the subalpine zone.

Applying inductive as well as deductive data, potential future vegetation and hydrological changes can be estimated. Hydrological change due to pasture abandonment and altered forestry policy are obviously low by comparison with predicted climate-induced shifting of vegetation and its influence on the catchment hydrology. According to climate change scenarios, huge areas from the present treeline up to the summits could potentially be invaded by krummholz. In contrast, an area of just 0.9 km^2 of potential krummholz stands is covered by seminatural plant communities, which represent just 4% of the catchment area. From our point of view, it is important to consider both land use and climate impact, which coincide especially at the level of treeline habitats.

The survey was a first attempt to design further approaches to produce prognostic vegetation maps that will be incorporated in a comprehensive decision support system for watershed management. Spatial estimation of future vulnerability under presumed environmental scenarios will facilitate long-term water resource planning.

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ACKNOWLEDGMENTS

This study was funded by the Department for Water Supply/Vienna (MA31). We are grateful to the staff of the Forestry Department/Vienna (MA49) and the Geological Survey of Austria (GBA) for considerable help in supplying data and other information. We are also thankful to Karl Reiter for computer assistance and Andreas Schild for reviewing a preliminary draft of the manuscript.

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