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Karst springs, groundwater and surface runoff in the calcareous Alps: assessing quality and reliance of long-term water supply

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Abstract The interdisciplinary geohydrological analysis of an area of 220 km^2 in the calcareous Alps of Lower Austria assesses the possibilities for long-term high-quality water supply from an Alpine shallow karst area. Geological and hydrogeological research quantifies dependencies of groundwater distribution and storage on rock types and on the fracturing of host rocks in an area which is typical of large Alpine regions. Estimated water budgets show a complex linkage and significant groundwater exchange between topographical catchment areas. Deep groundwater flow mostly follows tectonic fractures which became increasingly permeable by karstification. Fracture architecture and preferred groundwater pathways are analysed by structural geology techniques which support the delimitation of catchment areas and the linkage of groundwater sheds to infiltration areas. Geochemical, hydrochemical and pedological studies assess the sensitivity of groundwater chemistry to the input of polluted precipitation. Ion exchange during soil–water interaction leads to significant modification of the cation and anion ratios depending on soil type. The chemistry of soils and weathered zones strongly influences groundwater quality. The study shows the strength of interdisciplinary research including hydrogeology, hydrology, structural geology, pedology, geochemistry, soil and water chemistry, which provides integrated information on infiltration, groundwater pathways, quantified flow, groundwater discharge and pollution risks.

INTRODUCTION

We report on a project which was designed for the government of Lower Austria to assess the possibilities for long-term high-quality water supply from a typical Alpine shallow karst area. Parameters relevant for groundwater formation, storage, flow

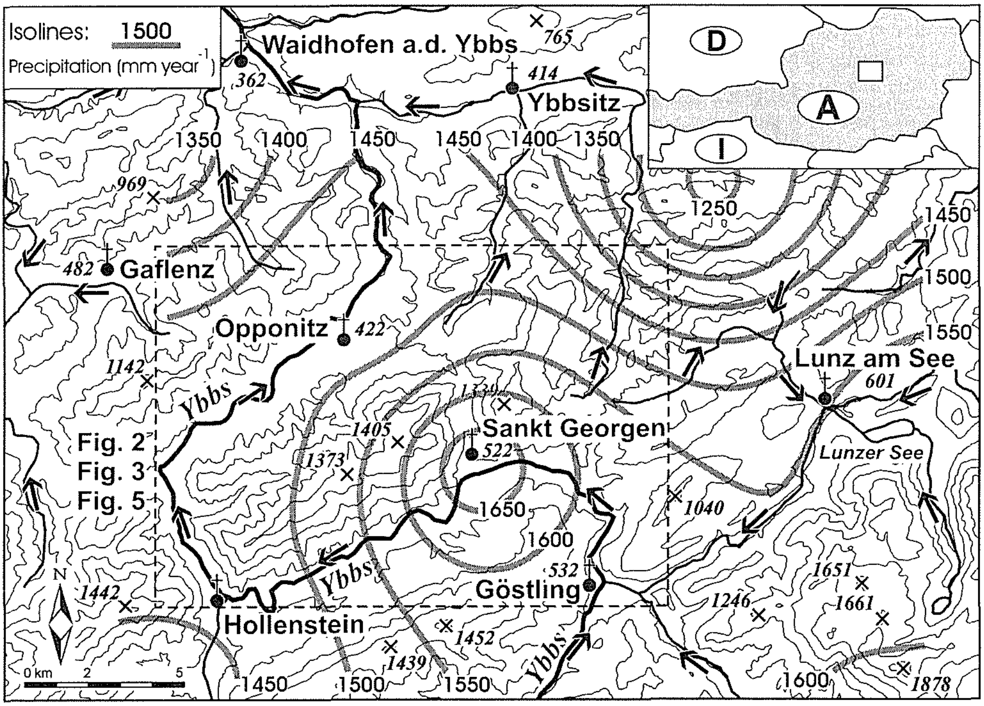

Fig. 1 Topographical map and isolines indicating the mean annual precipitation (isohyets, in mm year⁻¹) of the study area in the northern calcareous Alps of Lower Austria. The regional average precipitation equals 1480 mm year⁻¹.

through fractured aquifers, groundwater discharge and surface runoff, as well as atmospheric emission, water–soil and water–rock interactions influencing water chemistry and quality were analysed. Hydrological surveys considered 358 locations plus 47 stations with periodical runoff measurements. The area shows about 1 km topographical relief between the River Ybbs and the highest peaks (Fig. 1). The exposed rocks comprise Triassic limestones, marl-sandstone intercalations, dolomites, and various Jurassic to Cretaceous limestone and marl-limestone formations (Fig. 3; Ruttner & Schnabel, 1988). These sequences were deformed during Cretaceous–Tertiary folding and thrusting, and during Miocene strike-slip and extensional tectonics (Decker *et al.*, 1994; Peresson & Decker, 1997). Deformation led to complex geometries of intercalated rocks with distinct hydrological properties. The model area was selected for this geology which is typical of large areas of the calcareous Alps with dolomites as the predominant rock, and for the complex structure of land use with interlaced settlements, agriculture, forestry, meadows and cattle ranges. Situated on the northern slope of the Alps, the area is exposed to emissions from distant atmospheric polluters which are a crucial factor for water exploration on the regional scale.

GROUNDWATER PATHWAYS

Prognoses of groundwater flow consider semiquantitative water budgets (precipitation *vs* runoff) for all topographical catchment areas which are based on a regional precipitation model interpolated from eight meteorological stations (Fig. 1). The comparison of annual precipitation, surface, and groundwater runoff shows complex links and significant groundwater exchange between topographical catchment areas. Tracing of groundwater pathways and the linkage of springs to infiltration and storage areas use hydrochemical and tectonic analyses. Waters from the dolomitic host rock, from limestone, and from shale formations show distinct contents of Ca^{2+}, Mg^{2+}, HCO_3^- and SO_4^{2-} (Fig. 2). The frequent coincidence of springs and karstic caves with tectonic faults (Fig. 3) illustrates the importance of tectonics for deep groundwater flow and discharge. Most tectonic faults are preferred pathways with flow following zones where fracturing and subsequent karstification increased permeability. Location, orientation and fracture architecture of faults were mapped and analysed by the methods of brittle structural geology (Hancock, 1985) and by adopting the recent tectonic models for the calcareous Alps (Decker *et al.*, 1994; Peresson & Decker, 1997). The analysis of faults, tension gashes and joints revealed systematical structural patterns which define homogenous areas in which the hydrological features and orientations of structures are consistent and predictable

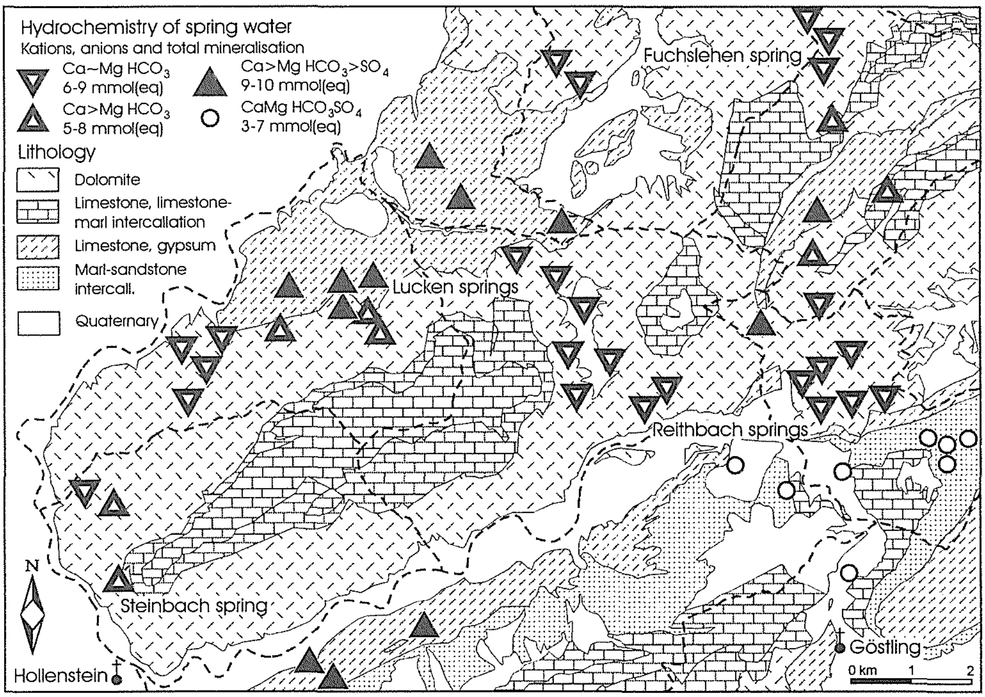

Fig. 2 Hydrochemistry of spring water. Ratios of Ca^{2+}/Mg^{2+}, HCO_3^-/SO_4^{2-} and total mineralization are indicators of the lithology in the infiltration and storage area. Dolomites: $Ca^{2+} \approx Mg^{2+}$; limestone: $Ca^{2+} > Mg^{2+}$; limestone with gypsum: $Ca^{2+} > Mg^{2+}$, SO_4^{2-}, high mineralization; shaly formations: very low to low mineralization.

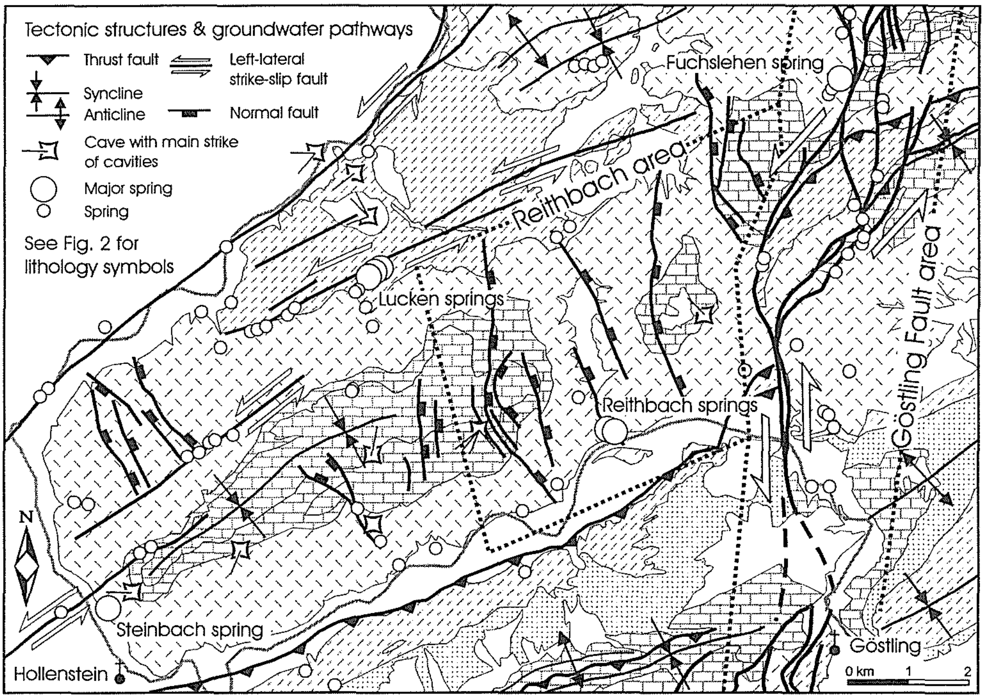

Fig. 3 Tectonic structures and groundwater pathways. Coincidences of springs with fault traces indicate the importance of strike-slip and normal faults for deep groundwater flow. Tectonics define distinct homogenous areas with regularly oriented structures which are relevant for hydrology (Reithbach, Göstling Fault area; Fig. 4).

(Reithbach-, Göstling Fault area; Figs 3 and 4). The Reithbach spring, one of the largest karst springs in the area (20–1000 $l\ s^{-1}$), is hosted by a Miocene normal fault. The hydrology of this system is almost entirely controlled by tectonic structures (Fig. 3). West-dipping bedding planes and east-dipping kataklastic normal faults establish a drainage system channelling water flow towards the spring (Fig. 4(a)). Kataklastic faulting, tilting of bedding during rollover formation, and small-scale jointing which determines the storage capacity of the dolomites occurred during the Miocene east-directed extension (Decker *et al.*, 1994). Sinistral strike-slip faulting in the distinct Göstling Fault area led to the formation of both kataklastic fault aquifers and faults with shaly fault gauge acting as aquitards (Figs 3 and 4(b)). The main fault strand of the Göstling Fault is a deep-seated, subvertical sealing fault forming the eastern boundary of the Reithbach catchment area which does not coincide with the topographical catchment boundary.

RUNOFF DYNAMICS AND STORAGE CAPACITY

The dynamics of surface runoff and spring discharge are characterized by strong variations and by short response times to precipitation events. Ratios of 1:24 for observed minimum *vs* maximum surface runoff are typical for catchment areas

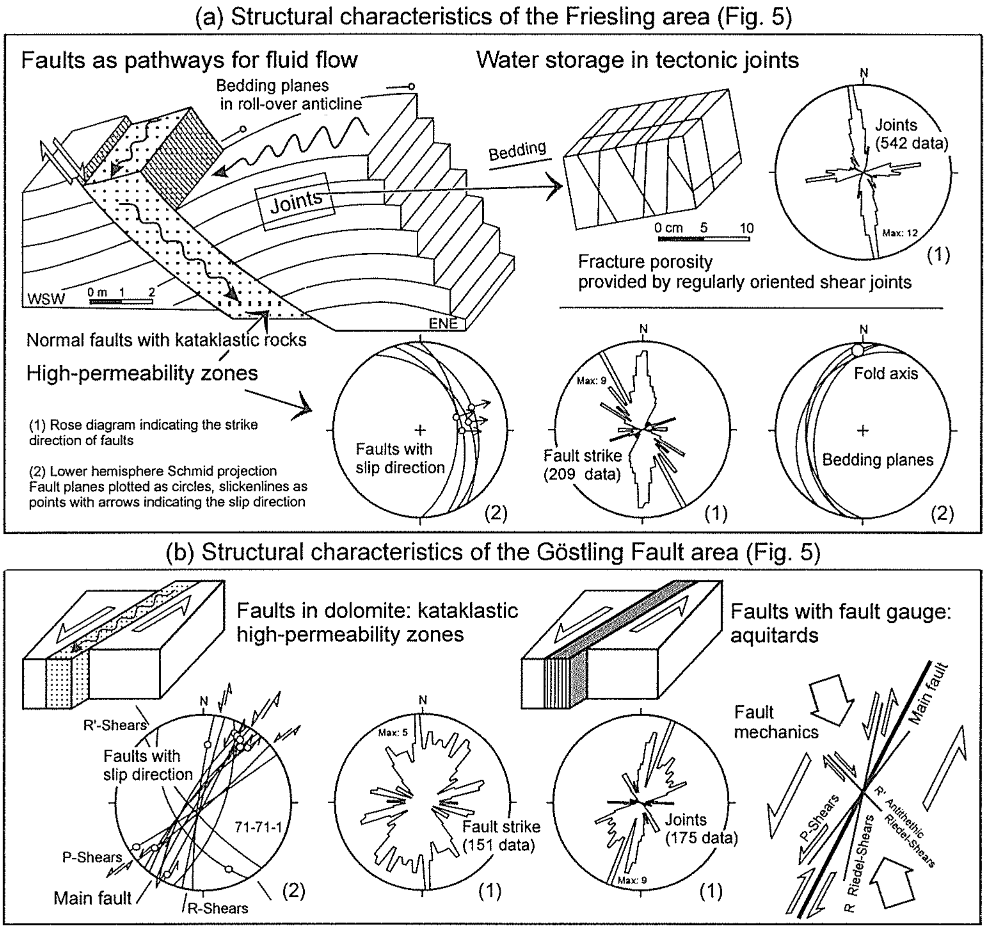

Fig. 4 Structural characteristics of homogenous areas and hydrological features of tectonic structures. (a) Structures in the Reithbach area formed during east-directed extension. Kataklastic normal faults and tilted bedding planes are sites of preferred water flow, shear joints provide fracture porosity for water storage. (b) In the Göstling area, sinistral shear on NNE-striking faults is the dominant deformation. Both high-permeability kataklastic faults and sealing faults with fault gauge occur. Fracture orientations obey rock mechanic laws and are predictable within homogenous areas.

dominated by limestones and marls with low water storage capacity (Table 1). Increased storage capacity of dolomite is indicated by ratios of 1:10 and by the occurrence of springs with constantly high discharge after dry-weather periods (Fig. 5). Such springs are positioned in and derive their water mainly from dolomites. High storage capacities reflect high fracture porosity due to intense tectonic jointing. Joints are here referred to as closed fractures with no measurable slip or dilation at the scale of observation and without mineral fill. Penetrative jointing produced regularly oriented fractures of several 100 cm^2 size which are spaced at distances of a few centimetres (Fig. 4(a)). Applied structural geology shows that the geometry of joints is not random. Orientation and spacing of joints,

Table 1 Lithology, runoff dynamics and water quality.

Lithology	Runoff dynamics:		Long-term sensitivity against acid and pollutant deposition:		
	Storage capacity	Variability of spring runoff	Soil	Jointed rock	Whole system
Dolomite	high	medium	high	medium	high
Limestone-marl	medium–low	high–medium	high–medium	medium–low	high–medium
Limestone, gypsum	medium	high	high–medium	medium–low	high–medium
Marl-sandstone	low	low	medium	medium	medium

and the abundance and orientation of intersection lines can be predicted within certain areas, thus determining parameters which are relevant for fluid flow through fractured aquifers. Water which slowly passes through such a jointed aquifer is delivered by the long-term low-discharge runoff of the Reithbach spring (Fig. 6). It is characterized by isotope ratios indicating 6–10 years apparent water age ($^3H \approx 20$ TU). This water is distinct from the short-term runoff of the spring which passes through open fissures and drainage channels within a few days to weeks ($^3H \approx 10$–15 TU) following snowmelt and severe rainstorms. The heterogeneity of the Reithbach aquifer is corroborated by the highly variable isotope ratios from 30 discharges

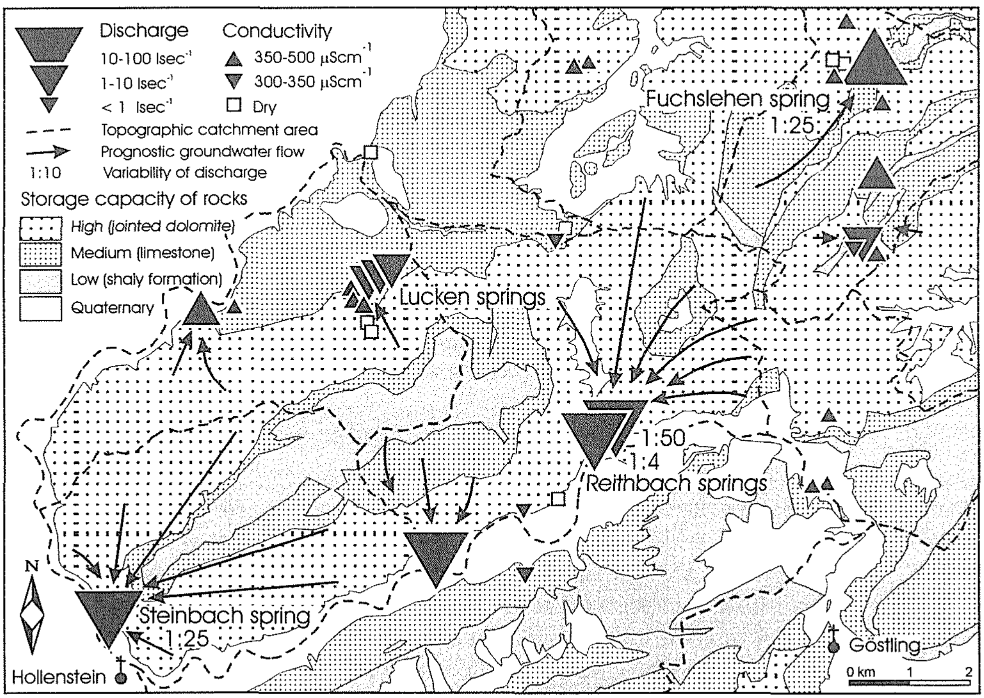

Fig. 5 Spring discharge after a dry-weather period (October 1994). Large springs are situated in and derive water from jointed dolomite with high storage capacity. Flow vectors were constructed from water budgets, hydrochemical data, and structural analyses.

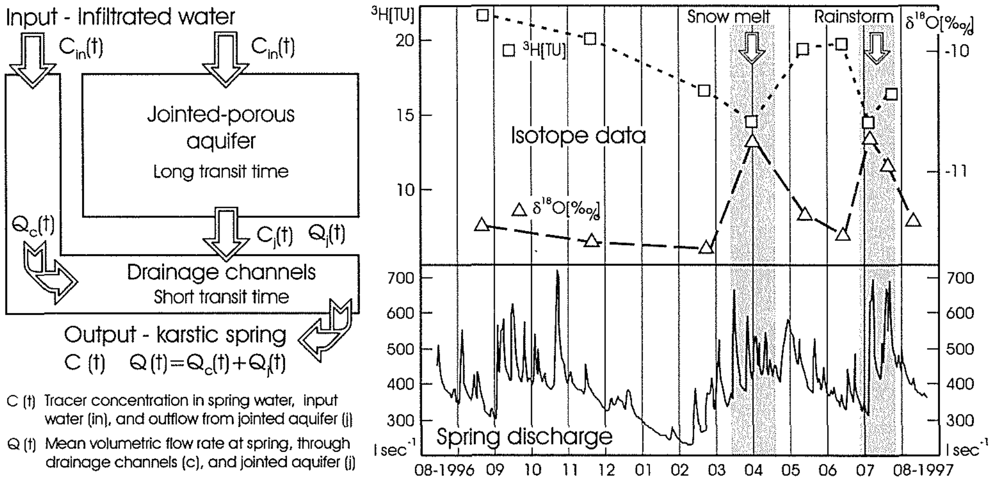

Fig. 6 Spring discharge (l s^{-1}) and isotope ratios (^3H, $\delta^{18}O$) for the Reithbach tubular spring (August 1996 to September 1997). Spring runoff consists of two components as indicated in the schematic sketch (*left*; after Rank *et al.*, 1992). High apparent water ages (high ^3H contents) characterize the long-term discharge which passed through the jointed dolomite aquifer, low apparent ages (low ^3H contents) are typical for short-time peak runoff following snowmelt and rainstorms which quickly passes through open fissures and drainage channels.

sampled in a 4 km long tunnel crossing the system. ^3H and ^{18}O data confirm a heterogeneous karstic aquifer with a large number of pathways. Different transit times correspond to different tectonic and/or karstic structures.

ATMOSPHERIC EMMISSION, SOILS AND LONG-TERM WATER QUALITY

Geochemical and pedological analyses assess the vulnerability of the area by emission from distant atmospheric pollution. Emission models showing high rates of NO_3^-, NH_4^+ and SO_4^{2-} deposition (Puxbaum, 1994) are supported by hydrochemical analyses indicating the high frequency of polluted precipitation which may lead to increasingly acidic soils. Ion exchange potentials and the capacity to retain pollutants are highly dependent on soil and rock type (Table 1; Blum, 1996). Probing of deep rendzinas overlying dolomitic rocks reveal the predominance of Cl^- with highly variable concentrations of NH_4^+ and SO_4^{2-} in aquatic solutions. In spite of the low concentration of heavy metals in the underlying rocks, up to 300 ppb Cr^{3+}, Pb^{2+} and Cu^+ have been found within soils. In spring water derived from dolomite, NH_4^+ and SO_4^{2-} dominate over Cl^- and peak concentrations of up to 30 ppb Cr^{3+}, Pb^{2+} and Cu^+ occur, indicating that soils overlying dolomites have low capacity to absorb pollutants. Intact vegetation and soil therefore is a crucial factor to sustain water quality in dolomite areas.

CONCLUSIONS

Tectonic structures are of prime importance for groundwater storage and dispersal in shallow karst areas. Structural geology and tectonic techniques are powerful low-cost tools to (a) map, extrapolate and predict hydrologically important structures down-section to levels below valley floors; (b) to evaluate hydrological properties of faults which may act as kataklastic and karstified fluid pathways or as fault gauge aquitards; (c) to analyse joint systems in fractured aquifers which are important for the retention capacity and long-term water runoff. The results also stress the importance of considering pedology and soil chemistry of the infiltration areas during an early stage of groundwater prospection as these parameters are crucial for sustaining high groundwater quality in areas which are exposed to significant emission.

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