ACTA CARSOLOGICA	30/2	15	203-213	LJUBLJANA 2001

COBISS: 1.08

TRACER STUDY ON THE TECTONIC CONTROLL OF THE DRAINAGE SYSTEM IN THE CONTACT KARST ZONE OF LAKE VORALP (SWISS ALPS)

PREUČEVANJE VLOGE TEKTONIKE PRI ODTOKU IZ KONTAKTNEGA KRASA V OKOLICI JEZERA VORALP (ŠVICARSKE ALPE) S POMOČJO SLEDENJA

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Prejeto / received: 14. 9. 2001

Izvleček UDK: 556.34.04(285.2)(494)

Jan-Henning Ross & Alfred Rieg & Chris Leibundgut: Preučevanje vloge tektonike pri odtoku iz kontaktnega krasa v okolici jezera Voralp (Švicarske Alpe) s pomočjo sledenja

Jezero Voralp je majhno kraško jezero, ki ga je zajezil pleistocenski podor in je brez površinskega odtoka. Sledilni poizkus ob poplavi je pokazal, da odteka voda iz jezera zelo na široko, v oddaljene kraške izvire in tudi neposredno v medzrnski vodonosnik v renski dolini. Ta kraški odtok prečka tudi nezakraseli fliš in lapornate plasti. Te plasti so litološko neprepustne in odtok kraške vode skoznje je dokaz o obstoju vodoprepustnih prelomnih con. Značilnosti odtočnih vzorcev so neposredno odvisne od hidrološkega stanja.
Ključne besede: kraška hidrologija, sledenje, kontaktni kras, tektonska struktura, Voralp jezero, Churfirsten, Švica.

Abstract UDC: 556.34.04(285.2)(494)

Jan-Henning Ross & Alfred Rieg & Chris Leibundgut: Tracer Study on the Tectonic Controll of the Drainage System in the Contact Karst Zone of Lake Voralp (Swiss Alps)

Lake Voralp is a small karst lake, dammed up by a Pleistocene rockslide and without any surface drainage. A dye tracer test under flood conditions shows a widespread drainage system to remote springs and direct afflux to the porous aquifer of the Rhine Valley. These karstwater passages are leading through nonkarstified flysch and a marly layer. Both layers are lithologically rather impermeable and karstwater passages through these layers indicates water leading fault zones. Properties of the drainage patterns strongly depend on the hydrological situation.
Key words: karst hydrology, tracing, contact karst, tectonic structure, Lake Voralp, Churfirsten, Switzerland.

INTRODUCTION

Tracer tests are a well known method to investigate karst groundwater (Käss 1998). Basic scopes of tracer tests are proving connectiors of karst water passages and delineation of catchment areas. Further results are ground water flow velocities and other geohydraulic parameters like dipersivities and tracer recovery rates (Leibundgut & Weingartner 1982).

The influence of tectonic structures on karst drainage patterns is already well known. E.g. development of cave rivers or location of karstic springs is often linked with fault zones. But not every fault zone has to be necessarily a preferential flow path. Compression and frictional sliding clay might seal a fault zone. In some cases an existing joint might be invisible at the surface. Geological mapping and geophysical survey are useful methods to localise tectonic structures and their spatial patterns. A tracer test is the tool to prove the drainage function of a fault zone.

AREA OF INVESTIGATION

The area of investigation is located in the Alps of Eastern Switzerland near Liechtenstein. The Voralp Valley is situated within the Churfirsten-Alvier range as a tributary valley to the Rhine Valley of St. Gall. In the central part of Voralp Valley the Lake Voralp is dammed up by a Pleistocene rockslide. The lake is drained sublacustric and has no surface outflow. Altitude of the lake is 1122 m and has an average surface of 1.3 km^2. Surrounding mountains are up to 2385 m.

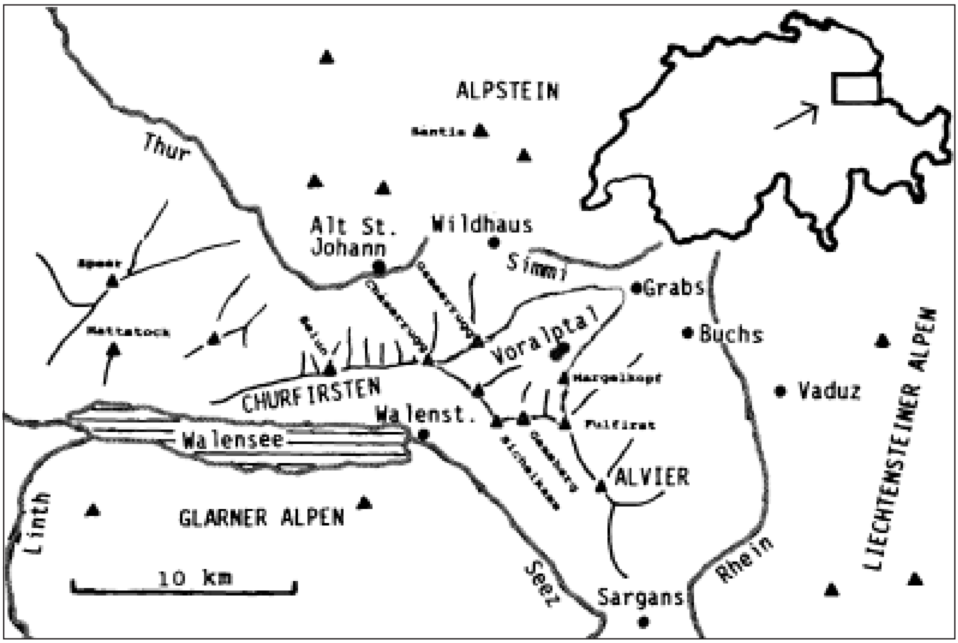

Fig. 1: Area of investigation and its location within Switzerland.

Calculated discharge from the lake varies from ca. 10 l/s in winter to 500 l/s under snowmelt events in spring or after heavy stormflow events (Ross 1993). This temporal drainage pattern fits well to the nival run-off regime of moderate alpine regions (Aschwanden & Weingartner 1986). The water level of the lake has a strong seasonal variation of several meters.

Previous studies and local people postulated a drainage system from Lake Voralp through the updamming rockslide material down to the next spring Rogghalmquelle at the base of the rockslide. This idea sounds very reasonable: the topography towards this spring, which is the closest, fits well, the boulder deposits might be permeable and spring discharge is in the same magnitude as lake drainage. Already in 1909 a tracer test should have prove this hypothesis, but it did not show any result (Hug 1911). A couple of tracer tests were conducted during the following decades (Weber 1976, Rohrer pers. comm., Rieg 1994), but none of them could prove the connection from lake to spring, not show any other results.

Due to intense mountain pasturage, tourism facilities and fishery use the water quality of Lake Voralp is temporarily very poor (Kaiser 1992, Ross 1993). This goes particularily for water hygienity. In the regional scale the area has an increasing demand for drinking water supply. Several important springs are situated in the lower part of Voralp Valley and in vicinity. For sustainable drinking water supply it is crucial to protect the catchment areas and to understand the lake drainage system.

GEOLOGY

Churfirsten and Alvier are part of the Helvetical nappes, which are formed by Cretacious layers of limestone and marl (Fig. 2). A hydrogeological characterisation in respect of water permeability of the most important layers shows Tab. 1.

Table 1: Hydrogeological characterisation of Churfirsten-Alvier geology.

Highly karstified limestones	Moderate karstifed limestones	Marly and non-karstified layers	Quaternary
• Seewerkalk • Schrattenkalk	• Gault • Kieselkalk	• Drusbergmarl • Flysch	• Pleistocene rockslide • Holocene moraines
Highly permeable and well developped karst features	Permeability depends on degree of fracturisation - usually moderate	Both layers are considered as impermeable	Medium permeable deposits with high spatial heterogenity

In the Tertiary during the orogenetic process of alpine folding the entire Helvetical nappe had been moved in two steps of maybe 10 km and 40 km north. This translation caused slightly north-east-ward dipping and various anticline structures occured (Heierli 1984). Voralp Valley had been an area of extreme strong tectonic actions with partial overdipping anticline structures and several very strong fault zones. Lake Voralp is underlain by flysch which is building a contact karst zone with seewerkalk (limestone) and rock slide material. The Rhine Valley has an Quarternary porous aquifer in contact to the under this aquifer dipping limestones of Churfirsten and Alvier.

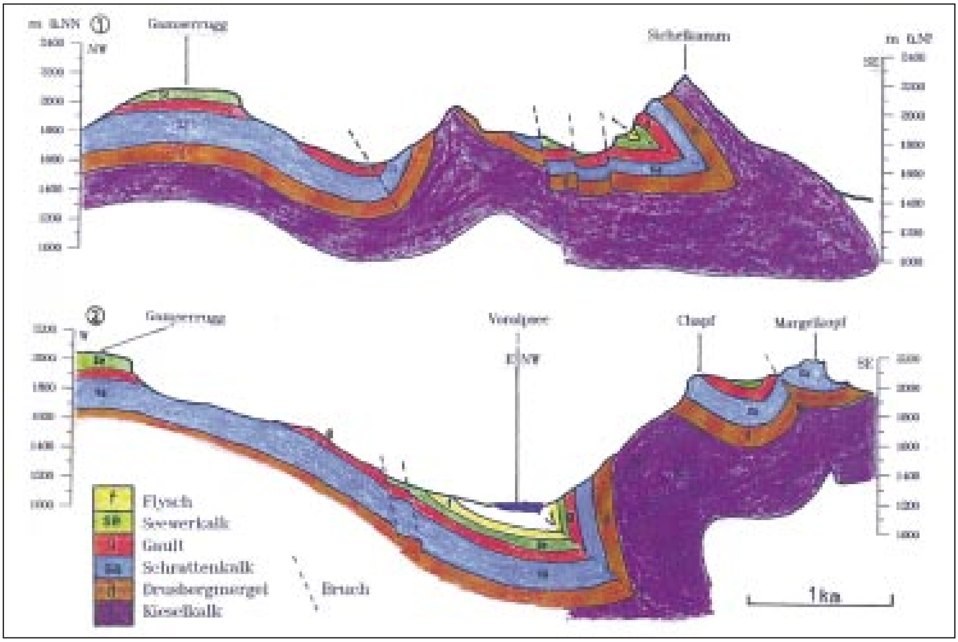

Fig. 2: Geological cross sections through upper and central Voralp Valley (Ross 1993).

TRACER EXPERIMENTS

In July 1992 a multi-tracer test was conducted at different sites of upper Voralp Valley in order to delineate the catchment area of Lake Voralp (Ross 1993, Rieg 1994). These tracer tests showed karstwater connections to springs beyond topographical ridges in other valleys and through marly layers which should be rather impermeable. The only way to explain these results is to conclude that water can pass the impermeable layers by some water-conductive fault zones. Thus Lake Voralp might be drained by fault zones, too.

As far as documentated all previous tracer test injections were made at low tide conditions (so access to sinkholes at the dry bottom of the lake is easy). In order to investigate the active drainage system a submerged sinkhole was spotted out precisely at the shore line of the lake. Injection took place on the 10th September 1992 few days after a heavy storm flow event. At this time the sinkhole funneled several l/s and was accessible from the shore. To avoid interference with fluorescent dyes from other tracer tests Rhodamine WT was chosen and 8 kg (diluted in 40 l of water = 20 %) were injected within a few minutes. Hence the natural and active drainage system was used no additional flushing was necessary.

Water sampling included all springs in lower Voralp Valley, springs in the next valley to the east and even some very remote but important springs were monitored. 7 springs were equipped with automatic sampling devices (Type APEG), six other sites were checked every other day by the local water supply authority. In addition all sampling sites were equipped with charcoal fil-

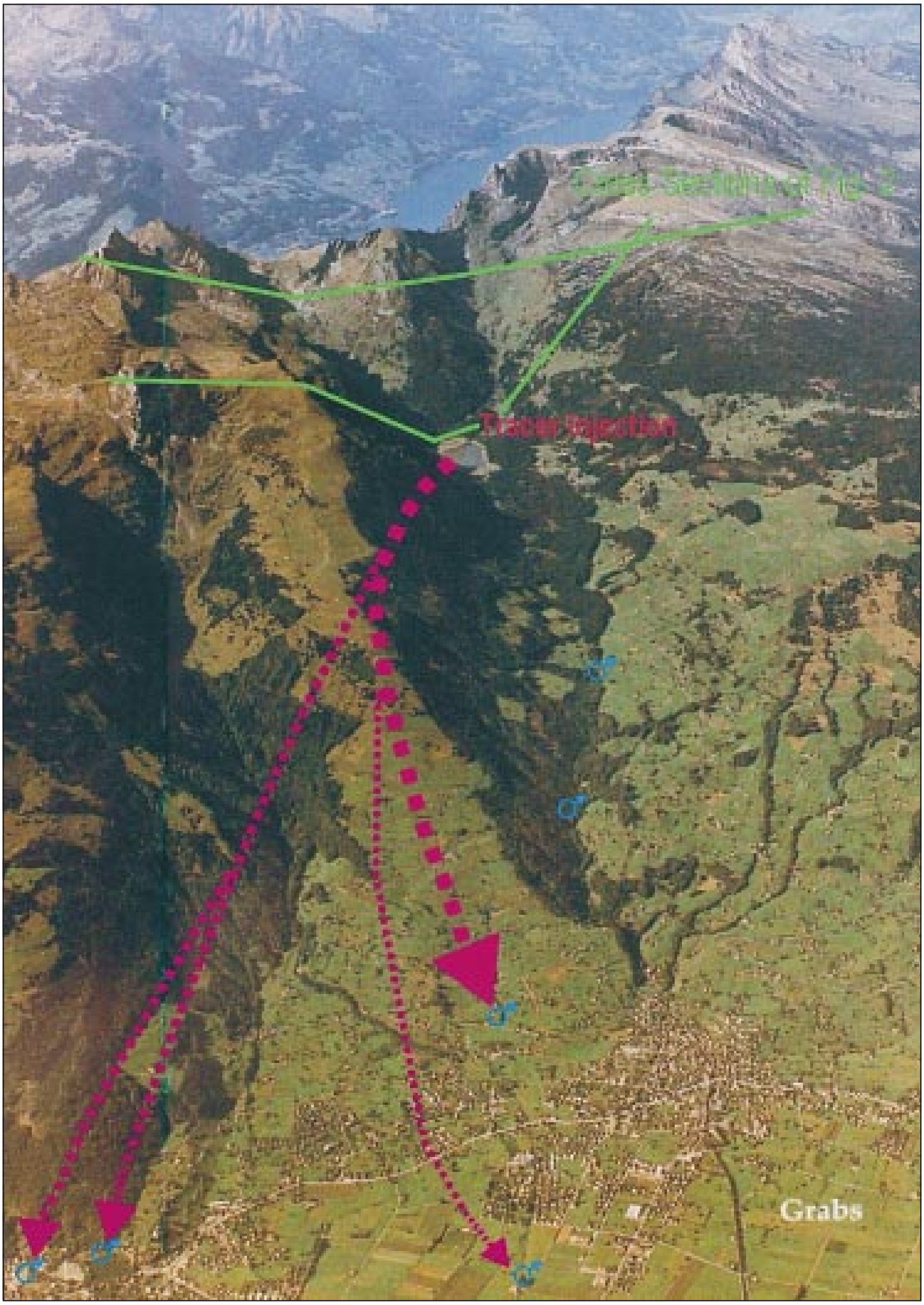

Fig. 3: Karstwater passages from Lake Voralp.

ters. Analysis was done at the lab of the Institute of Hydrology using a fluorometer type Perkin Elmer 3000 and the synchro double scan procedure.

Performance of the tracer test fulfils the requirements of the new Swiss tracer guideline (Schudel et al. in prep.). Aside of the basic scope to detect flow paths, the following flow parameters were estimated by tracer breakthrough curves:

1. Time between dye injection and first tracer detection.
2. Time between dye injection and arrival of the tracer peak.
3. Flow velocities (assuming a straight line from injection to sampling point).
4. Dispersivity as a represantive number for the spreading of a tracer plume within one flowpath - calculated according to the analytical solutions of Maloszewski & Zuber (1990).
5. Percentage of tracer recovery - calculated by tracer concentration and discharge in respect of injection mass. Hence accurate discharge gauging was not available; only rough numbers were estimated.

RESULTS

Lake Voralp drains to several springs in the next valley east of Voralptal and to the Rhine Valley (see Fig. 1). First tracer dye appeared less then two days after injection at Hugobühl spring, which is an important spring for local drinking water supply. Minor connections appeared few days later at two more remote springs (Werdenberger See and Traubenweiher) beyond this valley. And a very weak connection could be monitored at Butziferi spring of the porous aquifer of the Rhine Valley (see Fig. 3 for location of detection sites and flow paths). No tracer appeared at the Rogghalm spring at the base of the rockslide, where monitoring was very carefully carried out for more then two months until 17th November. Fig. 4 shows the tracer breakthrough curves, and key numbers are given in Tab. 2. Dispersivities and medium velocities were calculated by using a dispersivity model.

DISCUSSION - CONCEPTUAL MODEL OF THE DRAINAGE SYSTEM

The detected main karst water passage is leading to Hugobühl spring. Flow velocities are rather high and the travel time is short. The tracer breakthrough curve is very broad and shows a peak of a secondary tracer maximum (Fig. 4). The obtained tracer breakthrough curve looks like the result of several interfering flow paths. This interpretation is supported by dispersivity modelling, too. Dispersivity for the first peak is about 120 m, which is high but reasonable number. Modeling the entire breakthrough curve would give a very high dispersivity value.

Tracer concentrations of breakthrough curves at Werdenberger See and at Traubenweiher are by a magnitude weaker, but they indicate still quite fast flow paths. These karstwater passages show a wide spread and bifurcated drainage system for Lake Voralp. Butziferi is a small karstwater discharging spring at the bottom of St. Gall Rhine Valley. Tracer concentrations exceed only a little the analytical detection limit for Rhodamine WT (0.015 ppb), but it is an important tracer detection for the comprehensive interpretation of the tracer test. Tracer emerging at Butziferi must have passed the porous aquifer of the Rhine Valley.

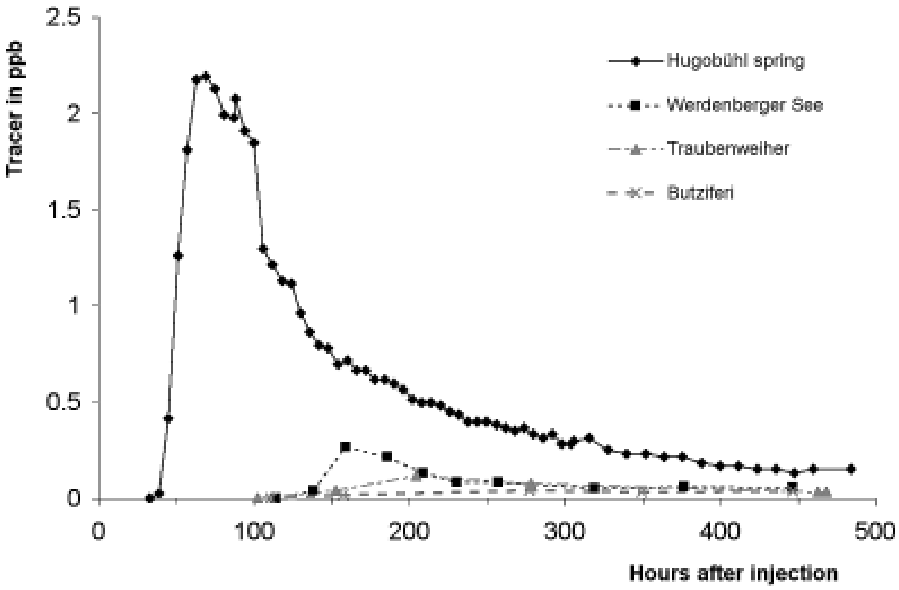

Fig. 4: Tracer breakthrough curves at the springs Hugobühl, Werdenberger See, Traubenweiher and Butziferi.

Table 2: Karst water passages from Lake Voralp (Injection 10.09.1992 02:00, 8 kg RWT).

Site:	**Hugobühl spring**	**Werdenberger See**	**Traubenweiher**	**Butziferi**
Distance	5,2 km	6,4 km	6,9 km	6,1 km
Min. travel time	39 h	138 h	152 h	157 h
Peak travel time	69 h	159 h	204 h	277 h
Max. Velocity	132 m/h	46 m/h	45 m/h	39 m/h
Peak Velocity	75 m/h	40 m/h	34 m/h	22 m/h
Mean Velocity	71 m/h	38 m/h	(29 m/h)	-
Dispersivity	120 m	80 m	(235 m)	-
Tracer Recovery	0,25 %	0,05 %	0,02 %	< 0,01 %

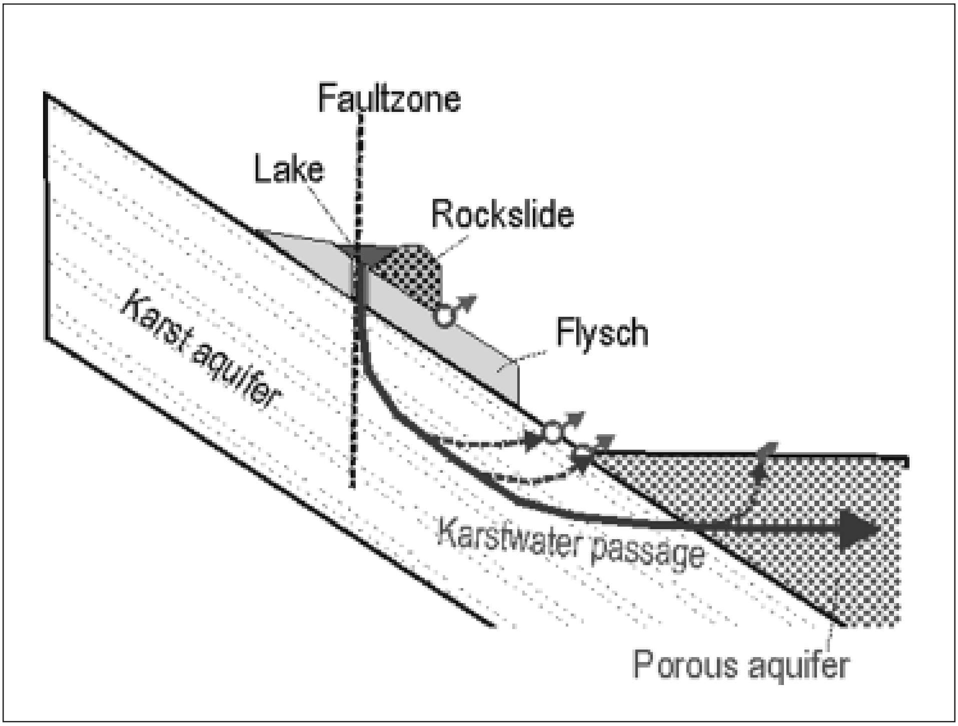

Fig. 5: Conceptual model of Lake Voralp drainage system.

Tracer recovery from the 4 proved flow paths is altogether, with less than 1 %, extremely low. In this study a tracer loss of 99 % cannot be explained sufficiently by tracer sorption phenomena. Rhodmine WT is a sorptive fluorescent dye, but injection conditions were ideal.

Neither this nor previous tracer tests showed a connectivity of Lake Voralp and Rogghalm spring. Thus Rogghalm spring is very unlikely to drain the lake. Discharge at this spring can be explained by another catchment area. Geological information and data from the tracer test can be used to set up a conceptual model of Lake Voralp drainage system (Fig. 5).

A fault zone within an overdipping anticline structure enable the lake to drain into the karst system. Otherways the water could not pass the impermeable flysch and marly layers. Flow path bifurcations do occur due to fracturisation. Most lake water drains directly as an afflux from the mountain karst system to the porous aquifer of the Rhine Valley. The marginal karst springs of Hugobühl, Werdenberger See and Traubenweiher serve as overflow. It is not possible to determine percentages of direct afflux and spring discharge within this drainage system. The ratio will vary in respect of the actual hydrogeological situation. Under low flow almost all water should flow directly into the porous aquifer whereas under flood conditions more and more karst water will emerge at the springs.

CONCLUSION

Tracing an active sinkhole of Lake Voralp provides a key to understand principles of the lake's drainage system. The lake does not drain via the updamming to the closest spring Rogghalm. The drainage system in the contact karst zone of Lake Voralp is controlled by fault zones. Key factors to understand the Lake Voralp drainage system are provided by tectonic structures and not by lithology of geological layers. Lake drainage system is a bifurcated pattern with a major connection to Hugobühl spring and other springs. Tracer at Butziferi and a low tracer recovery rate indicate a tremendous direct afflux of karstwater from the mountain range to the porous auqifer of the Rhine Valley. Contact of limestone and porus aquifer is another contact karst zone. Hydraulic properties of the karstwater passages depend strongly on the hydrological situation. Flood conditions were crucial for tracer test success the traced springs gave the hints to understand the system. Under low tide the tracer would have remained undetected as under previous tracer test. Choosing a suitible injection time is an important part of carefull tracer tests in karst environment.

ACKNOWLEDGEMENTS

Research at Lake Voralp was part of the project "Karstwasseruntersuchungen Churfirsten/ Alvier" entrusted by the State of St. Gall to the Institute of Hydrology at the University of Freiburg (Germany). Thanks to all the project members for assistance in the field and in the lab. Thanks to the Municipal Water Supply of Grabs for supporting the spring monitoring.

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Povzetek

Jezero Voralp je majhno kraško jezero v hribovju Churfirsten-Alvier v Vzhodnih Švicarskih Alpah. Hribovje je del krednih helvetskih pokrovov, ki jih sestavljajo plasti laporjev in zakraselih apnencev ter tudi fliša. Jezero je zajezil pleistocenski podor in je brez površinskega odtoka. Glede na hidrogeološki položaj bi sklepali, da voda odteka skozi podorno gradivo do bližnjega večjega izvira, toda razni predhodni sledilni poizkusi niso potrdili te domneve.

Sledilni poizkus z barvilom, ob poplavi, je pokazal, da odteka voda iz jezera zelo na široko, v oddaljene kraške izvire in tudi neposredno v porozni vodonosnik v dolini Rena. Ta kraški odtok prečka tudi nezakraseli fliš in lapornato plast. Te plasti so litološko precej neprepustne in odtok kraške vode skoznje omogoča preteklo tektonsko dogajanje. Kljub manj prepustni kamnini pod podornim območjem, je odtok pod jezerom odvisen od tektonskih struktur. Nekatere prelomne cone so dobro vidne na terenu ali dokumentirane na podlagi prejšnjih raziskav, toda brez sledilnega poizkusa ni mogoče potrditi njihovega prevladujočega vpliva na kraški odtok v kontaktnem pasu.

Ključ za razumevanje jezerskega odtoka je bilo sledenje vode iz aktivnega ponora jezera Voralp. Ključni elementi v razumevanju odtoka pa so tektonske strukture in ne litološka sestava geoloških plasti. Odtočni sistem iz jezera je bifurkacijske narave z glavno zvezo proti izviru Hugobühl in proti ostalim izvirom. Sledilo, ki se je pojavilo v Butziferu ter nizek delež povrnjenega sledila kažejo na močan neposreden odtok iz hribovja v medzrnski vodonosnik v renski dolini. Stik apnenca in medzrnskega vodonosnika je drugi pas kontaktnega krasa. Hidravlične značilnosti odtoka kraške vode so močno odvisni od hidrološkega stanja. Poplavno stanje je bistvenega pomena za uspešno sledenje - izviri, v katerih se je pojavilo sledilo, so ključ za razumevanje sistema. Ob nizkem vodnem stanju sledila ne bi bilo mogoče zaznati, kar se je zgodilo ob prejšnjih sledenjih. Pomemben del skrbnega sledilnega poizkusa je tudi ustrezno izbran čas injiciranja.